International workshop

Decision support systems (DSS) for river basin management

6 April 2000

Koblenz
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International workshop

Decision support systems (DSS) for river basin management

6 April 2000

Koblenz

In the past, river-basin management and planning used to focus on water-quality issues and, above all, on the safe discharge of floods. Thanks to the growing awareness that river-basin management is not feasible in the context of sustainable use of waters without paying due attention to ecological aspects, the questions of river ecology came more and more into the foreground of planning procedures and public discussions. Finally, since the amendment of water legislation in the sense of "managing waters as elements in the balance of nature", the interdisciplinary approach to the management of waters has gained also a political dimension.

Against this background, river-basin management requires a broad spectrum of specialized knowledge which provides the basis for decision making for planning or protective and preventive actions etc. While data acquisition is usually no serious problem, there are hardly any decision aids available so far. Either decisions are taken in secluded expert meetings, or they are the result of complicated, protracted procedures with the participation of those affected by the decision.

The Project "towards a generic tool for river basin management", being launched following an initiative of the German Federal Institute of Hydrology (BfG), is an attempt to bridge this gap, at first at the example of the river Elbe.

In November 1999, a feasibility study was started to explore the possibilities and requirements for the development of this generic tool as a Decision-Support-System (DSS). In such a DSS, a structured approach towards river basin management should be combined with the new resources of information technology, leading to an instrument that facilitates the processing, analysis and presentation of information. Use will be made of the data bases and existing knowledge on the river Elbe mainly gained in two research programmes financed by the German Federal Ministry for Education and Research (BMBF) (Elbe 2000, research on water quality and Elbe Ecology, research on ecological functionalities of the river, the floodplains and the catchment area).

The intention of this BfG-workshop in Koblenz is to pool the latest experience with DSSs related to water management in Europe. Therefore several experts representing different branches of river basin management were invited to present their knowledge concerning practical applications of DSSs or their design.

In addition to the themes covered by the Elbe project, the following topics from different European projects were presented. The DSSs already running were developed for certain aspects of traditional water management. One group of DSSs covers aspects of water management in the sense of water quality, wastewater discharge etc. (Czech Republic; Germany, rivers Oder and Neisse). A second group is related to flood protection and reservoir
management including ecological aspects (Germany, models: TALSIM, IkoNE [Neckar], developments for the Elbe; The Netherlands, extended LPR-DSS). The third group of DSSs, mainly still under development, covers overall aspects in river basin management like natural dynamics of ecosystems, economic welfare and social justice or equity under the overriding goal “sustainable development”. (Germany, University Karlsruhe). Another DSS with emphasis on library and management functionalities was designed for the mapping and assessment of ecomorphological river quality to meet the standards of the proposal of a Council Directive for a framework for community action in the field of water policy. In The Netherlands the system MODULUS as a generic spatial DSS for integrated environmental policy-making at regional level has been developed. In MODULUS different models from EU-projects are integrated that represent the physical, economic and social aspects of land degradation and desertification in Northern Mediterranean watersheds. Finally two DSSs (SimCoast, STEM) from the United Kingdom were presented in form of an expert system covering a wide variety of scenarios which are able to produce impressive visualized results in a very short time to support decision making in planning processes in coastal zones.

Dr. F. Kohmann
Head of the Devision Ecology

V. Hüsing
Department Ecological Interactions
Agenda

8.30  Opening
(F. Kohmann, BfG Koblenz, D)

8.40  Conceptional elements for an Elbe-DSS
System diagram for river-basin management and first results from feedback with Elbe Ökologie and Elbe 2000
(J. L. de Kok, Uni. Twente, NL)

Concepts of DSS systems
(G. Engelen, RIKS, NL)

Georeferenced regional simulation and assessment of water quality
(J. Berlekamp, M. Matthies, Uni. Osnabrueck, D)

Discussion

9.45  Coffee break

10.00 Existing DSSs for Water Quality Management (1)

TALSIM – Decision support for a river basin management
(M.W. Ostrowski, Uni. Darmstadt, D; H. Lohr, A. Leichtfuss, WIS Darmstadt, D)

Application of Decision Support Systems for water management strategies in the Czech Republik
(J. Krejčík, Hydroinform Prague, Cz)

Overview and developments of Decision Support Systems for large rivers in the Netherlands
(R. Schielen, RIZA, NL)

Discussion

12.00 Lunch
13.00 Existing DSSs for Water Quality Management (2)

Environmental Management Methodology to Support Sustainable River Basin Development, - Features of a Goal-Oriented Decision-Support System (DSS) -
(F. Nestmann; W. Buck, C. Kaempf; P. Oberle, S. Theobald; J. Ihringer, M. Helms, B. Buechele; IWK Uni. Karlsruhe, D)

Multi-objective Decision Support for water quality management of the rivers Oder and Lausitzer Neiße
(A. Gnauck, Tech. Uni. Cottbus, D)

A GIS-based Decision Support System for the Mapping and Assessment of the Ecomorphological Quality of Running Waters
(M. Haase, G. Barnikel, R. Beuerle, K. Tochtermann (FAW Ulm); R. Schaldach (Uni Braunschweig))

A spatial modelling tool for integrated watershed management: Lessons learned from the EU-project MODULUS
(G. Engelen, B. Hahn, Research Institute for Knowledge Systems bv, Maastricht, NL)

Discussion

15.00 Coffee break

15.15 Existing DSSs for Costal Zones

SimCoast, a fuzzy logic, rule-based expert system for coastal zone management
(H. Bottrell, K. Morris, GeoKronos, Plymouth, UK)

STEM (Spatio-Temporal Environment Mapper): A 4D GIS front-end data viewer to a generic data model
(K. Morris, K. Morris, GeoKronos, Plymouth, UK)

Discussion

16.15 Final session

16.45 Closure

organized by: Federal Institute of Hydrology
Kaiserin-Augusta-Anlagen 15-17
56068 Koblenz
Germany
1 Introduction

Over the last decades river basin management has become increasingly complex. Increasing demands of society regarding use and protection of water bodies, new views and strategies towards (the making of) policy for river basin management call for a multidisciplinary approach for river basin management.

Since methodologies and tools for such a multidisciplinary approach are not readily available, the Bundesanstalt für Gewässerkunde (BfG) has initiated the feasibility study ‘Towards a generic tool for river basin management’. The ultimate goal of this project is to develop a generic tool that helps the water managers to formulate policy for river basin management and to take appropriate measures to realise policy objectives. In this study we look at such a generic tool as a so-called Decision Support System (DSS). The focus is on the approach for the development of such a tool: design procedure, contents, functionality, technical specifications, opportunities and risks and required effort.

The Elbe river is selected as a case. Hence, the feasibility study will result in recommendations for a pilot study focussing on some selected topics in the Elbe catchment area, which could be considered for implementation in a period of three years following the feasibility study. The feasibility study consists of 5 phases: problem definition (1), system design for the DSS (2), available data and science related to the system design (3), the informatic framework for the DSS (4) and a covering note (5).

The problem definition forms the starting point for the design of the (pilot) DSS. The purpose of this phase is to identify the so-called end-users of the model (i.e. persons or institutes who can be identified as problem-owners), establish the desired functionality of the (pilot) DSS, make an inventory of relevant problems, determine the objectives to be achieved, identify tentative measures, and determine the spatial, temporal, economic and other boundaries of the system. In short: the problem definition delineates the scope of the study. It is most important to involve the end-users of the pilot DSS in this process. After all, they are the ones that are going to use the DSS. It is therefore necessary to accommodate end-user participation when developing a DSS.

2 Identification of problem owner and problems

There is not a single problem owner for the Elbe catchment. Instead a number of potential end-users, each having their own objectives and measures, were identified:

- J.L. de Kok, H.G. Wind, H. van Delden, M. Verbeek: System diagram for river-basin management and first results from feedback with Elbe Ökologie and Elbe 2000
Internationale Kommission zum Schutz der Elbe (IKSE);
Federal ministries and institutions;
State governments and institutions;
Biosphere Reserves.

The principal function of the prototype is to demonstrate how problems can be dealt with. By definition a problem is a difference between the actual and desired state of the system (Hoogerwerf, 1989). Without a problem there is no need to analyse measures. It is only possible to identify the problems to be addressed by the prototype model once a definitive choice for specific problem owners has been made. Nevertheless, a number of problems were mentioned by representatives of several of the institutes listed above, as well as researchers involved in the Elbe ecology program. The problems that could be worth including in the prototype model are:

- how to improve the socio-economic use of the river basin (shipping, tourism, fisheries, agriculture, etc.);
- how to provide a sustainable level of flood protection;
- how to reach a sustainable improvement of the physical, chemical and biological state of the Elbe and its tributaries;
- how to reduce the load of chemicals into the North Sea;
- how to increase the ecological value of the river and the floodplains in the Elbe river basin.

3 Management objectives and criteria

A management objective is a desired state of the system that a decision-makers want to achieve. The objectives are closely related to the problems. For example, if river navigation is a problem, the objective can be to make a particular section of the Elbe river navigable. Achievement of the objectives is measured by means of (usually quantitative) criteria such as a guaranteed water depth of 1.60 m. For the design of the DSS the objectives are of particular importance as they determine which information the model should provide to its users. Referring to the identified problems the following main objectives can be discerned:

- improvement of socio-economic use:
  - improvement of navigability of the Elbe river;
  - maintain/improve agricultural yield;
  - growth of tourism & recreation;
  - improve conditions for fisheries;
- flood protection:
  - reduction of the risk of flooding;
- improvement of physical, chemical and biological state of the Elbe and its tributaries and increase of the ecological value of the river and floodplains:
  - river and ground water quality, including toxic chemicals
  - sediment/soil quality of the river bed and the floodplains;
  - reduce input into the North Sea;
  - improve ecological functions of the catchment area;
  - improve ecological functions of river and banks;
  - improve ecological functions of flood plains.
4 Measures and themes for the pilot DSS

As stated before the main function of the DSS is to link the measures that can be implemented to solve the problems to the objectives. Suggestions for promising measures can be made by the end-users themselves, or the team of researchers designing the model. Although the measures are tentative their selection should be made with care. There is no point in analysing measures that are too expensive or unacceptable for other reasons. Furthermore, one should be aware of the models and data that are needed to analyse the consequences of the selected measures. For the prototype model it is recommend to select limited number of measures. These measures come under the following five themes:

1. High water management: dike shifting and other measures:
   - dike shifting (space for the river);
   - reduction of buildings and other treasuries in the foreland;
   - provide information on high water management.

2. Water quality:
   - reduction of point- and non-point-source pollution by improving agricultural practice (Nährstoffe, Bekämpfungsmittel);
   - reduction of pollution by hazardous substances (Schadstoffe);
   - improving/building waste-water treatment plants.

3. Groin modification:
   - groin modification.

4. Reduction of erosion:
   - adding material to the river bed/sand suppletion.

5. Reduction of erosion:
   - several measures.

5 Scope and functions of the DSS

The DSS can be used to perform different functions for the following purposes: learning, analysis (analysis-based), information, management, database, communication between end-users and to the public (information/communication-based).

In the case of the Elbe the most important functions are analysis, followed by communication, management and the library function. For internal use of the BfG it is also important to have a knowledge management function, which can be used to see what areas the different models cover and if there are blank spots (gaps in the information).
6 Preliminary system design

A modular structure is suggested for the DSS to deal with different spatio-temporal scales of the processes involved. Module 1 is defined at river-basin scale, and describes the relationship between landuse and runoff. Module 2 pertains to the Elbe river and focusses on water quality, shipping, flood control, and large-scale ecological changes. Module 3 is defined for a representational section of the floodplains and describes the local ecomorphological consequences of selected river engineering measures.

Information

For information about the Elbe DSS please refer to Bundesanstalt für Gewässerkunde (BfG), Herrn Dr. F. Kohmann, +49-261-13065320 / kohmann@bafg.de, Dr. S. Kofalk +49-30-63986436 (Fax: -439) / kofalk@bafg.de, or http://elise.bafg.de.

![Tentative design for the DSS](image-url)
1 Introduction

Over the last decades river basin management has become increasingly complex. Increasing demands of society regarding use and protection of water bodies, new views and strategies towards (the making of) policy for river basin management call for a multidisciplinary approach for river basin management. Since methodologies and tools for such a multidisciplinary approach are not readily available, the Bundesanstalt für Gewässerkunde (BfG) has initiated the project ‘Towards a generic tool for river basin management’.

The ultimate goal of the project is to develop a generic tool, which helps water managers to formulate policy for river basin management and to take appropriate measures to realize policy objectives. The software realization of such a tool is called a Decision Support System (DSS) or more specific for the domain at hand: Integrated River Basin Management Decision Support System (IRBM-DSS).

In this paper we focus on two aspects of the development of an IRBM-DSS:

1. What does it mean for the IRBM-DSS to be ‘generic’?
2. What is appropriate software architecture for the IRBM-DSS?

1.1 What is a Decision Support System

Decision Support Systems can be described and categorized from a variety of viewpoints. A good overview of the various proposed classification methods is given in [Marakas 99]. For our purpose here it is sufficient to distinguish between two main groups of DSS, namely data-oriented and model-oriented DSS.

Data-oriented DSS are primarily concerned with retrieval, analysis and presentation of data. Model-oriented DSS include activities such as simulation, goal-seeking and optimization.

The domain of integrated river basin management is concerned with understanding and acting upon a highly complex and dynamical system of interrelated physical and non-physical processes. The DSS provides a representation of this system in form of an integral model. Although data analysis and presentation are important functions of the IRBM-DSS, it therefore clearly falls under the category of model-oriented DSS.

A DSS can be distinguished from more straightforward engineering applications by its capability to address ill-defined problems. To achieve this, the DSS often features a knowledge engine that applies various artificial intelligence methods to a formal representation of expert knowledge from the problem domain.

- Assists in exploring decision space

Integrated river basin management confronts the decision maker with numerous possible measures, as well as multiple, possibly conflicting objectives. Together these measures and
objectives form the *decision space*, and the decision maker uses the simulation facilities provided by the DSS to explore and navigate it.

- Applies scientific knowledge to policy
- Nowadays policy makers more than ever need to apply the latest scientific knowledge to their decision-making, due to . In order to and the need to provide scientific justification for their decisions
- Makes use of quantitative techniques
- Readily accessible to the high-level decision maker
- Adaptable to changing needs and environments of the problems studied

2 Requirements

2.1 Scope and functions of a IRBM-DSS

2.1.1 Analysis

A complex integral model provides a holistic representation of the system, by explicitly defining the linkages between the natural system and the socio-economic system. In general analysis functions require a description of the system at the appropriate levels of spatial detail and temporal scales. In practice analysis skills are one of the most important functions of the DSS. Analysis capabilities will be important at different points/levels of the DSS system. First of all the user may want to analyze the current state of the river basin. This includes an inventory of all relevant functions of the river basin (e.g. socio-economical and ecological functions) for the desired decision process. Secondly analysis functions are necessary for evaluation of the effects and impacts of the measures on the river basin. The calculated projected state of the river basin has to be compared to the current state as well as to the desired state. By comparing projected and desired state the user will be able to decide if further measures are necessary to reach the desired state.

2.1.2 Communication

An integral IRBM-DSS can facilitate communication between policy makers and stakeholders in participative planning efforts. Interactive simulation of the integral model shows the stakeholders how their different views on the system are related to each other. Transparency of the system guarantees that the stakeholders recognize their domain explicitly represented in the system. Transparency and user friendliness thus are the key factors for the system to function as a mediating device in a collaborative planning context. Part of the user friendliness is the responsiveness and speed of the system, which are particular important in brainstorm-like sessions, where one wants to explore different scenarios during a discussion.
2.1.3 Library (knowledge base)

An IRBM-DSS based on an integral model can serve as a knowledge management infrastructure. It gathers, orders and links existing knowledge about a system and therefore can fulfill the function of a dynamic library. It may reveal knowledge gaps, and thereby give impetus to further research and data collection. Through the IRBM-DSS knowledge about a system becomes available in operational form. The IRBM-DSS can be a common infrastructure for storage and transfer of the knowledge for participating organizations and possibly the general public.

2.1.4 Management

Management is a function of the DSS that is important for the users that have to evaluate general decisions and turn them into realizable measures. From the set of possible measures they have to select those that fit best to the objectives. Of course financial aspects must be taken into consideration and therefore have to be evaluated.

2.1.5 Learning

A DSS cannot only be used for analysis, communication or other of the already above mentioned functions but also for learning purposes. Primarily this means learning about the linkage of processes, natural and user functions, which build a complex network of the system with multiple interdependencies. Even if experts are familiar with the dependencies in their special field of interest they may use the DSS for learning about the linkage to unknown functions.

2.2 Generality and flexibility

Before heading into requirements engineering and systems analysis for the IRBM-DSS, we think it is essential to define more precisely what it means to state that the system should be ‘generic’. Such a definition is needed because generality and flexibility may be built into software systems in a number of different ways and at various degrees.

Choices in this area not only have a huge impact on the development effort for the IRBM-DSS, but also affect the entire product lifecycle and even can make a difference in what is perceived as ‘the product’. In this sense generality and flexibility could be seen as meta-requirements, because they define conditions for the development of other functional and non-functional requirements of the system.

Within the context of this feasibility study and the development of a pilot version of the IRBM-DSS, our discussion of generality and flexibility issues is related to the following questions:

1. What do we want to demonstrate with the pilot?
2. How should we allocate our resources to various development activities?
3. What is an appropriate development process?
Naturally the pilot study is more biased towards demonstrating what is usable and technologically possible for selected problem areas of river basin management systems, rather than working out a flexible but abstract architecture that could form the basis for future DSS applications in this domain.

However, from projects like WadBOS and EnvironmentExplorer, which have survived the prototype phase of their lifecycle and are now in use for real world policy support, we have learned how important it is to put effort in a flexible and generic architecture as early as possible.

Despite better intentions in the beginning, prototypes are rarely thrown away. Once users get enthusiastic about the system, the distinction between ‘prototype’ and ‘product’ starts to vanish and the prototype/product is incrementally improved. It is then the flexible and generic architecture that makes it possible to deal with the frequent requests to add, change or replace models, indicators or other tools in the system while maintaining high quality and keeping the costs for this continuous change under control.

Thus depending on the answers to the above questions, we should define the dimensions as well as the level of generality at which we want to aim with our system architecture. With such a definition at hand, we are better equipped to design a system framework, which provides useful spots for variability and extension.

In the following paragraphs we will discuss the various options open to us to build generality and flexibility into our system, the economics of generality in terms of costs and benefits, as well as the relation between various kinds of system generality and user roles. In particular reusability and extensibility, two important aspects of generic systems, will be discussed.

2.2.1 Reusability

With respect to generality the problem definition report mentions one important requirement: … an IRBM-DSS developed for the Elbe should be applicable to other large river systems as well.

Obviously this requirement is concerned with reusability. As we will soon see, achieving reusability is an ambitious goal for an IRBM-DSS, both from a scientific (with respect to the models) and a software engineering point of view. The remainder of this paragraph will focus solely on the software engineering aspects of reusability within the context of the development of an IRBM-DSS. This does not mean that the scientific aspects of (model) reusability are less important or less difficult to deal with. These problems however are dealt with in a dedicated section of this feasibility report.

In software engineering reusability neither happens automatically nor is choosing an object-oriented development method sufficient to obtain reusable system components. Reusability does not come ‘for free’. It requires a deeper conceptual and technical analysis and additional software engineering effort, compared to what is necessary for a perfectly working one-time solution for the same problem. Therefore developing for reusability should be seen as a long-term investment and, as with any investment, it is a calculated risk. The risk factor is, to weigh
the chances that the system or some of its components actually will be reused against the extra effort that is required to create a more generic reusable solution.

In order to take into account the reusability requirement for the IRBM-DSS systems architecture, it is helpful to formulate and answer the following questions:

1. What are the reusable artifacts?
2. Who is reusing what?
3. When does reuse take place?

**2.2.1.1 What are the reusable artifacts?**

Here follows a list of possible reusable artifacts that will be generated during the development phase of the IRBM-DSS (adapted from [D’Souza 99]):

- System as a whole (one large executable object: black-box component)
- Scientific models with or without software implementation
- Compiled code, executable objects (black-box component)
- Source code; classes, methods (white-box component)
- Designs and models: collaborations, frameworks, patterns
- Plans, strategies, algorithms and architectural rules
- Interface specifications
- User interfaces

Note that nearly all artifacts being produced in the system development process have the potential to become reusable assets. Which ones are most appropriate is not only a technical choice, but also depends on organizational and economic aspects of the project.

In [D’Souza 99] some helpful rules are given for making a rational choice:

**Reuse Law 1**

Don’t reuse implementation code unless you intend to reuse the specification as well. Otherwise, a revised version of the implementation will break your code.

**Reuse Lemmas**

1. If you reuse a specification, try a component based approach: Implement against the interface and defer binding to the implementation.
2. Reuse of specifications leads to reuse of implementations. In particular whenever you implement standardized interfaces, whether domain-specific or for infrastructure services, you enable the reuse of all other implementations that follow those standards.
3. Successful reuse needs decent specifications.
4. If you can componentize your problem domain descriptions themselves and reuse domain models, you greatly enhance your position to reuse interface specifications and implementations downstream.

Reusing more abstract artifacts like interfaces, specifications, (collaboration) patterns and frameworks yields the largest benefit, but these artifacts are also the most difficult to produce from scratch. Generally, the easier way is to evolve from the concrete towards the abstract:
Suppose we are working with an object-oriented development environment and have represented our relevant domain concepts as classes and objects. We try to identify common behavior in the classes and factor it out into a set of base classes, which gives developers the benefit of code reuse by inheritance. Often we will discover, that many typical operations and interactions between these base classes can be specified without providing any particular implementation. Such a specification is called an interface. Interfaces bring us one step further towards reusability, because they can be defined independently of any class hierarchy. Base classes, interfaces and collaboration patterns together form the basis for domain specific object-oriented application frameworks (see section 3.6). Application frameworks offer huge reuse potential and can be seen as major asset within a knowledge management infrastructure for a given domain.

2.2.1.2 Who is reusing what?

The list of potential reusable artifacts given in 2.2.1.1 contains items of various levels of abstraction, with some of them being more accessible to software engineers, while others being of greater interest for scientists, domain experts or end-users. The choice of what should be reused is therefore related to who is reusing something.

Since developing for reuse is an investment, this raises the question, which participants in the development of an IRBM-DSS do want to commit them to this investment. Who owns, administers, and takes the responsibility for further development of the resulting library of reusable IRBM-DSS components? In many cases this is the organization or firm that develops the software, on the other hand it also could be the end-user organization or a consortium of end-user organizations and software firms.
Table 1 gives an overview of the reuse potential of various artifacts with respect to several classes of users.

As reuse lemmas (3) and (4) state, the most benefit is generated from reuse as far upstream as possible in the development process, because this way chances for reuse further downstream are maximized. The question about who might want to invest in the development of a library of reusable IRBM-DSS components can be reformulated as the question whether the development of an IRBM-DSS (prototype) should be technology driven or user driven.

The authors experience from similar development projects is that policy support DSS projects tend to start technology driven and then, if successfully applied to real policy problems, tend to evolve towards a more user centered development process. The maturing process of the DSS goes along with a transfer of responsibilities from the developers to the user community. This pattern can be used as a guide when we have to decide how much and which type of reusability we want to build into the (pilot) system.

2.2.1.3 When does reuse take place?

In reuse oriented DSS development, two parallel and interrelated activities take place:

- Product development:
  Within product development we can further distinguish (1) user product development and (2) developer product development.
User product development deals with the design and implementation of specific DSS applications. With a library of reusable assets already existing, this is where we harvest from our earlier work, by assembling new applications from generic frameworks and components.

Developer product development deals with the design and implementation of the generic framework. Geonamica® (see paragraph 3.6.4) together with its software development kit (SDK) is an example of such a developer product.

• Library development:
  Library development creates reusable components by generalizing, certifying and enhancing artifacts that were developed in product development.

Product and library development are coordinated processes. A full description of the techniques available that allow managing and coordinating these processes in a collaborative effort of several participating organizations is beyond the scope of this report. The history of similar projects has shown, that forming an organization or a consortium in which developers as well as end-users are represented seems to be a good approach. The benefits of early and active end user involvement in both development processes cannot be overestimated.

In the specific context of the IRBM-DSS, our advice concerning reusability is to be rather modest on this criterion, certainly in the early development phases of the system. Choices relative to the architecture and system design should maximize the level of reusability, but it should not become the main thrust of the project (which it easily could). The first versions of the system will need to be evaluated on their ‘usability’, rather than on their ‘re-usability’. Given the fact that it is not as yet very clear who will be the main end-user of the system, what his technical skills will be, how he will use the system, and what the main theme of the system will be, reusability should be maximized at the level of the Software engineer and the modeler first. They will benefit most and always, even from the most concrete artifacts discussed.

Our discussion of reusability initiated from the requirement that an IRBM-DSS developed for the Elbe should be applicable to other large river systems as well. In our view the best way to achieve this kind of system level reusability is to use/develop an object-oriented application framework (see section 3.6) for model based spatial DSS in the domain of integral river basin management. Since the development of such a framework is a huge investment, we suggest evaluating whether already existing (commercial) application frameworks for integral spatial DSS (e.g. Geonamica® see section 3.6.4) meet our requirements and can be used as a basis for the development of IRBM-DSS. Such an evaluation could be part of the requirements engineering phase of the pilot study.

2.2.2 Extensibility

For IRBM-DSS extensibility is a requirement, the importance of which can hardly be overestimated. This type of application exists in a continuously evolving environment of user requirements. As stated earlier, experience with similar systems has shown that from the moment an organization starts to use the system for real policy support, users issue frequent requests to add or change functionality. This is mostly so for policy support systems, because
the policy context within which these systems are used changes rapidly, continuously and in ways that cannot be anticipated from the beginning of the development process. For the IRBM-DSS this is not different. It is not possible to know in advance all the problems an analyst or policy maker will want to explore in a field as broad and complex as integral river basin management. This holds even more if the system will be used to support participatory policy design.

During the DSS life cycle, system level extensibility makes cost-effective handling of user requests for new or altered functionality possible. During DSS development component level extensibility is required when we want to reuse an already existing component, that implements only part of what we need. As long as there is scientific progress, the models that form the simulation kernel of the system will evolve, thus the models themselves should be extensible and/or exchangeable parts.

Extensibility can be achieved with state of the art development techniques like component based development (CBD) and object-oriented application frameworks. The technical aspects of these techniques are described in more detail in section 3.5 and 3.6.

2.2.3 The modeling gap

Model based software tools for decision support in planning and policy-making always face the problem of the modeling gap. The modeling gap is the distance between the concepts the end-user uses to describe the problem at hand and the concepts directly expressed by the software tools he uses. Since the modeling gap is closely related to the abstraction level of the various DSS tools we discuss it here under the aspect of the ‘generality’ requirement of the system.

Increasing the generality of the tool in most cases also widens the modeling gap and therefore might decrease the usability of the tool for users that work at a high level of abstraction (e.g. policy makers). Rather than trying to develop a single tool that bridges the whole modeling gap and suits every class of user, we believe that it is better to develop generic as well as specific tools at different levels of abstraction, servicing different roles and tasks in the process of DSS development, use and maintenance. Together these tools then form a generic DSS framework for integral river basin management. The modeling gap and the various roles and tasks of end-users are critical factors to consider when conceiving a ‘generic’ framework architecture for the tool.

Table 2 gives an overview of several classes of users, their roles in a decision process supported by integral models, and the software tools that correspond to the abstraction level of their activity.

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Bernhard Hahn and Guy Engelen:
Concepts of DSS systems

- 17 -
**User** | **Role** | **Tools**  
---|---|---  
Policy Maker | Uses interactive graphical DSS like WadBOS or Environment Explorer for policy exercises | Interactive graphical IRBM-DSS  
Domain expert / Analyst | Provides domain knowledge in natural language, heuristics, rules, databases, mathematical formulas… | Visual IRBM-DSS shell, with customizable algorithms, rules and run-time model configuration  
Modeler | Defines sub-models in mathematical formulas, codes model building blocks in C++ or other general purpose programming language | Model Building Blocks (MBBs), COM interfaces, C++ class library,  
Software engineer | Builds integral model from model building blocks and implements graphical interactive DSS. Defines interfaces | General purpose object-oriented programming language (C++), component technology middleware  

**Table 2: A role-oriented classification of IRBM-DSS users with the corresponding tools**

Note that in Table 2 the tasks at the highest level of abstraction (policy maker) require the most specific, thus least general tools and vice versa. Also note the tool reuse hierarchy in the table. On every level the corresponding tools are used to build artifacts that serve as tools on the next higher level.

The modeler uses model components, COM interfaces and application and framework classes to build complete (sub) models. The domain expert / analyst may use these models in a visual development environment to develop or maintain a specific DSS application, foremost by assembling and configuring prefabricated components. Finally the policy maker uses the interactive IRBM-DSS.

Of course in real-life projects the neatly separated roles shown in Table 2 will overlap most of the time and often individuals will be active in more than one role. However the general approach to provide a hierarchy of reusable artifacts on various levels of abstraction, corresponding to different human roles in the decision making process, results in a long-term component-based development strategy for a more flexible and general IRBM-DSS framework, that can be customized for various projects.

To our knowledge, there exist at this moment, and in the domain of integrated watershed management, no tools to service the Domain expert or Policy maker as described in Table 2.
During the development of the IRBM-DSS we advice to take on board the general concern to service each of the users of the DSS with the appropriate tools, however, to also be realistic as to the feasibility of this aim and concentrate on the needs of the Modeler and Domain expert first and most.

### 2.2.4 Technical requirements for generality

What does generality mean for the technical architecture of the IRBM-DSS? As we will see, it sets a rather ambitious goal, which is only achievable by fulfilling, at least partly, a set of more modest generality requirements:

The modeler uses model components, COM interfaces and application and framework classes to build complete (sub) models. The domain expert / analyst may use these models in a visual development environment to develop or maintain a specific DSS application, foremost by assembling and configuring prefabricated components. Finally the policy maker uses the interactive IRBM-DSS.

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### 2.2.4 Technical requirements for generality

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1. **Data**
   
   First of all, to be applicable to more than one area, an IRBM-DSS must be generic with respect to data. It must be capable of loading and saving maps in various formats. Measurement data perhaps even connections to real-time monitoring data feeds, as well as different policy scenarios should be editable at run-time or at least not require a recompilation of the application.

2. **Models**
   
   When applied to a new river basin, it is very likely, that some if not most components of the integral model as well as its spatial and temporal resolution will be different. Therefore the
The architecture of the integral model should be modular and based on model building blocks that function as pluggable components. Just like chips on an electronic circuit board, alternative blocks may replace model building blocks, as long as they adhere to the same interface specifications.

3. Interfaces
Interfaces between components of a system often are the most stable parts of a system. However flexible interfaces allow for much easier integration of already existing models, where changing the interface is often not an option.

Maximum flexibility can be achieved with a component architecture that can discover interfaces at run-time, however a considerable price in terms of efficiency has to be paid to achieve this level of flexibility.

4. Functions
Spatial DSS based on integral models may be used for very different tasks:

- Analysis of policy options
- Exploration and learning about the dynamics of a complex system
- Management of a complex environment
- The DSS may serve as a library knowledge management tool
- The DSS may serve as a communication medium, which is especially useful in participatory approaches to policy design
- For every task the DSS provides specialized tools. When applying the DSS to a new region, it is likely that the relative importance of the different tasks as well as the specifications of the tools needed to fulfill them is subject to change. Therefore, what was said about the models in a generic IRBM-DSS also holds for the tools, they should be interchangeable parts of the system.

5. Context
Last but not least, the context in which an IRBM-DSS is used is likely to change when it is applied to a new region. Things that may be different include: methods of distribution, operating systems and computer platforms, maintenance policies, organizational aspects, and most important, the role of the end user may be defined very differently.

Each of the items in the above requirements list corresponds to a level of generality to the system. Together they span a scale of generality and we should decide about the appropriate point for our product on that scale. To that effect, we believe it is useful to describe briefly the products at both extremes of the scale.

On the least generic end of the scale, we find a DSS running on fixed data and based on a fixed model, with static interfaces, or even a monolithic model with no internal interfaces at all, a predefined set of functions and tools that cannot be extended. Of course, this system would only function well in its predefined context. One might think that such a DSS would be useless, or at least be a waste of investment, but actually to our best knowledge, quite a number of (successful) DSS fall within this category.

On the opposite end of the generality scale, we can define a product that is not a DSS in itself, rather a software component framework and development environment for the domain of
integral river basin management. Such a product then enables a quick implementation of an IRBM-DSS as part of diverse projects.

When moving on the scale towards more generality, the granular size of reusable components decreases, while the effort needed to implement a concrete solution increases.

Because the level of generality has considerable impact on the software development effort, we have to decide how much generality we want to put into the system architecture for the IRBM-DSS in the long and the short run (the pilot study). In particular for the pilot study we might want to give up some generality in order to get a more complete feature set. Further (financial) support of the project to a large extent will depend on how convincing the prototype is, while generality only pays off in the long run, when more systems of the same type are implemented. To come up with useful generalizations, we must ask ourselves, or better, ask our DSS-users, which aspects of the system they expect to change and which they believe to be rather stable. Unfortunately, these questions are notoriously difficult to answer, especially in the relatively new domain of integral modeling, where few examples of systems with a complete lifecycle exist.

3 System Architecture

3.1 Basic components of a DSS

Decision Support Systems (parts of this text are adapted from [Engelen et al., 1993] and [Engelen, 2000b]) are principally made up of four components (See Figure 3-1): (1) a user interface enabling easy interaction between the user and the system, (2) a data base containing the raw and processed data of the domain and the area at study; (3) a model base with relevant models of the decision domain, and (4) a tool base with the methods, analytical techniques, and software instruments required to work in an effective manner with the domain models and the data.

*Figure 3-1: Basic functional components of the IRBM-DSS*
All four components have a complex internal structure, but for the moment we will focus our discussion on their role and internal interaction. Note that the four-component view does not necessarily match with the user’s perception of the DSS, because the user interface layer may present things in a way that differs from the internal structure of the system.

The user interface:
Decision-support systems are intended for use by high-level decision makers to solve ill-structured problems. Although often specialized in their domain, these decision- and policy-makers may be unfamiliar with information science and technology. The user interface, the vehicle of interaction between the user and the computer, takes into account differences in the cognitive styles and relative knowledge of the users. It is designed to hide the complexities of the internal computer system without hampering its flexibility and provides insight into the structure of the mathematical models, methods, variables, parameters and processes, the underlying theoretical assumptions, the boundary conditions and other constraints. It allows the user to address the different components of the DSS (tools, data, models, etc.), translates the user input into appropriate computer instructions, and reports back the results of the computations. To provide maximal user-friendliness, state-of-the art interactive graphic techniques are being applied extensively.

Thus, the most important, but also the most difficult task of the user interface is to hide the full technical complexity of the system and at the same time to provide structured access to the system. In WadBOS [Huizing 98] this was achieved by introducing several user access levels (modes) corresponding to the various user profiles that were described in section 2.2.3 as well as an alternative front-end tailored for policy-makers (the so-called Policy Wizard).

The database:
A thorough database serves as an input medium for the data required in the models used. It is filled with information that is appropriate to the management or policy issues dealt with in the DSS. There is a growing trend to store spatial, social and ecological data in GIS databases. Consequently, a good interface linking GIS and the DSS is of utmost importance for policy-making and planning. Particular solutions will be discussed in section 5.3.

The tool base:
The convenience, richness and scope of a DSS is primarily determined by the spectrum of tools and models available from the tool base and the model base. Typically decision methods, statistical and operations research techniques, as well a tools to describe, portray, compare, rank, and evaluate different policy alternatives are part of the tool base. More basic, but just as essential, are simpler tools such as editors, and devices to represent output in its truly multi dimensional and dynamic nature. Tools that are considered of immediate relevance to the IRBM-DSS will be discussed in section 3.4.

The model base:
Finally, most essential in representing the decision domain are the domain-specific (simulation) models capable of grasping the complexities of the system and the problems at hand. The elements in the model base are of a formal nature, and exclude decision-making solely based on common sense or intuition. Elaborate model bases will contain
both mathematical and rule-based techniques, often playing complementary roles in the decision-making process. In the context of the IRBM-DSS the models available for use in the DSS are available in a distributed manner from different authors and institutions. This fact, the end-use requirements and a set of performance criteria should be essential considerations in the selection of an architecture for the IRBM-DSS (see section 3.2).

Figure 3-2: Approaches to model integration in DSS architecture

The basic functional components can be integrated into a DSS application in various ways. Four alternatives will be discussed in section 3.2. They differ foremost in tightness of model integration. The alternatives are evaluated on the basis of 15 performance criteria including among others the development cost and various usability aspects.

3.2 System architecture alternatives

In Figure 3-2 a graphical representation of the 4 architectures is given. For each solution, the user is represented at the left. He interacts with the IRBM-DSS via a user-interface and has access to an integrated model. The integrated models consist of different component sub-models available from the model base of the DSS. On the right of the diagram is shown how precisely the sub-models are integrated.

The solutions can be synthesized as described in the following sections. Table 5-1 contains a kind of score table showing the weak and strong points of the four solutions.
3.2.1 Access to loose and distributed models

In this solution, the integration of the models is only weakly developed. Most sub-models are available to the user as they are and in a near to original form. Only the most essential adaptations have been carried out for making them more useful in the context of the IRBM-DSS. The adaptations to the models, their maintenance and their management remains very much with the owners and original developers. The models basically reside on the computer of the owner, usually together with the data required to run them, hence the burden to store and run the models resides with the owners equally well. When the DSS is used, it will make use of the sub-model either via a direct network access, or via the owner as an intermediate. In the former case, synchronous usage is possible, while in the latter, the usage will always be asynchronous. Rather than running the model directly, the owner will be requested to run it on his machine and return the results to the DSS end-user for further analysis.

This solution is not user-friendly. In the worst case it requires complicated procedures to do even the simplest things. It is also very slow, in that it might take a long time to get model results. It has also some advantages. Providing that a sufficient set of procedures and protocols are being adhered to, a distributed development is possible. The development and maintenance costs are kept rather low, and the models are updated by those knowledgeable.

We believe this solution is to be selected if access to very complicated models is required, e.g. models that would not run easily on the platform of the end-user. Models too, that are used for technical tasks and not so much for explorative or learning purposes. For the IRBM-DSS it would only be an acceptable solution if the access to the sub-models would not require human agents acting as interfaces and if the DSS could simplify greatly the transfer of data from one sub-model to the other.

In summary:

• Low development cost
• User-friendliness low
• Thin knowledge management shell to link and reference various research models
• Distributed architecture
• Distributed development and maintenance
• Weak integration
• Human and / or software interface agents
• Asynchronous
• Internet based client-server architecture
### Table 5-1: Four architectures evaluated against 15 criteria

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Distributed KM shell</th>
<th>Components (weakly integrated)</th>
<th>Systems model</th>
<th>Systems model &amp; Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Policy relevance</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Collaboration</td>
<td>--</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Explorative learning</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>User friendliness</td>
<td></td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Transparency</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Integration</td>
<td>-</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Interactivity</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Flexibility</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Correctness</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Performance</td>
<td>--</td>
<td>+</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Development cost</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Maintenance cost</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>--</td>
</tr>
<tr>
<td>Completeness</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td>Abstraction level</td>
<td>--</td>
<td>-</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Implementation (level of difficulty)</td>
<td>++</td>
<td>+</td>
<td>-</td>
<td>--</td>
</tr>
</tbody>
</table>

#### 3.2.2 Existing models coupled into a single system

This solution differs from the previous one in that the integrated model consists of sub-models that are more tightly coupled and reside on the machine of the end user. This results in a system that is user friendlier. It is more suitable for explorative use and learning; yet, it enables rather technical usage as the constituting models will usually be moderately changed versions of the originals. The performance of this system will be better as well.

But, the development and maintenance costs will be medium, as models will need to be partly rebuilt and re-implemented to fit the integration scheme. Also, the system needs to be equipped with tools and techniques to run models operating at different geographical and temporal scales simultaneously. Providing that the system is build on the basis of state-of-the-art component technology (see section 5.5), it will be possible to re-use sub-models written in different programming languages. The latter will also enable a distributed development, and allow for the owners of the original models to participate actively in the design and implementation of the ‘light’ versions of their (sub) models. If this kind of collaborative effort can be organized and kept alive, then the DSS will be strongly anchored in the relevant research fields.
This solution combines a high degree of integration with acceptable development and maintenance costs. It is to be advised for the development of the IRBM-DSS if analysts and policy-makers will use the system alike. It will become more interesting and feasible if a good collaboration with the original model developers can be guaranteed.

**In summary:**
- Medium development and maintenance costs
- User-friendliness medium
- Standalone application
- Linked (adapted) research models
- Medium integration
- Various spatial and temporal scales
- Component and wrapper technology
- Programming language independence
- Collaboration between domain experts of various disciplines

### 3.2.3 Reformulation of existing models into a systems model

The core element in this architecture is the integrated model. It is fully tailored to the precise role of the DSS and the needs of the end-user. Hence, a clear problem definition and in-depth user requirements analysis and a precise user profile are essential elements to decide on the precise depth and the extent of the integrated model and its constituting sub-models. More than in the previous two solutions, this integrated model is very strongly coupled. The model is a truly complex model. It is so by design, and, as each of the sub-models are (re-)developed and (re-)implemented for this purpose it is also materialized technically. Once realized, this system is user-friendly and, it usually will have a high performance. More than in the previous two cases, the system will represent all relevant processes at the same level of abstraction, namely the level demanded by the end-user. The processes will be modeled at an appropriate level, which does necessarily produce the most detailed or most accurate results possible.

Because of the effort spent in the design and implementation it is also a medium to high cost solution. Also the maintenance costs can be very high. This will certainly be the case if the use of the system changes. Development and maintenance of this system can be kept in the hands of a small group of modelers and system developers. There is no real need for distributed development as the near complete model is build from scratch. However, with a view to keep the maintenance costs within limits, it is advisable to choose a component-based technology to implement this solution.

This solution is to be recommended if the IRBM-DSS is used by high-level policy user and for explorative integrated assessment exercises mostly, because it enables the development of a well-balanced, transparent system. For the same reasons this solution supports explorative learning very well.

**In summary:**
- Medium to high costs
- User-friendliness high
• End-user involvement in development high
• Interactivity is high
• Highly integrated DSS for policy support
• Policy-model developed from adapted or rebuild research models
• Knowledge acquisition phase to fill gaps (missing links) with newly developed models
• Standalone application

3.2.4 Single systems model with access to original models

One of the disadvantages of the previous solution is the fact that the integrated model lacks the accuracy to perform detailed calculations on what would be considered less important components of the real world system represented. It would for example be very difficult to include beetle dynamics, observed in a very particular river ecosystem, in an integrated model covering the complete Elbe watershed. This level of detail would be difficult to attain because in most of the watershed the data required would not be available. The policy maker might not find this a problem, but an analyst using the system, an ecologist for instance, might have a different view on this. As a solution to this problem, an architecture could be chosen representing the watershed by means of an integrated model as explained in the previous solution, but which in addition permits access to more precise, original models for a selected set of processes. The latter models can be run on particular relevant spots in the watershed for which the data are available. Moreover, the output of the detailed models could be exchanged with the integrated model, and visa versa, thus permitting a more complete analysis of a problem.

This architecture combines the advantages of the second (5.2.3.2) and the third (5.2.3.3) solution presented. It is not to wonder that it is the most expensive of all, both in terms of development and maintenance costs. But it has major advantages too. It is a user-friendly solution, providing maximum accuracy, completeness, interactivity, and flexibility. Also, the policy relevance is high, while the analytical user can still make use of the system effectively.

This solution is to be recommended for the IRBM-DSS. This is mostly so because of the vastly different spatial and temporal scales, which need to be covered in the system. Also, the requirements on behalf of the intended end-users are rather different.

In summary:

• High development costs
• User-friendliness max
• End-user involvement in development maximum
• Various spatial and temporal scales
• Standalone or distributed
• Policy-model developed from adapted research models and integration of full-size models
• Knowledge acquisition phase to fill gaps (missing links) with newly developed models
Providing that model integration is a major obstacle in the development of the IRBM-DSS, and based on the information gathered so far, it would seem that the most appropriate architecture is the last one described. It combines the advantages of a stand-alone system running on the machine of the end-user and those of a strongly integrated model. The development of the system could in part be implemented in a distributed manner, and thus involve the scientists and developers of the original research models at best. The suggestions made in the modeling chapter relative to the nature of the integrated model are fully compatible with this conclusion.

3.3 Model integration

3.3.1 Approaches

As discussed in section 0 a core element in every DSS is the model base. This is not different in the IRBM-DSS. The very technical character of ‘watershed management’ itself and the addition of the characteristic ‘Integrated’ to this requires a very rich model base with models operating at different spatial and temporal scales and in very different domains.

Moreover, the IRBM-DSS will be developed on the basis of existing modeling material available from a great number of organizations distributed over Germany and the Czech Republic. This modeling material has been developed primarily for research purposes and will need to be made available in an instrument intended for policy purposes. Chapter 5 of the paper in Appendix A explains at some length the difficulties that are involved in adapting and coupling this research material for policy-making purposes. We will not repeat this here; rather refer the interested reader to the appendix.

A thorough analysis of the available modeling material has been carried out. A description of the available models has been given and a suggestion for a first selection and integration of compatible models at three different levels of spatial detail has been presented in the dedicated chapter. We will focus our attention on the consequences the above has for the development process and the architecture of the system.

We believe that essentially four different types of architecture could potentially be used to build the IRBM-DSS. They differ from one another mostly in terms of:

- their policy support, policy relevance, and performance;
- the development and maintenance costs;
- the expected technical and organizational difficulties involved in the development of the DSS.

These characteristics have been captured in 15 selection and evaluation criteria. We will first give a brief working definition of each criterion and next will discuss the merits of each of the four architectures.
3.3.2 Evaluation Criteria

We retained 15 criteria to evaluate the different architectures. Other lists would probably have been possible and other interpretations of the terminology and definitions could have been used. However, we believe that this list is sufficient to demonstrate the differences between the architectures and their relevance for the usage and the end-user of the IRBM-DSS.

**Policy relevance**
Policy relevance refers to the way in which the system provides immediate support for the policy end-user. It is about how well it is tailored to his needs, his skills, and his method of working. In this study we have defined the policy user as a person knowledgeable about the policy domain, but less proficient in computer usage in general. Further, this person is a high-level user, meaning also that he does not necessarily have the time to work his way through lengthy computer procedures and routines.

Policy relevance is also important with respect to the various models and processes that are represented in the DSS. The policy relevant processes are a (possibly small) subset of all scientifically interesting processes in the problem domain. Generally a process becomes policy relevant if the policy maker has some direct or indirect measure to influence the process.

**Explorative learning**
Explorative learning refers to the ease with which the user can learn about (a part of) a problem by means of the system. Learning will only take place if the user understands causes and effects in the system. Hence, the system will need to be highly transparent and user friendly. The level of complexity of the system should be within the limits the learner can handle, and the system needs to be responsive, meaning that an input of the user should result in an output by the system in a manner that makes intuitive sense to the learner. Moreover, the system should produce output that is as instructive and as concise as possible: geographical output in the form of maps, time series as time charts, etc. Further, the user-interface should be uniform for as much of the components of the system as possible and the system is best equipped with a model that represents all the processes at the same levels of abstraction and detail.

**User friendliness**
User friendliness of the system refers very much to the ease with which the system can be used by its intended end-user. As little as possible time should be lost in executing tasks that are not immediately relevant to the problems for which it is developed. User friendliness is among others obtained if the system has a well designed, intuitive and uniform user interface which is set-up according to guidelines pertaining to the operating system and platform on which the system (at least its front-end) runs. Also, a system is most user-friendly if it is equipped with an appropriate and easy to manipulate set of tools required for carrying out the analytical tasks.

**Transparency**
Transparency refers to the tractability of the results generated by the system as well as the documentation of the different tasks carried out by the system. The more the system will carry out its tasks in a manner that makes intuitive sense to the end-user, the more
transparent it will be. The more models and tools of the system are opened up and documented, the more transparent it will be. Black box systems lack transparency.

**Interactivity**
Interactivity refers to the ease with which the end-user can interact with the system. What proportion of the tasks can the user carry out directly and via the user-interface of the system without having to fall back on other analytical instruments? What tools are available in the system to support the user in carrying out these analytical tasks during a session with the system? How much effort then is involved in carrying out the tasks, and what kind of maneuvers are required on behalf of the user? How much of this can he do on the spot as he pleases and without having to refer to other software or other instruments?

**Integration**
Integration refers to the level of model and tool integration attained in the system itself. The different models in a system can be loosely coupled only, or they can be very strongly coupled. Coupling refers to complexity of the models: the number of state variables that are exchanged among the models in the system. Integration also refers to the way in which the tools fit the functional and analytical requirements of the models.

**Flexibility**
Refers to the notion discussed in section 4.4. Flexibility refers to the ease with which the system can be adapted or changed for tackling other problems, or for similar problems in another region or context.

**Correctness**
Refers to the quality of the output generated by the system. The level of correctness of the system will mostly depend on the quality of the models used in the system and by the way these models are coupled into a single integrated model. It is a difficult scientific notion, which is strongly linked to uncertainty, predictability, the complexity of the problem modeled, etc. In the context of this analysis, we look at correctness partly as the loss of information from the original representation of the process by means of a model.

**Completeness**
Completeness refers to the proportion of relevant domain processes that are generally represented by the models and the tools of the system at a sufficient level of detail. Completeness differs from abstraction level in the sense that a complete system does not need to consist of models that are fully coupled, nor do these models need to run at the same levels of detail, same temporal scales, same set of state variables, etc.

**Abstraction level**
The abstraction level refers to the level of detail with which the system represents the decision domain. The level of detail attained in the system should be appropriate and relevant to the kind of problems that need to be solved by the end-user. In this study the end-user is a policy maker rather than a researcher, hence the models in the system should be evaluated on their policy relevance rather than their research relevance.
**Performance**

Refers to the speed with which the system, its models and tools generates results that are immediately relevant to the end-user. Performance therefore is relative to the platform and the machine, which is typically available to the end-user. A system that runs fast on a standard machine and on a widely available platform, such as MS Windows, is said to have a high performance.

**Development cost**

Refers to the costs required to build a running version of the final version of the system. Development costs include not only the software implementation, but also the preparatory work involved in functional and technical design of the system. It does not include the maintenance costs.

**Maintenance cost**

What are the costs involved in maintaining and upgrading the system? In the maintenance costs we include the costs to adapt the system to the changing needs of the end-users as well as the software and hardware standards.

**Collaboration**

Collaboration refers to the potential for the distributed development, maintenance, and use of the system. This quality is dealt with in section 5.5.

**Implementation (level of difficulty)**

Implementation refers to the technical difficulties that need to be solved by those involved in the construction of the system. This includes the difficulties in the practical realization of the architecture and the functional components of the system: its model base, its tool base, its databases, and its user interface. Generally speaking the higher the level of difficulty the more risks are involved that the production of the system will meet with a lot of technical and organizational difficulties.

### 3.4 Tool integration

The tool base is the component that usually gets the least attention in the DSS. Many authors will either consider it to be an integral part of the user interface. Others still will consider it to be part of the model base. Both views in our opinion are wrong and tools should be treated with particular attention because they decide to a large extent on the usability and effectiveness of the DSS. Indeed, in a well-designed DSS the tools are the gnomes that will carry out the many small technical tasks in the background of the system. The user will hardly be aware that he is using a tool when he is editing a parameter or viewing a variable, but without them, the most sophisticated model would be totally useless. Tools are among the most robust elements in a DSS; hence they can be re-used easily in applications in combination with vastly different model bases and accessed by different types of user interfaces.

We will not dwell extensively on the specifications of the many different tools that are required in a fully blown DSS. Instead we present in Table 5-2 a list of tools that we consider at the least useful in the context of the IRBM-DSS. Most of these tools are available from the DSS applications, which we have developed in the past. We order the tools relative to the type of task they carry out in the DSS, and distinguish between Input tools, Output tools, Exploration
tools, Evaluation Tools, to end with a number of tools worth developing for incorporation in a DSS aimed at integrated river basin management.

Among the **Input tools** there are the typical editors required to change single numbers, or series of numbers in a textual or graphical manner. As part of the latter, the table editor, which enables entering 2-D relations as a curve and the map editors are very powerful instruments.

The **Output tools** take care of the difficult task to present massive amounts of data generated by the DSS as concise and precise a manner possible. The developer of the DSS will make decisions on the kind of tool to use. To present spatial and dynamic data dynamic maps are essential, and so are recorders and players of animations, because they enable the user to take more time to analyze the results generated.

**Exploration tools** enable the user to interactively perform searches in the solution space. The possibility to generate scenarios, produce map overlays, perform map comparisons, and carry out sensitivity analysis puts great analytical power in the hands of the end-user.

**Evaluation tools** will help the user decide on a ‘best’ solution. Techniques such as Multi Criteria Analysis, Score Tables and the like are wanted. But, rather than running the risk that the ‘best’ solution is never attained when series of ‘what-if’ analyses are carried out, the user might be much helped with some from of goal seeking and optimization techniques.

Finally, and in the particular context of integrated watershed management, we could think of a couple of instruments that would enable carrying out tasks that otherwise would be difficult to perform. We refer here to very specific interventions such as groin modification and dike shifting. But also more generic operations like cell-to-network and network-to cell conversion, or cell aggregation and cell disaggregation seem like very useful instruments.
### Tools

<table>
<thead>
<tr>
<th>Tools</th>
<th>Analysis</th>
<th>Communication</th>
<th>Learning</th>
<th>Library</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input tools</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>text editor</td>
<td>++</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
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<tr>
<td>value editor</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>series editor</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>table editor</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>function editor</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>network (points and lines) editor</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>2D map editor</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
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<tr>
<td><strong>Output tools</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>on-line documentation</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
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<tr>
<td>on-line help</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
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<tr>
<td>time graphs</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>dynamic maps (2D)</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>dynamic maps (network)</td>
<td>+++</td>
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<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>3D representation</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>Animation</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>tracing tool</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
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<tr>
<td><strong>Explanation tools</strong></td>
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<tr>
<td>POLICY-wizard</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>OVERLAY-Tool</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>ANALYSE-Tool</td>
<td>+++</td>
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<td>+++</td>
<td>+</td>
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<tr>
<td>SCENARIO-Tool</td>
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<td>+++</td>
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<td>+</td>
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<tr>
<td>MONTE CARLO-Tool</td>
<td>+++</td>
<td>++</td>
<td>+++</td>
<td>+</td>
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<tr>
<td><strong>Evaluation tools</strong></td>
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<tr>
<td>SCORE-Table-Tool</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
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<tr>
<td>EVALUATE-Tool (MCA)</td>
<td>+++</td>
<td>+++</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Optimization</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Goal seeking</td>
<td>+++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td><strong>IRBM-specific</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dike shifting</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Groin modification</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Cell aggregation / cell disaggregation</td>
<td>+++</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Cell-to-network / network-to-cell conversion</td>
<td>+++</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 5-2: A list of tools and their usefulness to different users

In Table 5-2 we also value the importance of the tools relative to the potential uses or functions of the Decision Support System. From the table it is clear that the **analyst** will be serviced best by as complete a set of tools. He will need both the very down to earth instruments to enter data, to read the input and to analyze the output. When the main purpose of the DSS is **communication**, then the need for pertinent output instruments is very essential. The **learner** needs a bit of everything, his usage of the system is not fundamentally different from the
analyst’s. The main difference is that the analyst will want the more sophisticated instruments in support of his analysis, while the learner is foremost interested in the documentation systems and the simpler input and output tools. Finally the library function of the system requires the facilities to quickly enter, update and retrieve the information stored in the library. A good documentation system is paramount.

3.5 Component-based development

In section 2.2 we have argued that our system should fulfill certain requirements of generality and flexibility. In section 5.2 we have referred a couple of times to distributed development and re-use of existing models. In this section we will dwell more on these issues and describe how state of the art software technologies enable to develop information systems that to a large extent use and integrate existing parts. The integration effort does not stop with the delivery of the first prototype but is a constant activity during the whole lifecycle of the system. To our knowledge the best state of the art software engineering method to achieve these goals is component-based development (CBD).

The basic idea of CBD is old, simple and powerful: to build a complex whole, try to assemble it from less complex parts, which you might already have. Organizing things in whole-part hierarchies is a basic human strategy to deal with complexity and its application can be seen in nearly every modern product of mechanical or electrical engineering. To be able to assemble something useful from parts, the parts need to fit together. This is where interfaces come into play. Interfaces can be seen as a specification or contract to which parts must adhere to be compatible with each other. A good metaphor for an interface from the physical world is the plug with its corresponding socket. CBD lets software engineers build complex systems in a way that is very similar to how their hardware colleagues design a new car or a computer motherboard: by assembling compatible parts.

A convenient 1-page overview of CBD is given in the summary of a recent paper by Alan Wills [Wills 00b]:

The basic principle of CBD is polymorphism, or pluggability: variant behavior is produced by parameterizing & reconfiguring components, which themselves have fixed designs. The same principle applies on any scale. There are a variety of technologies by which the components can be composed.

Components should preferably be designed in kits. A kit is a coherent set of components, with a minimal set of interfaces.

There are three principal activities in component-based development, requiring different balances of maintainability and cost:

- Kit architecture: defining common models and interfaces
- Component development
- Product assembly from components
Interfaces defined as lists of function calls, are too low-level for component-based design. It is better to design with more abstract connectors, which include different kinds of transfer or transaction. The choice of connectors used in a particular kit is part of its architecture; the ‘wiring’ may support some of them directly.

Each component may have its own partial view of the complete business model. The design method must include ways of mapping these views.

Components may be distributed across different machines. In this case, the design method must include patterns that deal with the possibility of links and machines going out of service, and treat links as potential bottlenecks.

In order to achieve good component based development:

- The structure of the software producing organization must be such as to resource the three development levels (architecture, components, products).
- The teams must be appropriately skilled in an appropriate design method that includes appropriate patterns for component and distributed development; including the notation and means to define connectors, to define components, and to build products from components.
- Select appropriate tools to support the design method; and select tools and platforms to support the architecture.

For a more thorough introduction into CBD we recommend the excellent papers by Alan Wills [Wills 00a] and [Wills 00b]. A lot of useful and up-to-date information on CBD can also be found at: [http://www.cbd-hq.com/](http://www.cbd-hq.com/).

The value of CBD for DSS development in general and of component technologies COM and ActiveX specifically was demonstrated in the MODULUS project (see Appendix A). With model integration and reuse being the main themes of MODULUS, RIKS developed a wrapper technology based on ActiveX and COM, that made it possible to integrate models from various sources and implemented in various programming languages.

Component technology also can help to enhance the flexibility of the DSS by decoupling its subcomponents (e.g. tools, models, GIS access, user interface…) and introducing interfaces as their only way to exchange information among each other. For example separating the user interface layer from the simulation kernel yields a much more flexible architecture. A stand-alone version and an Internet version of the DSS could then be built with identical simulation kernels but different front-ends. The simulation kernel would not even need to know to which kind of front-end it is connected. Of course the same holds for the various tools needed in the DSS. By ensuring that all information exchange between the tool and its environment goes via its component interface, the tools internal structure is completely hidden.

Catalysis™ is a mature and industry tested CBD methodology and is fully described in [D’Souza 99]. Catalysis™ is based on object oriented analysis and design principles, but goes much further than classic OO by including explicit representations for patterns, frameworks, design by contract, interfaces, connectors, rule sets, a process model etc… Catalysis™ uses the Unified Modeling Language (UML) as its graphical formalism. For a short-term IRBM-DSS
prototype project, depending on budget and project run-time, it might be worthwhile to consider a ‘light’ version of Catalysis™, to prevent too much method overhead.

### 3.6 Object-oriented application frameworks

In the previous paragraph, we discussed component-based development and how this technique may be applied in the DSS development to achieve a more flexible and modular system architecture. Application frameworks are built upon object / component technology and go even further in achieving reusability. While component libraries could be described as providing ‘bottom-up’ reuse, object-oriented application frameworks provide ‘top-down’ reuse. An object-oriented application framework for an IRBM-DSS provides a generic application template for this type of DSS. It would provide interfaces and extension points for the developer to ‘fill-in’ the application specific models, tools and data. It therefore allows saving substantial development costs for extensions to an existing application or subsequent DSS applications.

This section will give an introduction on what object-oriented application frameworks are and how they are used for the development of DSS. Section 0 describes Geonamica®, an example of such a framework, which we recommend to use for the development of the Elbe-DSS. For in depth information about component and framework development we recommend [D´Souza 99] and [Fayad 99]

#### 3.6.1 What is an (object-oriented) application framework?

Like many other concepts of modern software engineering (e.g. patterns) the notion of a ‘framework’ has its roots in architectural design. Timber frame or steel frame building constructions are the basis for many low cost building designs of high quality. Framework users build specific solutions, benefiting from reuse of a generic architecture of collaboration patterns and building blocks of proven design.

A framework is a reusable design of a system that describes how the system is decomposed into a set of interacting components. The framework describes the component interfaces as well as the collaboration patterns between the components by means of special purpose textual (IDL, OCL) or graphical (UML) languages. Besides an abstract design specification, application frameworks typically provide an implementation in the form of a semi-complete skeletal application that can be specialized to produce custom applications.

Object-oriented frameworks are designed and implemented as a collection of collaborating abstract classes. They make use of the three basic principles of object technology [Graham 98]:

| Encapsulation | data and processes are combined in objects and hidden behind an interface. |
| Polymorphism  | is the ability to use the same expression to denote different operations. |
| Inheritance   | implements the idea of classification and represents a special case of structural inter-relationship between a group of objects. |
Essentially all these are basic human strategies to manage complexity; this is why object-oriented models often are perceived as more ‘natural’ compared to other approaches.

The recent focus of attention on component technologies like COM+, CORBA and Enterprise Java Beans (EJB) as well as component based development (CBD) in general, has triggered a lot of discussions about what ‘objects’ and ‘components’ have in common and what distinguishes them. Most of this discussion is outside the scope of our discussion of frameworks in this text. Where appropriate differences between ‘objects’ and ‘components’ will be explained. In our view component technology is largely built upon the foundation of object technology and shares with it the above-mentioned basic principles. See [Wills 00b] for a more detailed discussion of this topic.

3.6.2 What are the benefits of application frameworks?

The primary benefits of application frameworks stem from two types of reuse: design reuse and implementation reuse. The observation that core concepts and components and their interactions within a domain are relatively stable, has led to the notion of ‘design patterns’. By delivering a useful set of patterns as a documented design (design reuse), as well as a partial solution in form of a skeleton application (implementation reuse), a framework may save a lot of costs for rediscovery and reinvention.

In [Fayad 99] Fayad et. al. describe the following benefits of application frameworks:

| Modularity  | Frameworks enhance modularity by encapsulating volatile implementation details behind stable interfaces. […] |
| Reusability | The stable interfaces provided by frameworks enhance reusability by defining generic components that can be reapplied to create new applications. […] |
| Extensibility| A framework enhances extensibility by providing ‘hook methods’ that allow applications to extend its stable interfaces. […] |
| Inversion of control | The runtime architecture of a framework is characterized by an inversion of control. This architecture enables canonical application processing steps to be customized by event handler objects that are invoked via the framework’s reactive dispatching mechanism. […] |

3.6.3 Framework classifications

In [Fayad 99] object-oriented application frameworks are classified by their scope and by the techniques they offer for extension:

3.6.3.1 Framework classification by scope

| System infrastructure frameworks | simplify the development of portable and efficient system infrastructures […]. They are primarily used internally within a software organization. |
| Middleware integration frameworks | are commonly used to integrate distributed applications and components. |
Enterprise application frameworks address broad application domains [...] and are the cornerstone of enterprise business activities.

Geonamica® is an example of an enterprise application framework for DSS in the domain of complex spatial policy problems. Geonamica® also has some features of a middleware integration framework in the sense that it supports the integration of external models with component technology.

3.6.3.2 Framework classification by extension technique

White-box frameworks rely heavily on OO language features like inheritance, dynamic binding, templates (C++) or generic classes (Eiffel) in order to achieve extensibility. Existing functionality is reused and extended by (1) inheriting from framework base classes and (2) overriding pre-defined hook methods and using patterns like the Template Method [Gamma 95].

Black-box frameworks support extensibility by defining interfaces (IDL, Java) for components (COM, JavaBeans, CORBA) that can be plugged into the framework via object composition. Existing functionality is reused by (1) defining components that conform to a particular interface and (2) integrating these components into the framework using patterns like Strategy and Functor [Gamma 95].

Geonamica® is an example of a white-box framework. White-box frameworks are much more widely used than black-box frameworks. This is partly because they are conceptually easier to develop and partly because (programming language independent) interface description languages only recently became available to the software engineering community.

Despite their wide use, with respect to extensibility, white-box frameworks have some considerable disadvantages compared to black-box frameworks, especially when the planned extension involves the integration with other frameworks. White-box frameworks require the application developer to have deep knowledge about their internal structure, especially the inheritance relationships. For example, application developers that want to reuse functionality from the Geonamica® library, need to inherit this functionality from the Geonamica® base classes and need to override their virtual methods.

In contrast with the former, in black-box frameworks reuse is realized by composing new objects from predefined framework components and by implementing framework defined interfaces in application objects, in order to enable these objects to participate in framework defined collaboration patterns. This form of reuse is more flexible, since it is not coupled to a specific inheritance hierarchy.

3.6.4 Geonamica® — a DSS Generator

Geonamica® is an object-oriented application framework, developed by RIKS. It is specially tailored for developing Spatial Decision Support Systems featuring integral dynamic models as their core element. Examples for interactive SDSS built with Geonamica® are among others: RamCO, SimLucia [Engelen 98a], WadBOS [Huizing 98], Environment Explorer (LOV) [Engelen 98b], MODULUS [Engelen et al. 2000a], and MURBANDY.
It is the support for dynamic modeling and simulation that distinguishes *Geonamica*® from other planning tools, in particular from those based on standard GIS technology. In particular the need for dynamic modeling on high-resolution data lead to the implementation of highly efficient computational techniques and algorithms. *Geonamica*® supports the development and execution of integrated models consisting of sub-models running at multiple spatial and temporal resolutions. Typically it will combine system dynamics models and cellular models for this purpose. In particular use is made of spatial interaction based models, different kinds of cellular automata models, multi agent or other kinds of rule-based models. But also the visualization of modeling results and the support of an iterative and interactive working method has been given special attention.

*Geonamica*® runs on the PC platform and manipulates primarily grid data. The available internal memory of the host machine is the only limiting factor in the size of the grids and the amount of spatial variables the system can handle. Grids with 1 million cells are processed without problems. For calculations involving limited spatial interactions, the calculation and refreshment of this kind of grids will be in the order 10^{-2} seconds on a state of the art PC.

*Geonamica*® is not only equipped with a series of fast computational routines, but it also includes an important amount of analytical tools, visualization tools, and input, export, and output tools. It is equipped with a number of cartographic tools, in particular map editors and display tools for 1D network and 2-D map objects. Also it supports interactive map comparison and analysis as well as interactive overlay-analysis.

### 3.6.4 Other examples of enterprise application frameworks

- OpenGIS
- Standaard Raamwerk Water (SRW)
- Framework Integral Water-management (FIW)

### 4 The DSS Development Process

Every project that aims to develop a complex product, requiring substantial financial and/or human resources, should define and organize its activities in some kind of process based upon a methodology. This more or less formal process is what separates engineering from art. Despite the name ‘Software Engineering’, our young discipline has just begun to develop from art to engineering and this holds even more for the development of decision support systems.

A full-fledged, theoretically sound, development methodology for model-based spatial decision support systems is not yet available. Instead of that, in this section we will present what we have found to be ‘best practices’ in DSS development together with selected aspects of a process model for component based and object oriented systems development.
4.1 Lifecycle planning

Most DSS development proposals contain a description of a more or less formal development process or life cycle model. In most cases this is some variation of the well-known waterfall model. The waterfall model describes the software development process as a linear sequence of non-overlapping development activities: (1) Software Concept, (2) Requirements Analysis, (3) Architectural Design, (4) Technical Design, (5) Coding and Debugging, (6) Testing, Delivery and Maintenance.

The waterfall model has been successfully applied in projects where the requirements are well understood from the beginning. However, we don’t recommend this model for DSS development because it has only weak support for user involvement and iteration in the system development process. Iteration in the waterfall model tends to generate a lot of rework and therefore is extremely expensive. Furthermore the waterfall model does not define a process for reuse management and is proven to be less suitable for object-oriented and component-based development.

In DSS development, requirements are seldom well understood at the beginning of the project; therefore early user involvement and a collaborative and co-operative approach between all stakeholders throughout the project are critical success factors. Such an approach is much better suited by an incremental development method that elicits requirements in joint workshops and delivers working prototypes at regular intervals. There are several object-oriented development methods with these properties, in particular we recommend SOMA (see section 4.3).

4.2 Changing requirements – hitting a moving target

One factor that distinguishes software development from many other engineering disciplines is the relative ambiguity and instability of the product requirements. This general property of software development projects holds even more for DSS development.

Ambiguity stems from the fact, that users usually express product requirements more or less informally in natural language.

Users usually start to recognize and articulate what they really want, at the time when developers provide them with the first working prototypes of the product. From then on requirements will never stop to change and to evolve together with the users organization or business. Our experience with systems like WadBOS or EnvironmentExplorer is, that in systems for policy support requirements change even faster and more frequently than in other types of DSS.

General acceptance of the fact that in most projects it is impossible to eliminate requirements ambiguity and continuous change has triggered the search for alternatives for the classic waterfall lifecycle model.
4.3 DSDM / SOMA

For the development of the ElbeDSS we recommend to adopt a development process that is suitable for incremental and iterative object-oriented development. We will give a short summary of the SOMA life-cycle model, which falls in this category. The reader who requires more information is referred to [Graham 94] and [Graham 98].

SOMA is an object-oriented development life cycle model that extends and refines the well-known Dynamic System Development Method (DSDM) [Stapleton 97]. DSDM starts with feasibility and business studies, which are followed by three iterative and overlapping phases: functional model iteration, design & build iteration, implementation.

The SOMA method defines projects as a network of activities that have dependencies but no explicit sequence. Each activity produces a tested result / deliverable. All transitions between activities are guarded by pre-conditions, which is why the model is called a contract driven life cycle model. Management control over the project is ensured by time-box planning that sets rigid limits to prototype iterations.

The main build time-box consists of a number of nested and iterated activities:

- Prototyping
  - Rapid object-oriented analysis, design and programming
  - Testing
- User review
- Consolidation, documentation, identification of reusable components

5 Conclusions

Based on the problem definition for the Elbe IRBM-DSS, in the IT-framework part of the feasibility study, we analyzed the key requirements for such a system and presented an outline of the system architecture. To conclude the IT-framework part, we provide a list of critical success factors, for the development of a pilot version of the Elbe-DSS, assuming an architecture that is similar to WadBOS / MODULUS. This list is derived from our experience with similar development projects, as well as from the requirements discussed in this report.

5.1 10 critical management success factors for an IRBM-DSS pilot:

1. Highly motivated end-users, with both, a visionary as well as pragmatic attitude towards the domain at which the DSS is targeted.
2. Highly motivated development team, with a broad interest in the application domain, DSS development, formal analysis and knowledge representation methods…
3. A small group of highly motivated software engineers with outstanding skills in knowledge engineering, software architecture, user interface design, object-oriented development environments, distributed systems, standards…
4. A small group of highly skilled modelers, with experience in combining various spatial and temporal scales in one model. Furthermore the modelers should have a broad interest for the application domain and should be able to take a pragmatic attitude as well as to achieve compromises, when they need to discuss solutions to technical problems with the software engineers.

5. A DSS architect, perhaps the most difficult role in the process. Like a building architect, this generalist is responsible for the overall vision of the product and must be able to professionally communicate with all participating specialists and stakeholders.

6. A project manager. For small projects this role is sometimes taken by the DSS architect. The project manager should have experience in managing interdisciplinary projects with participants coming from scientific, technical as well as public administration backgrounds.

7. Sufficient time and budget to build a high quality first prototype of the system. A successful prototype will further increase the end-user commitment and eventually will trigger further investments in the DSS development.

8. Early and ongoing end-user involvement in the development.

9. Respect for the role and knowledge of participants from other disciplines than your own.

10. Willingness and ability to take a calculated risk by putting substantial effort in the development of a highly innovative product.

5.2 10 critical technical success factors an IRBM-DSS pilot:

1. Use object technology and component based development.

2. Use existing application frameworks for spatial decision support systems.

3. Integrate GIS and database functionality as a component layer.

4. Separate the front-end (user interface) from the underlying tool-, model- and database with clean interfaces.

5. Keep in mind that re-implementation of existing scientific models is sometimes a more efficient and cost-effective ‘integration’ solution compared to extensive ‘wrapping’.

6. Techniques for handling various spatial and temporal scales simultaneously are new. They should be implemented early in the pilot phase, to allow some experimentation.

7. Provide templates and standard interfaces for sub-models (model building blocks).

8. Use standard data formats and protocols for inter-application information exchange (e.g. XML).

9. Test the behavior of the integral model under realistic conditions early and often.
10. For the pilot project maintain a realistic balance between generality and feature completeness.

References

[Engelen et al. 98a] Engelen G., White R., Uljee I., Vulnerability Assesment of Low-Lying Coastal Areas and Small Islands to Climate Change and Sea Level Rise – Phase 2: Case Study St. Lucia, Report to the United nations Environment Program, Caribbean Regional Coordinating Unit, Kingston, Jamaica. RIKS publication, 1998
[Gamma 95] ..........Gamma, E., Helm, R., Johnson, R., Vlissides, J., Design patterns: Elements of Reusable Object-Oriented Software. Addison-Wesley, Massachusetts, 1995
[Graham 94] ..........Graham, I., Migrating To Object Technology Addison-Wesley, 1994
1 Introduction

European countries cover a great variety of river basins with heterogeneous demographic and economic factors leading to variable chemical impact on aquatic ecosystems and man. The spatial and temporal pattern of waste water discharges and diffuse pollution is determined by the economy operating in that region and the population living there. Many chemicals are directly discharged from households, industries and trade or via treatment into surface water bodies (rivers, streams, estuaries). Others, e.g. nitrate and pesticides, enter the river water by run-off from agricultural land (Fig 1). The environmental pathways of pollutants include coastal waters, estuaries and oceans as well as volatilization and atmospheric long-range transport. Critical receptors of pollutants are aquatic ecosystems, endangered species and utilization like drinking water quality or fishing.

Fig. 1: Impacts on European river basins.

European rivers are hydrological systems having a huge variety of geometry, water flow, quality, etc. The environmental and ecological complexity can best be represented in a Geographic Information System (GIS), which provides appropriate tools for the storage, management, retrieval, analysis and visualization of hydrological, demographic, and other spatial databases. Simulation models describe the dynamics of the transport and transformation
of a chemical through the chain of waste water from its use and treatment to the receiving water bodies taking into account the physical, chemical, and biological processes which affect the quantity, structure, concentration and properties of the chemical on the considered spatial-temporal scale. By coupling a GIS with such simulation models for river basins the concentration of chemicals in specific aquatic systems can be predicted. The resulting software-system may be used for tasks in risk assessment and water quality management.

2 Geo-referenced simulation and aquatic exposure assessment

The European project GREAT-ER (Geo-referenced Regional Exposure Assessment Tool for European Rivers) was launched and carried out as an international effort to develop and validate the basic software and data methodology for the geo-referenced exposure assessment of aquatic systems. Pilot study areas in the UK, Germany, Italy and Belgium were selected and spatial and non-spatial data sets for down-the-drain chemicals (Boron, LAS) and intermediates were collated and integrated on a Windows NT platform using the desktop GIS ArcView. Chemical emission and waste water pathway as well as hydrological flow data are processed to obtain a consistent spatial data set for the catchment under investigation.

Fig. 2: Modular approach of GREAT-ER.

GREAT-ER follows a modular approach (Fig 2). The whole river network is segmented into river stretches, which are related to geographical units (GU) or subcatchments (Fig 3). A hydrological model is used to estimate the magnitude of river flow and flow velocities at ungauged river reaches. Waste water pathway and chemical fate models are connected to approach the impact from land use and human activities from each GU. The models can run in different complexity modes depending on the available data on the chemical and environmental properties (Trapp and Matthies 1998, Boeije 1999).
GREAT-ER’s direct output provides simulated environmental concentrations linked to a river network, which are visualised as colour-coded digital maps using a GIS. Very important is the possibility to deal with variability and uncertainty of the input data (Fig. 4): with Monte-Carlo simulations the probability distribution of the resulting concentrations as a function of the input data variability and uncertainty is determined. Temporal as well as spatial probability distributions represent stochastic values for $\text{PEC}_{\text{initial}}$ (near the discharges) and $\text{PEC}_{\text{catchment}}$ (for the whole catchment) (Boeije et al., 1999).

3 Pilot study area applications

The GREAT-ER software was developed and tested for various catchments in the UK (Yorkshire), Italy (Lambro), Germany (Itter, Rhine, Rur) (Koormann et al. 1998, Schulze et al. 1999) and Belgium (Rupel). Comprehensive monitoring studies over more than two years were carried out and over 2000 river water and over 600 waste water treatment effluent samples were analysed for the surfactant LAS and Boron. Fig. 5 shows the graphical output of the simulation of the surfactant LAS in the Calder catchment located in Yorkshire (UK).
simulated LAS concentrations in the river are shown and classified by colours. Additional background information, e.g. general water quality maps, can also be given by overlaying onto the simulation output.

Fig. 5: Map of mean simulated LAS concentration in the Calder (UK Yorkshire) catchment.
Fig. 6: Concentration profiles of simulated and measured LAS in the Calder (UK Yorkshire) catchment

Fig. 7: Concentration profiles of simulated and measured Boron in the Calder (UK Yorkshire) catchment
Fig. 8: Mean simulated LAS concentration in the Calder (UK Yorkshire) catchment under current conditions (top) and under the scenario of improved technology (activated sludge plus primary settler) for three selected waste water treatment plants (bottom).

The measured concentration profiles from the monitoring programs were compared to the simulation results (Fig. 6 and 7). The accuracy of the prediction is for most of the investigated catchments below a factor of three and shows the general applicability of GREAT-ER. It is proposed to integrate more catchments located all over Europe and to extend the approach to other environmental media (e.g. soil, estuaries, air) and intermedia mass exchange processes (e.g. run-off, deposition).

As a tool for management purposes GREAT-ER can be used to estimate various effects of changed conditions in the river basin by formulation of possible scenarios. For example the effects of changed emission rates (e.g. by reduced consumption of household chemicals) or improved waste water treatment plants on the simulated concentrations in the river system can be calculated (Fig. 8). Under the boundary condition of limited capital this may help the water manager to select the highest effective measure concerning the reduction of water pollution.

4 Conclusions

River basins are environmental systems which receive, transform, accumulate and release all kinds of anthropogenic substances discharged from various social and economic activities.
Economic, e.g. production, and social factors, e.g. consumption, has to be integrated with the hydrological, ecological and physico-chemical components of the river basin. The combination of spatial data bases with simulation models and analytical tools provides geo-referenced information for river basin management. Simulations demonstrate the general applicability of the GIS-Model-System for water pollution control and chemical risk assessments. Therefore the GREAT-ER methodology may be an important module of an DSS for an integrated river basin management.

Note


References


Acknowledgement

GREAT-ER was sponsored by the Environmental Risk Assessment Steering Committee (ERASM) of the Association Internationale de la Savonnerie, de la Détergence et des Produits d'Entretien (A.I.S.E.) and the Comité Européen des Agents de Surface et Intermédiaries Organiques (CESIO), in cooperation with the UK Environment Agency and Yorkshire Water.
The project is managed by a task force of ECETOC (European Centre for Ecotoxicology and Toxicology of Chemicals). The GREAT-ER 1.01 CD-ROM and the manual can be obtained free of charge from ECETOC, Av. Van Nieuwenhuyse 4, Box 6, B-1160 Brussels. Further information is available on the Internet http://www.usf.Uni-Osnabrueck.DE/projects/GREAT-ER.
1 General Introduction

The development and operation of sustainable water resources systems and related management strategies becomes continuously more important; major reasons are uncontrolled population growth in large parts of the world and the general increasing demand for water of sufficient quantity and quality. The development of water resources systems, however, has major impacts on socio-economy and the environment on a regional scale. Integrated over the globe, it also contributes considerably to global change. In some cases such impacts only become visible after several years or decades of operation. Thus, it is important to avoid negative long term impacts already during the planning stage or to adjust systems and their operation rules after these impacts have become visible. In fact, it is most difficult to identify all negative impacts during the planning phase due to the high system complexity and unknown feedbacks involved.

Throughout the world the construction and operation of reservoirs and reservoir systems has been considered as the ultimate measure to influence local and regional water balances. Once, a reservoir system has been developed as a physical system, future structural changes are often technically or financially infeasible. Hence, the most effective approach seems to be the reconsideration of existing operation rules under changing boundary conditions like climate, land use, demand and socio-economic as well as environmental objectives.

The process of reassessment of reservoir systems in respect to their economical and ecological functioning and also in respect to risk related with larger dams requires improved complex and effective decision support tools, usually named decision support systems DSS. Although there are several simulation and optimisation software packages, flexible, i.e. generic simulation and optimisation procedures combined with evaluation and decision making procedures are hardly known.
To account for the direct relationships and feedbacks between reservoir watersheds, the reservoir itself and downstream or linking reaches the reservoir simulation tools must be imbedded into a comprehensive simulation tool box suitable for integrated watershed management presently discussed intensively on a national, European and international level.

On behalf of the Environmental Protection Agency of the federal state of North-Rhine Westfalia, Germany the reservoir simulation and optimisation software package TALSIM had been developed by the Institute of Engineering Hydrology and Water Resources Management in the Department of Civil Engineering of Darmstadt University of Technology, aiming at the representation and simulation of controllable reservoir systems.

In a comprising initial phase of the project existing operation rules and additional feasible operation strategies were analysed, classified and generalised, which led to a common terminology and to a basic approach for reservoir operation. In combination with other elements of integrated watershed modelling and management this approach allows to represent most differently composed reservoir systems controlled by manifold operation rules and strategies. This provides the valuable advantage of generic application over specific solutions without the ability of generalisation. Consequently, the design and programming of tailored simulation models becomes abundant.

The model is operational and has been applied in different practical problems. References to these projects are given in the appendix.

2 Model description

2.1 Program structure

The program structure describes the basic software concept of a simulation model and the related management of system data. This has a major importance for the general applicability of a model.

Simulation with TALSIM is based on the consequent separation of system data and simulation model. System data are administered in a relational data bank management system. By means of a comfortable graphical interface the user has access to all data, system characteristics and parameters. Thus, he is able to compose the reservoir system according to local boundary condition, system characteristics and problem to be solved. It also includes all types of operation strategies. This flexibility imposes specific requirements on programming of the user interface as well as simulation modules combined in a modular program system. Modular systems, however, provide the opportunity of further program development and maintenance.

For a simulation run system data are temporarily transferred to the simulation program to compute current system states and related processes; results are then prepared for animation, e.g. through visualisation. After completion of a specific run results are stored in a RDBMS to make them available to the user, often to compare them with other scenarios.
2.2 Description of system elements

A simulation model for the operation of reservoirs systems requires the consideration of all relevant processes in water resources system, if relationships and feed backs between other hydraulically and hydrologically effective elements like (sub)basins and river reaches are of importance. This automatically leads to the definition of system elements. To be rather complete to model complex systems the following elements were implemented in model TALSIM which are listed below:
<table>
<thead>
<tr>
<th>Element</th>
<th>Important loads</th>
<th>Characteristics/methods</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural sub catchment</td>
<td>- Precipitation</td>
<td>- Soil parameters</td>
<td>- Surface runoff</td>
</tr>
<tr>
<td></td>
<td>- Temperature</td>
<td>- Land use</td>
<td>- Base flow</td>
</tr>
<tr>
<td></td>
<td>- Evapotranspiration</td>
<td></td>
<td>- Total flow</td>
</tr>
<tr>
<td>Urban sub catchment</td>
<td>- Precipitation</td>
<td>- imperviousness</td>
<td>- Surface runoff</td>
</tr>
<tr>
<td></td>
<td>- Temperature</td>
<td>- excess precipitation</td>
<td>- Baseflow</td>
</tr>
<tr>
<td></td>
<td>- Evapotranspiration</td>
<td></td>
<td>- Total flow</td>
</tr>
<tr>
<td>External Inflows</td>
<td>- Precipitation</td>
<td>- Import to the system</td>
<td>- Total flow</td>
</tr>
<tr>
<td>Transport reaches</td>
<td>- Inflow</td>
<td>- Translation</td>
<td>- Outflow</td>
</tr>
<tr>
<td>Consumer</td>
<td>- Inflow</td>
<td>- Consumer behaviour</td>
<td>- Return flow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Import from other regions</td>
<td>- External Inflow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Return flow to system</td>
<td>- Total outflow</td>
</tr>
<tr>
<td>Dividers</td>
<td>- Inflow</td>
<td>- Division rule</td>
<td>- Two outflows</td>
</tr>
<tr>
<td>Storages</td>
<td>- Inflow</td>
<td>- Stage-Volume-Function</td>
<td>- Releases</td>
</tr>
<tr>
<td></td>
<td>Optional:</td>
<td>- Stage-Area-Function</td>
<td>- Storage content</td>
</tr>
<tr>
<td></td>
<td>- Precipitation</td>
<td>- Hydraulics of operating gates</td>
<td></td>
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<tr>
<td></td>
<td>- Evapotranspiration</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Operation rules</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(- Infiltration behaviour)</td>
<td></td>
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<tr>
<td></td>
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<td>- ...</td>
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</tr>
</tbody>
</table>

Aquifers including wells have not yet been incorporated into TALSIM. Integration of irrigation schemes is in progress. Simulation modules so far are:

(Sub) catchments:
optional:
- Simple rainfall-runoff coefficient
- SCS-approach with 21 days antecedent precipitation index
- Soil moisture simulation based on elementary hydrologic units
External Inflows:
Read inflow time series via interface as
- Measured flows
- synthetic generated flows

Transport reaches:
optional:
- simple translation element without retention
- non pressurised pipe flow including translation and retention
- open channel using cross sectional data, based on extended Kalinin-Miljukov method
- use of stationary stage-discharge relationships (e.g. derived from water surface profile computations)

Dividers / separators:
optional:
- linear per cent devision
- according to threshold value
- according to relationship depending on inflow

Reservoirs / Storages:
- lake retention considering non linear relationships
- multiple operation options, e.g.
  - volume-release functions
  - level pool functions
  - Inflow-release functions
  - Optimum releases for hydropower production

2.3 Composition and simulation of water resources systems

The generation of a water resources system is achieved by graphical means composing the system of system elements. The spatial order follows actual flow patterns and forms an abstract picture of reality. After definition of all system components on the graphical interface according to their physical and logical characteristics, the complete system structure is also defined.
In a second step the necessary information and parameters have to be entered into the data bank to define the element behaviour. Finally the actual or planned operation rules are defined.

If the analysis is based on historical time series, a further step is the provision of measurements. TALSIM has its own time series management, supported by a RDBMS. Values can be transferred by Drag&Drop functionalities from other Windows-application.
3 Simulation

TALSIM allows simulations with different temporal resolution, varying between 5 minutes up to one month. Using small time steps care has to be taken that the system configuration chosen for representation is suitable for small time steps. Recent development in scale issues has been considered.

Depending on the load scenario chosen for simulation the following options are available:

- Simulation based on historical (synthetical) time series
- Forecasts

3.1 Simulation based on historical time series

Load input for simulation are measured historical time series. After choosing the simulation period measured values required are read and are made available to the simulation kernel. The simulation time interval can differ from the temporal resolution of measurements. Usual types of data are precipitation, potential evapotranspiration, flow and possible releases if recorded.
The simulation will often answer the question:

"Which control strategy will lead to the optimum system behaviour under conditions observed in history"

The procedure can be demonstrated by means of the following flow chart:

3.2 Forecast

Forecast scenarios are aimed at the operational, i.e. the current operation of reservoir systems. Not starting from assumed, but from known current initial conditions and an estimated forecast of precipitation or flows simulation is carried out to identify probable system states in the near future. Weather forecasts can be entered by hand or transmitted through a monitoring systems, which can be linked to TALSIM as realised at present in the WVER water board (appendix).

The source of forecast is unimportant for simulation itself, it plays a bigger role, however, for the evaluation of results.

If no forecasts are available, results from preceding extreme event analysis can be optionally used. TALSIM offers the opportunity to store results of extreme value analysis and characteristic flood hydrographs in the RDBMS and to use it as simulation input for heuristic optimisation.

A further option is the use of several design storm concepts for temporal distribution of forecasted precipitation height.
Forecast with design storm:

Forecast with characteristic flood hydrographs:
4 Results

Effective procedures for the evaluation of results contribute to the acceptance and general applicability of a sophisticated computer simulation model. For this reason emphasis was put on the visualisation of a magnitude of results from simple mass balances via hydrographs and duration curve to probability density functions.

A special feature is the animation of results during simulation runs. Of special importance is this feature during flood forecasting applications to effectively identify critical states of the system. Such critical situations can be handled by changing releases, either based on heuristic knowledge or optimisation using evolutionary algorithms.

M. W. Ostrowski, H. Lohr, A. Leichtfuss:
Simulation Model TALSIM
Animation:

A)

At the start of the event there are no critical states visible.

B)

Flooding of a tributary.

C) The situation on the tributary improves, flood control storage in the reservoir is activated. Increased releases of reservoir lead to surcharge at downstream narrow cross section.
5 Optimisation

5.1 Optimisation criteria

Every optimisation requires the choice of suitable criteria, i.e. the definition of an objective function. In general, the definition of control strategies and operation rules consists of a minimisation of critical states and/or the maximisation of single or multiple benefits, regardless whether these are of monetary or non monetary type.

The development of operation rules requires some a priori knowledge of optimum or desirable system states.

For the definition of desirable system states it is essential to reduce the decision space which still fulfils necessary boundary conditions or is in accordance with defined development guidelines.

5.2 Optimisation process

The optimisation of reservoirs system management shall lead to release decisions providing the best possible operation in regard to the criteria defined. In practice optimisation results are only useful, if they lead to clear recommendations for decision makers, how much and to which destination water is released under arbitrary inflow conditions and all possible system states.

For optimisation the evolution strategy is used. This is a model representation of evolutionary processes including mutation, recombination and inversion to influence individual genes. These genes or decision variables to be optimised differ according to the problem to be solved. Optimisation can aim at

- Variation of releases

Optimisation of releases means that under consideration of boundary conditions each release during a chosen time step is considered as a decision variable. This option is applied e.g. for real time operation during extreme flood events.

- Variation of rule parameters

Rule parameters define relationships e.g. between storage content and release or other system states and releases as mathematical functions. In this case the evolutionary strategy changes the mathematical functions until the best possible solution is found. This approach is chosen to identify mean or long term operation rules.

The optimisation procedures are fully described by /Lohr, 2000/ or in the TALSIM documentation.
6 Summary

The reservoir operation support tool TALSIM is a coupled system of a hydrological catchment model, flow propagation in river reaches and reservoir operation.

The tool is designed to represent systems with arbitrary structures and operation rules. The user can compose systems by use of a graphical interface. The use of the model requires up to date PC knowledge and a basic training for the application of the software package. Hardware requirements are low. Minimum standards are:

PC with min 133 MHz
64 MB RAM
sufficient hard disk storage > 2 GB
17’ Monitor (resolution 1024 x 768 or higher)

Through continuous maintenance and further development of the modelling system by Darmstadt University of Technology (DUT) in cooperation with the water resources consultants mll-WIS (Darmstadt) the compliance with the actual state of technology and science is guaranteed.

The owner of the program is the federal state of North-Rhine Westphalia. The application of the model can be organised through DUT and the mll-WIS (Darmstadt) in agreement with the environmental protection agency of NRW.
7 Appendix / examples

7.1 Koka dam in Ethiopia

Koka dam forms one of the biggest reservoirs in Ethiopia. It dams the Awash river in the headwaters 100 km downstream of the capital Addis Ababa. The catchment area is 11300 km². Downstream of the reservoir the Awash continues for 1000 km before it infiltrates and evaporates close to Djibouti without reaching the ocean.

The dam was build in 1960 to use hydro power and to provide irrigation water. The maximum storage was 1860 Million m³, which has been gradually reduced to 1100 Million m³ due to high sedimentation rates, resulting in complete blockage of the bottom outlet and reduced retention volume.

The reduction of the volume required the reassessment and reformulation of operation rules, which was carried out at DUT in 1998 /Shimeles, 1999/.
7.2 Water supply Windhoek

Namibia’s capital Windhoek is mainly supplied with water from three large reservoirs, combined in a system connected through pipes. The supply reliability is mainly influenced by the high variability of rainfall patterns and by very high evaporation rates.

Simultaneous occurrence of precipitation in the three reservoir catchments is seldom. Thus, it is tried to route and reroute water between reservoirs to maximise storage. Water stored in the reservoirs, however, is soon lost by evaporation, with highest losses in the reservoir with a large surface. For this reason water was first drawn from this reservoir. To improve planning and supply reliability, the operator NAMWATER initiated a check of the system. The goal of the study was the identification of improved operation rules to increase supply reliability. The analysis was carried out with TALSIM both in Windhoek and at DUT.
7.3 The WVER scheme

By operating a complex reservoir system in the western part of Germany WVER is responsible for multiple objectives, comprising

- Flood protection
- Domestic and industrial water supply
- Electric energy production
- Low flow augmentation

This system with partly competing uses will be operated by means of TALSIM, coupled with the monitoring system WISKI (Kisters Engineers, Aachen). Installation occurred in 9/1999.
7.4 Dam safety of Agger- and Genkel dams

As part of extended dam safety checks Agger- and Genkel dam sites were analysed concerning their ability to withstand extreme floods. In contrast to usual design storm approaches a probability approach was chosen, combining probabilities of extreme storms and high initial storage contents.
APPLICATION OF DECISION SUPPORT SYSTEM FOR DEVELOPMENT OF ACCESSION STRATEGIES IN THE WATER SECTOR IN CZECH REPUBLIC

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1 Introduction

The study /1/ was completed with the general objective of assessing the legal, institutional and technical implications of accession of the Czech Republic to EU as background for evaluating the economic and financial implications for meeting the requirements of the EU legislation in the water sector.

An essential part of the project was to establish a Decision Support System (DSS). The purpose of the DSS was to support the development and assessment of policies and cost efficient strategies for meeting the legal requirements of directives. Moreover, the DSS are going to be used for development of national water management plans being maintained and applied by Water research Institute under the umbrella of Ministry of Environment. In pursuance of this, the DSS includes relevant data and information and adequate modelling tools to:

- Provide a national overview of pollution sources, river systems, water quality conditions, existing water supply and waste water treatment facilities, technical options for improvements and facilities for calculation of associated costs;
- Assess water quality conditions as a consequence of implementing various scenarios and estimate the corresponding investment and operation and maintenance (O&M) costs;
- Identify least cost strategies for meeting requirements of directives for water supply and wastewater treatment specified as effluent standards and/or water quality standards.
- Estimate economic and financial implications of accession, including effects on investment programmes, recurrent costs and financing options

The user has access to the data bases and modelling tools through a graphical/GIS interface allowing a user friendly specification of the scenario wanted to be investigated as well as an easy retrieval of the results generated by the models.

Within a particular basin the definition of a scenario includes a specification of the most important parameters involved. This e.g. includes the timeframe involved (i.e. an intermediate and final year of compliance), assignment of certain areas as “EU sensitive areas” (requiring nutrient removal) or “Czech protected areas” (requiring other standards), allocation of selected effluent standards to some groups of point sources (by category, size and/or location),
assignment of water quality objectives to selected river segments, assumed developments within the industrial and agricultural sectors, and others.

These parameters allow the user to explore the range of options offered by different interpretations of the ultimate EU directives, alternative technical strategies, specification of intermediate compliance targets and final timeframe for meeting the requirements.

Based on these specifications the water quality simulation will be employed to assess the resulting water quality conditions at given control points and hence the extent to which given objectives are met. The corresponding investment and O&M costs for individual sources and/or categories of users form inputs to the economic and financial models to provide a further evaluation of the cost implications. Key outputs in terms of water quality maps and economic/financial diagrams are being returned to the user interface.

2 DSS components

The DSS comprises databases and models and function as an integrated and user-friendly tool, which is capable to evaluate alternative options for compliance considering legislative requirements, technical options, environmental impacts and economic/financial implications. The basic components of the DSS are shown in Figure 1.
The DSS facilitates access to relevant information on the national scale and provide a computational capability for the analysis and evaluation of different options to assist in the identification of viable strategies. This is accomplished by means of the following components:

- Data base, providing an overall overview of pollution sources (municipal, industry and non-point), recipient waters, existing water quality and hydrological conditions, water supply and waste water treatment facilities, technical options for improvements; basic statistical data from MOE and hydrological and topographical data,

- Parametric cost functions for the different technical options showing the required investments and annual O&M costs as a function of the number of person equivalents and required effluent standard; in case of treatment or water supply facilities and connectivity of inhabitants,

- Water quality models for determining the load from non-point sources and simulation of the resulting water quality conditions as a consequence of assigning different treatment levels to the individual point sources. The model also accounts for the corresponding investments and O&M costs. If appropriate, the simulation models may be used within optimisation procedure.

- Optimisation model to identify least cost strategies for meeting specified ambient water quality objectives, which are accessible in the combination with certain effluent standards for upgraded treatment. There are available two optimisation-ranking algorithms, one based on ranking of effluents from point sources related to executed investment through cost matrix, and the second based on imission principle taking into account pollution reduction in rivers due to the target investment based on ranking. The letter is fully dependent on simulation of WQ by the models;

- Economic and financial models for determining the net present value of compliance costs covering capital investment plans and associated O&M costs in both economic and financial terms. Further, cost allocation between the public sector and water users is assessed based on the various institutional scenarios. The user will have access to the data bases and modelling tools through a graphical/GIS interface allowing a user friendly specification of the scenario, which is to be investigated as well as an easy retrieval of the results generated by the models.

The Decision Support System has been designed to model pre-defined scenarios for accession process and its economical and technical incidence. Relevant data needed for the application of the different models and for the evaluation of defined scenarios have been included in a database, comprising a combined GIS (ARC VIEW) and database product (WINbase).

Basic information stored as layers in GIS-system, such as digitised map of the study area including the river network, digitised map of districts and the borders of catchments of 3rd order. Basic database information such as codes for locating information in approx. 400 sub-basins in the MIKE BASIN model for the computations on the national scale. There are available codes for locating information into 106 sub-basins (catchments of 3rd order) in a GIS-system. The tool can provide the user the basic layout for presentation of the simulation and

J. Krejcik, S Vanecek: Application of Decision Support System for Development of Accession Strategies in the Water Sector in Czech Republik - 72 -
scenario results and codes for locating all sub-basins within 5 major basins were stored in WINbase.

3 Application example

The scenario definition is one of the essential parts of using DSS. The user has to decide among many different options and technical parameters in order to define just one selected scenario. The most important of those parameters which could be defined by user are:

- List of the settlement, where some level of the WWTP is required. This list can be created either interactively inside the DSS or globally using SQL. Set-up of required level of wastewater treatment is enabled by a dialog which can be triggered by selecting menu item in DSS. The purpose of the dialog is to specify the type of wastewater treatment in a settlement of certain category. The category of settlement is defined by a number of person equivalents (PE).

- Costs for new sewer connections. Two matrixes based on Czech and EU standards are available.

- Cost matrix table for the new WWTP, upgrades of the existing WWTP, cost of the operation and maintenance and reinvestment costs have to be selected. Currently two options of the matrixes are included into the system.

- Percentage of the sludge disposal from WWTPs among the landfill sites, incineration and agriculture has to be specified. Those percentages are used for computation of the additional operation and maintenance costs for the WWTP.

- Required percentage of the connection to the central water supply for district must to be given. This list can be created or interactively inside the DSS or globally with using of the SQL. Global value for whole country can be used as well.

- Ranking coefficients for BOD and total N generated either by database or MIKE BASIN has to be selected in order to apply the optional ranking procedure.

- Starting years, number of the years of the investments for all categories of the investment as well as number of the years and profit for the computation of annualised cost have to be selected for DSS computations

Besides the options, which are selected by user, another data can be changed by system administrator for sensitive analyses as follows, e.g. cost of the connection of the new WWTP to the one common WWTP for more settlement (different result of the merging of new WWTP and different economical profit can be obtained by these changes), coefficients for computation of the final ranking coefficient from ranking coefficients for BOD and total N, new cost matrixes can be filled into the system, economical and financial data such as prediction of GDP development, water taxes etc…
3.1 Scenario definition

Three main scenarios were defined and computations by DSS were done for these scenarios. The requirements for wastewater treatment and WQ objectives were defined as follows:

Scenario 1 - EU requirements for NON-SENSITIVE areas were applied for whole country
Scenario 2 - EU requirements for SENSITIVE areas were applied for whole country
Scenario 3 - All basins, where the reservoirs for drinking water supply are situated + all basins where reservoirs assigned for recreation are situated + catchments of all river reaches which are assigned as a source for water supply exceeding 500,000m3/year were assigned as sensitive areas. According to such definition the sensitive area will be 61% of whole country (see Fig. 2)

Fig. 2. Scenario 3 (green and yellow coloured areas)

For all of three scenarios were basic additional options defined as follows:
- EU cost level for the new sewer connections were used.
- 20% of the sludge disposal to the landfill side and 80% to incineration was assigned
- Optimisation of the new WWTP by the merging was applied
- Percentage of the connection to the central water supply was assigned to 94% globally.
- Ranking procedure based on load reduction has been applied

3.2 Results of economical and financial modelling

Using the database part and the ranking procedure, investment programme matrix for the intermediate compliance targets was computed. The example of results obtaining by database modelling for one particular scenario is shown in Fig. 3. Investments needed for each scenario are divided into five categories according the ranking results. For each of those categories the
final WQ simulation were carried out by MIKE BASIN in order to investigate the environmental benefits of each particular scenario.

![Image of a map showing distribution of total investment costs for Scenario 3 over districts within the Czech Republic.](image)

*Fig. 3. Results of economical modelling. Distribution of total investment costs for Scenario 3 over districts within the Czech Republic is shown in the picture*

### 3.3 WQ simulation results

The concentrations for all WQ indicators are generated for all of more than 400 computational nodes for all of intermediate stage of compliance. In order to evaluate environmental benefits of each particular scenario and IP matrix the data were assorted and processed. In order to present the environmental benefits of the each intermediate investment programme the change of water quality in selected river branch during the time is presented. The user is able to compare the reduction of the concentration of the selected indicator in any of computational node within the system. The shape of the “reduction curve” generated by applying the intermediate stages of one scenario could be presented. The relation between environmental benefits and total of investments is could be thus demonstrated.

In order to present environmental benefits of all scenarios within Czech Republic the maps of WQ for the entire river network were generated directly from DSS (Fig. 4). All river branches are drawn and water quality for selected parameter is assorted to user-defined intervals by different colours. The improvement of water quality for any stage of any selected scenario could be investigated directly and “user-friendly”.
Fig. 4 Maps of WQ in rivers as results of simulations for ranking of Scenario3 (BOD). The baseline status is shown on the left while on the right water quality reached by implementation of all investments within Scenario 3 is presented.

References

Recent History and Future Developments of Decision Support Systems for the Dutch Rivers

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1 Introduction

In the Netherlands, there is a history of continuing studies towards measures to protect the land from flooding. Until a few years ago, these studies usually resulted in dike reinforcement along the greater rivers, i.e., the Rhine branches (Rhine, Waal and IJssel). In 1993, yet another study was initiated by the so-called ‘Commission Boertien’ which would most likely result in a new round of dike-reinforcements. From landscape point of view, these developments were viewed with some reluctance. In the same period, the World Wildlife Fund (WWF) issued a report entitled ‘Natural rivers’ (see [1]). In that report, a prominent place was reserved for the discussion about an ecological restoration of the river area by stimulating the development of a flowing water eco system in the winterbed of the river. The main measures to achieve the restoration were the construction of secondary channels and clay excavation. As a result, the banks would get a more natural character, and floodplain forest could develop.

In 1993, a vote in the Dutch parliament was accepted, in which the government asked for a testing of the initiatives that were expanded in the WWF report. In the testing, the focus should be on the consequences for the basic functions of the river (safety, shipping, drinking water supply, etc) and on the financial aspects. Besides, the coherence of the plans is association with existing landscaping plans and with policy-developments with respect to shipping, agriculture and excavations should be investigated.

The main result of the testing was a scorings table, in which the effects of the WWF-plans separately and in connection with the existing landscaping plans were made visible. It appeared that the plans of WWF could indeed lead to a re-introduction of natural processes normally found along the floodplains. However, the statement that this could be done without extra costs (in the opinion of the WWF, the excavated clay could be sold on the market, and that would provide the finance of the landscaping plans) was found to be a too optimistic point of view. It is interesting to note that development of nature, shipping interests and safety aspects did not necessarily interfere.

It is emphasized that this was one of the first studies in which an integral approach of re-styling the river area was proposed, but of course the term decision support system doesn’t apply here yet. The tools used for the analysis of the WWF-plans were developed ‘on the fly’, and were used specifically for testing the WWF-plans only. On the other hand, it was recognized that an instrument which would nowadays be called a decision support system, i.e. an instrument which is capable of testing in a quick and consistent way various initiatives on different scales (floodplains, as well as series of floodplains, up to catchment basins,) and visualize the

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outcome not only in tables and text, but also in figures and maps, would be very convenient. Especially because it was expected that, due to the promising outcome of the WWF-study, similar studies for other river systems would be executed in the near future.

2 The next step: Landscape Planning of the river Rhine

The analysis of the WWF plans was recognized as a quite successful approach to tackle the re-styling problems of the river Rhine and its branches. At the same moment, a discussion started in which the climate change took a prominent role. Climate change could result in a much higher discharge of the Rhine, higher that the discharge on which the dikes along the branches were designed (15000 m$^3$/s at Lobith). On the other hand, one became aware of the fact that a new round of dike-reinforcements was not the solution to this problem. Furthermore, a lot of plans were already proposed to enter recreation possibilities in the floodplains along the rivers. Also, a study was planned for improving the shipping on the river Waal (in which mainly the shipping was studied and hence, the opportunities of an integral approach as proposed by the WWF were ignored). Finally, nature itself gave a sign by means of the high waters of 1993 and 1995. All these facts rose the question, whether there was enough room for the river Rhine to satisfy recreation and shipping demands, to provide minerals and drinking water, to maintain areas of cultural importance and agriculture and above all, maintain the safety of the land.

From this, it was clear that one needed an instrument which would could act as a base for testing the many measures and analyze the various results with respect to water level reduction (if any), to morphological and ecological facts and to the cost aspect. This was actually the sign for the start of the development of the Decision Support System Landscape Planning of the river Rhine (LPR-DSS) (see [2], [3]).

LPR-DSS was developed as an instrument to act as an assistant in seeking answers to the question: Has the river Rhine enough room to satisfy all the demands (recreation, minerals, shipping, etc.). LPR explores the alternatives for sustainable landscaping of the riverine area, but does not provide a blueprint. One should keep in mind that re-landscaping is a dynamical process and due to the lack of knowledge of all aspects of the river system, some caution is required with regard to the outcome of the system.

The core of the instrument is a one-dimensional model for the simulation of water movement and morphology (SOBEK, developed by RIZA and WL|Delft Hydraulics). With this instrument, the various landscaping variants (consisting of combinations of various measures) are tested against the design water levels and water depth and bottom configuration. Other results are ecological features and financial aspects. It is emphasized that LPR-DSS had an exploitative character, and had no intention to give ‘exact’ answers. It was merely meant to explore the landscaping possibilities in a broad sense and hence, it has the character of a tool for feasibility studies.

As a first exercise in the use of the DSS, two landscaping variants were defined, the so called P50 and P90 variant. In P50, all the plans designed for the flood plains along the Rhine that were in a advanced stage or were already under construction by the end of 1994 (approximately 50 plans) were taken into account. These plans had mainly to do with mineral production and
development of nature. In P90, all the planned initiatives up to 2010 (approximately 90 plans) were taken into account. Both variants were tested against the design discharge of 15000 m$^3$/s. A typical outcome of the LPR-DSS is presented in figure 1. Calculations showed that in the case of P50, about thirty percent of the river reach had to deal with exceeding design water levels. For P90, the percentage was even higher, about fifty percent. Some of the results are given in figure 1.

![Diagram of floodplain management measures](image)

**Figure 1. Some results obtained with the LPR-DSS**

During the study, The Netherlands had to deal new period of high water which happened in January 1995. This wave was the worst since 1926. Taking this, and the high water of 1993 into account, the design discharge was increased from 15000 to 16000 m$^3$/s. If a possible climate change was taken into account, the discharge became even as high as 18000 m$^3$/s. The initiatives taken in the floodplains along the river (mainly nature development projects) were insufficient to cope with these higher discharges. They had to be extended with more rigorous measures such as large scale clay excavations, to reduce the water levels at these high discharges sufficiently to provide the land from flooding. The already available LPR-DSS instrument was a perfect tool to see whether the intended measures were sufficient and to study in a exploitative way a wide variety of measures (see figure 2 for an impression of possible measures).
As climate change is typically a long term process, the variants that were tested against this scenario should also have a long term character. Two of them were considered in the LPR-study, both with a window on the year 2050. Both variants were tested against discharges of 16000 and 18000 m³/s. The first one took the current use of land as a starting point and the measures were restricted to large scale clay excavations. At a design discharge of 18000 m³/s, dike reinforcement was still necessary to prevent flooding. In the other variant, all existing agriculture was removed, and nature development got priority. At the discharge of 18000 m³/s, widening of the floodplain appeared to be necessary, and even then, in some cases, the dikes had to be reinforced. The outcome is summarized in table 1: these facts should however, due to the exploitative character of the study, be viewed with great care.
Ditto, at a design discharge of 18,000 m³/s

Table 1. Some results for the long-term alternatives obtained with LPR-DSS.

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management like policy-makers, environmental organizations, local river boards and other interest groups who took care of landscaping aspects and valuable geological and cultural sites were invited.

3 Extending the LPR-DSS

In the exploitative LPR-DSS study, a limited range of measures had been taken into account. For the sequel of the project, which was called Room for the river Rhine, a lot more interventions were considered. Apart from the floodplain plans that were already developed, hydraulic obstacles were investigated, and also measures like retention and dike repositioning were discussed.

Having the LPR-DSS instrument available, and being confronted with the design discharge of 16000 m$^3$/s, it was clear that the totality of plans around the floodplains should be submitted to a new test to see if these plans, or combinations of plans together with the more rigorous measures as described above, didn’t lead to exceeding water levels. Therefore, the LPR-DSS instrument needed adaptation, however.

Having the LPR-DSS instrument available, and being confronted with the design discharge of 16000 m$^3$/s, it was clear that the totality of plans around the floodplains should be submitted to a new test to see if these plans, or combinations of plans together with the more rigorous measures as described above, didn’t lead to exceeding water levels. Therefore, the LPR-DSS instrument needed adaptation, however.

First of all, all the flood plain plans (about 254 in number) were screened one by one, and the characteristics (hydraulical and morphological effects, costs and efficiency),were put in a database. This was also done with 5 variants (with respect to more or less excavation of the flood plain) of the individual plans.

Furthermore, a GIS-shell was added. On a chart of the river area, one could easily define landscaping variants, by clicking on the floodplain, and selecting one of the available plans or variants (which also included high water free areas, retention basins etc.). The characteristics of the chosen variants were then given to the hydraulic module, and water levels and other hydraulic data was calculated. As a next step, the results could be compared with the preferred situation, and, depending on that comparison, the variant could be adapted by selecting another, pre-defined plan. In this way, a cyclic, iterative process is initiated until the preferred situation was reached. A screenshot of the resulting instrument which may be called LPR-DSS$^+$ is given in figure 3. LPR-DSS$^+$ is coming close to a full-fledged decision support system (see also [4] for the background information on this project).

One important feature however, is still missing. In LPR-DSS$^+$, all the measures are in a rigid way contained in the system: they cannot be adapted. In a full-fledged decision support system, one should have the opportunity to, in an interactive way, change the measures by adding a secondary channel, reduce the clay excavation or add a forest, and calculate ‘on the fly’ the hydraulic, morphological and ecological consequences. This was missing in the current system.
As a spin-off of LPR-DSS⁺, a number of other decision support systems for other areas in The Netherlands were developed which was of course in accordance with the premises of the fourth bill on the water management. For the Meuse, the lower river area (where the influence of the tide is still present) and lake IJssel, similar systems, inspired on LPR-DSS⁺ were introduced. Also, the development of a decision support system for dredging on the river Waal (see [5]) and a system for integral management of the Wadden sea (see [6]) is worth mentioning.

The results of the study Room for the river Rhine and the similar study in the lower river area have been offered to the Dutch State Secretary of Transport. Public Works and Water Management on February 28, 2000.

4 Towards a generic DSS

The experience of the several individual systems, together with the social need for technical as well as informative support by landscaping projects where the integral approach is still a key issue, has led to the development of a generic decision support system. The main aim was to develop an instrument to evaluate initiatives in the (or, a) river catchment in a comprehensive and quick way, by means of an iterative process, and gain insight in hydraulic, morphological, ecological and other aspects that are important to policy-makers. Measures are always, in the same, uniform way, translated into input for the hydraulic, ecological and possible other models, which form the core of the DSS. The instrument should help in formalizing the planning process, should assist the formation of a policy for the river area, as well as guide the design strategy on a floodplain level, and above all should be flexible and user friendly. Due to
these demands, the covered level of detail should vary between the 2D to cope with the floodplain-related problems, up to 1D for stretches.

The benefit from such a decision support system is threefold. First, the planning process, and the way of designing landscaping variants for floodplains is formalized. This is achieved by calculating effects of the plans on the base of (mathematical) models which are rigidly contained in the DSS (and are characterized by a version number), and on the base of geographical data which is also structured and labeled in a coherent way. Hence, the results can be traced, and are reproducible. The role of the database in this respect is crucial. It provides a base from which geographical data is issued throughout the organization, and can assure that everyone uses the same data. To achieve this, good management of the data is crucial.

Second, the DSS is a way to bring together specialists from different working areas. It forces them to tune their working processes and their results.

Third, the instrument is a obvious tool to collect, manage and consult features of plans, of the effects of plans or of the area itself. Results of former calculations can be saved and act as input for the expert system.

The design method of the DSS is based on the philosophy that plans are being created in a cyclic and iterative process. Ideas and plans are regularly tested and adapted, refined and if necessary detailed on a smaller scale (see also figure 4).

In order to do this, three phases in the process are being distinguished.

The first one is the so called data-line, used for the exploration of global ideas and initiatives. GIS-data of various kinds is usually the starting point for this analysis. However, also an expert-system, filled as time goes by using the analysis of actual plans, comes in as a helpful tool.

Then, there is the policy-line, in which the restyling alternatives are being tested against pre-defined scenario’s, with a focus on aspects like safety against flooding, shipping, ecology, costs, etc. The instruments used for this analysis are 1-dimensional hydraulic and morphological models, together with simple, also 1-D ecological models.

Finally, there is the design-line, which provides the largest level of detail. On the individual floodplains, represented as GIS-maps, plans can be sketched (using for instance standard ARC/VIEW) and testing is performed using 2-D water movement models and 2-D ecological models. The connection between the GIS-data and the hydraulic models is provided by Baseline, a tool which is able to generate on the basis of GIS-maps, schematisations which can act as input for the 2D hydraulical models (see [7]). This of course, is one of the important extensions of this DSS compared with the previous systems discussed above. It provides the possibility of interactive and cyclic design, testing and adaptation of the design, up to the point where the measures have the appropriate result.
A substantial part of the system is the so called hierarchic planning system. Goal of this system is consider the various measures on the different levels of detail. Hence, it is not necessary to specify the measure right from the beginning, but during the design process, the measure is made more and more specific. A measure at the 1D-level could for instance be: Excavation, and in the 2D situation, this could be specified to: excavation with recultivation, or construction of a secondary channel.

5 Recent Developments

The above mentioned systems are now in use for some time at the regional directorates of the Ministry of Transport, Public Works and Water Management in the Netherlands. Based on the experiences of the users, and motivated by recent developments with respect to the general policy regarding landscape planning, several improvements have been suggested. Implementing these improvements is also important to create a proper basis for the use of the DSS within the organisation. Questions like:

- What are in your opinion the basic tasks of a DSS
- What should a DSS do for you, such that you will indeed use it
- What is absolutely NOT necessary in a DSS
- What efforts are needed within your organization to introduce and maintain a DSS

have forced users to really think about the practical use of a DSS. The outcome involved things like:

- A modular basis is important
- It should collaborate with existing systems
• A DSS should contain different scale levels
• Apart from a single ‘answer’, a reliability interval should be denoted.
• An attractive (GIS-based) presentation and user friendly interface is vital

More specifically, there was a strong demand to incorporate modules for cost calculations, graded sediment and probabilistic analysis. All these facts, and the experiences gathered from the operational DSS are currently used to improve the various existing DSS (which sometimes need a complete redesign). It is expected that by the end of the year 2000 a full fledged decision support system for the Rhine and the Meuse is available.

6 Conclusions

In the continuing process of testing numerous individual plans along the floodplains of the greater rivers of the Netherlands against increasing design discharges, as well as in the development of a general policy regarding landscaping the river area in general, a decision support system as described above, has proven to be an effective instrument for the exploration on different scales. The exploration addresses not only hydraulic and morphological effects, but depending on the modules that are available in the DSS, ecological effects and predictions and cost of measurements, among others, can be derived.

The DSS turns out to be a quick and accurate instrument for testing individual plans and combinations of plans (variants), and for tracing possible bottle necks. Input and output is in a standard format, and facilitates communication and drawing up reports. Due to the fact that the database is given a central and leading role, results are reproducible, and ambiguity concerning the usage of geometrical data is avoided.

The DSS can support and ‘smooth’ the discussion over landscaping plans, by quickly (for instance through the use of the expert system) show results to the general public.

However, there is one point that is worth mentioning. In improving the ‘look and feel’ of the DSS, and make the GUI more accessible there is a danger that non-experts are going to play around with the system. In other words, the system becomes too generic, and an expert judgment with respect to the proposed measures is no longer needed. Hence, ridiculous measures can be tested against equally ridiculous scenarios, and one can off course not expect that the results have any realistic meaning whatsoever. For those cases, the saying ‘Garbage in, garbage out’, is still valid.

Speaking about decision support systems in general, they explore the alternatives for sustainable landscaping of the riverine area, but do not provide a blueprint. One should always keep in mind that re-landscaping is a dynamical process and due to the lack of knowledge of all aspects of the river system, some caution is required with regard to the outcome of the system.
Literature


[3] *Integrale Verkenning inrichting Rijntakken*, reports 1 to 12. (In Dutch), (1996). These are the detailed results of the study which among other deliverables, resulted in the LPR-DSS instrument.

[4] *Ruimte voor Rijntakken*, reports 1 up to 15. (In Dutch), (1998-2000). These are the detailed results of the study which among deliverables, resulted in the LPR-DSS+ instrument.. The main report (also in Dutch) is currently in preparation. A summary in English will most probably also be issued.


Environmental Management Methodology to Support Sustainable River Basin Development

– Features of a Goal-Oriented Decision-Support System (DSS) –

Franz Nestmann, Charlotte Kämpf, Werner Buck, Peter Oberle, Oleg Evdakov, Stephan Theobald, Jürgen Ihringer, Martin Helms and Bruno Büchele

Environmental Management to Support Sustainable River Basin Development: an Introduction

Franz Nestmann and Charlotte Kämpf

Environmental development equals the changes in ecosystem functions which are potentially used. Environmental management therefore is tightly coupled to changes in economic and social welfare. The development process is influenced by various factors as e.g. population change, climate change, pollution, civil engineering measures or land-use changes – in any combination, some are far beyond control. Since the 1990-ies environmental management is oriented towards "sustainable development" (SD), i.e. it is generally accepted in society that for all actions to manage environmental development any of the following three objectives are taken into consideration ("magic triangle"): (1) natural dynamics of ecosystems, (2) economic welfare, and (3) social justice or equity, thus bringing together divergent development objectives of individual stakeholders.

Today SD is accepted as the overriding goal for environmental management worldwide and it is layed down in all administrative levels (local, regional, national, inter- and supranational). The following may serve as examples: Local Agenda 21, UIP (Act on the Freedom of Access to Information on the Environment, UVPG (Environmental Impact Assessment Act), DVWK Publications and Proposal for an EU Water Framework Directive.

The major task of environmental management is to tune development factors to the objectives of the "magic triangle". The groups involved in environmental management are authorities as policy and decision makers, the science community, the public as interested parties and citizens, and the media. All four groups are challenged to support the environmental development process with their expertise. To solve problems and to realize opportunities they need to provide an adequate mix of tools, i.e. tools which will allow user-oriented presentation of information on environmental change and tools to support consensus on management plans in view of divergent objectives of individual users, problem owners, stakeholders (Fig. 1).
The environmental functions of a river basin allow various potential uses. The river, the flood plains, the catchment area, with hillslopes and tributaries, may serve three different functions: (1) an ecological function as biotopes (habitat for endangered species, areal for biome specific vegetation), (2) a socio-economic function as sources of natural goods (drinking water, produce, wood, gravel) and as development areas (industrial zones, transportation ways, shopping centers, housing, schools), and finally (3) a socio-cultural function as areas of cultural identity. The predominant interest groups and advacats will vary depending on the function used (Table 1). Therefore any present or future use harbors a potential for conflict situation. Development objectives of all interest groups need to be tuned to sustainable development at an early stage of planning to ensure various uses, e.g. nature preservation, protection of developed areas from floods, and consequently optimum economic and social welfare. Overriding development goals are set by national and regional legislatives.

**Figure 1**: Environmental Management for Sustainable River Basin Development
The purpose of this report is to contribute to the joint management effort to realize sustainable river basin development; i.e. to provide a methodology for a well founded and well-structured comprehensive decision tool. In the following sections at first a conceptual framework how to structure a modular goal-oriented Decision-Support System (DSS) in view of the pending EU Water Framework Directive is given (COUNCIL of the EUROPEAN UNION, 1999; s. contribution KÄMPF and BUCK). Secondly two case studies were chosen which are currently under investigation. Both studies are sub-ordinate projects of comprehensive research projects with aspects of flood management for the river Neckar and Elbe basins respectively. Computer-based decision support is explained with examples of practical application with already implemented modules. Established methods will be adapted and new "paths", especially in the field of information exchange, will be explored.

Table 1: River basin as environment – functions, potential use and predominant interest groups

<table>
<thead>
<tr>
<th>potentially used socio-ecological functions</th>
<th>interest groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>ecological (&quot;Naturraum&quot;)</td>
<td></td>
</tr>
<tr>
<td>space for biome-specific vegetation</td>
<td>habitats for endangered species, biotopes/areal for riverine- and floodplain-specific biocoenosis</td>
</tr>
<tr>
<td>socio-economic (&quot;Entwicklungsraum&quot;)</td>
<td></td>
</tr>
<tr>
<td>source of natural goods</td>
<td>biomasses (wood, crops, fish)</td>
</tr>
<tr>
<td></td>
<td>energy (hydropower)</td>
</tr>
<tr>
<td></td>
<td>(drinking) water</td>
</tr>
<tr>
<td>space for development projects</td>
<td>gravel, sand</td>
</tr>
<tr>
<td>socio-cultural (&quot;Erlebnisraum&quot;)</td>
<td></td>
</tr>
<tr>
<td>places of cultural identity</td>
<td>vistas (aesthetics); camping sites; sports facilities (golf course, soccer ground)</td>
</tr>
</tbody>
</table>

During the course of the Neckar Project (s. contribution of OBERLE, EVDAKOV and THEOBALD) a state of the art linkage of a model simulating development processes to a GIS-based Digital Terrain Model (DTM) was developed. The conflict between nature conservationists and other interest groups arising from dike shifting along the Elbe River shall serve as another example for a challenging problem in river basin management (s. contribution of IHRINGER, HELMS und BÜCHELE). Nature conservationists may welcome future flooding in the flood plains whereas other interest groups defend the low lands against flooding. They resist to give back cultivated land its "natural" status, last, but not least, as centuries ago these flood plains had been reclaimed under great effort from "nature".
It is expected that the overall results of both research projects will contribute to further interdisciplinary discussions about integrated management of flood plains and that the new tools will serve as modules in a comprehensive computer-based decision-support system. In the future they may contribute to the creation of a generic tool for sustainable river basin management.

Conceptual Framework for a Goal-Oriented DSS

Charlotte Kämpf and Werner Buck

To fulfill their tasks authorities, public and media need information on environmental development of which the science community will provide the most. The latter in turn needs input data, e.g. archived data of authorities and statements of preferences (of goals and objectives). Media will shuttle information from the science community and the authorities to the public. The groups' tasks and needs are supplemental to each other in their joint effort for sustainable environmental management. All four groups have to act as partners, they need to plan together to prepare generally accepted policies and lasting decisions (Fig. 2).

It follows that the smooth and fast exchange of information, the transfer of data and expert knowledge is a central issue for successful environmental management. Each of the groups maintains archives containing environmental information: measured data as well as descriptions on environmental structures and processes, the terrain, development factors and SD-indicators. Operable environmental information systems (EIS) are just recently becoming available for a broader public.

The science community will support the consensus-forming process preceding policy and decision making with a DSS oriented towards sustainable development of environmental resources (biotopes, natural goods, development area, area of cultural identity). The tools provided shall offer the following capacities: assessment of effects of development factors (direct and rated with respect to SD as overriding goal), weighting and compensating of divergent objectives against each other, ranking of scenarios, and practice-oriented presentation of results (Kämpf 2000).
Charlotte Kämpf Werner Buck: Conceptual Framework for a Goal-Oriented DSS

Figure 2: Environmental Management System

Two major paths of information exchange: online exchange, mostly asynchronous; and direct exchange, mostly synchronous, meetings, conferences

The basic structure of a modular SD-oriented DSS is given by the following sequence of data processing steps (Fig. 3):

- **DSS I – mandatory**: simulation model(s) + common database + GIS-based DEM/DTM + ancillary tools (statistical analysis, data query ...) This complex tool, usually addressed as a DSS, will allow to assess past events and the status quo as well as to forecast future environmental development under variant conditions, and of course to analyse structural and dynamic features in detail. Expert knowledge will define and select so-called SD-indicators, i.e. of measurable criteria suitable to indicate sustainable environmental development (s. case studies on Neckar and Elbe management).
  → results: tendencies or quant. effects of individual development factors on selected indicators

- **DSS II – optional**: value functions and/or statements (rule based expert systems) allow to transform tendencies or quant. effects of individual development factors on selected indicators into % development goal reached.
  → results: rated effects or loss and benefit respectively (Fig. 4)

- **DSS III – optional**: multicriteria decision making techniques (MCDM; optimization procedures) allow to aggregate indicators to form objective-oriented SD-indices, to weigh these indices reflecting objectives of various stakeholders against each other as well as to rank planning variants (s. also DVWK 1998 and 1999).
  → results: comprehensive environmental impact, ranked lists of decision alternatives (Tab. 2)
DSS (I): integrated system of sectoral simulation models  
+ data base + +/- GIS-based DEM/DTM  
expert knowledge in simulation models: cause-effect network, basic  
parameters, empirical system functions, dose-response functions in  
ecosystems and/or economic system and/or social system; selection  
of goal-oriented criteria, i.e. indicators for sustainable development  

DSS (II): value functions, statements  
to transform rel. and quant.  
effects into goal-oriented rated effects, evaluation of effects  

DSS (III): multi-criteria decision making techniques (MCDM)  
aggregation + weighting + compensating of indicators (> indices)  
optimization of planning variants  

DSS (IV)  
operable meta data  
and information base  
with search and retrieval features  
environmental information system  
(EIS)  
list of (ranked) decision alternatives  
additional information to data selected links to DSS (I ... III)  
links to other case studies  
decision making reports  

Figure. 3: Environmental Management Methodology – DSS I, II, III, and IV. Modular  
structure of a goal oriented Decision-Support System (DSS)  

Table 2: Environmental Management Methodology – DSS III: available interactive Multi-  
Criteria Decision Making techniques (MCDM; examples): comprehensive or partial aggregation of  
predicted and rated effects to support decision makers and other interested parties by comparing  
alternative planning variants (scenarios)  

<table>
<thead>
<tr>
<th>MCDM-technique</th>
<th>main features</th>
<th>author(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analytical Hierarchy Process (AHP)</td>
<td>hierarchical system of goals and measures respectively, system inputs, value judgements by pairwise comparison, aggregation</td>
<td><strong>SAATY</strong></td>
</tr>
<tr>
<td>Additive Weighting Method (&quot;Nutzwertanalyse NWA I&quot;)</td>
<td>hierarchical system of goals, cardinal transformation functions and weighting, aggregation by additive weighting → weighted mean</td>
<td><strong>ZANGEMEISTER</strong></td>
</tr>
<tr>
<td>Composite Programming</td>
<td>distance based extension of additive weighting method by introducing non-compensation factors for objectives</td>
<td><strong>BÁRDOSSY</strong></td>
</tr>
<tr>
<td>ELECTRE, ... PROMETHEE</td>
<td>outranking procedures to find a set of acceptable solutions</td>
<td><strong>ROY, ..., BRANS und MARESCHAL</strong></td>
</tr>
<tr>
<td>WinHOST, ..., VISA</td>
<td>flexible decision-support software packages with visual and interactive tools</td>
<td><strong>JUNGERMANN, ..., BELTON</strong></td>
</tr>
<tr>
<td>Expert System for Computer-aided Environmental Planning Tasks (EXCEPT)</td>
<td>offering various rating and aggregation procedures for environmental impact studies</td>
<td><strong>WEILAND</strong></td>
</tr>
</tbody>
</table>
The results of DSS I, II and III will all be directed to an internal environmental information system (DSS IV). This internal discipline-bound EIS is structured as a meta data and information base, i.e. it shall be equipped with search and retrieval functions. Aside from the results of DSS I, II and III it does offer additional information on primary data (source, analytical method), links to the database in DSS I, links to other case studies, and the decision making reports. The system will be equipped with a hypermedia help- and explain system (client server architecture).

The advantages of this DSS for decision processes in environmental management may be summarized as follows: (1) The decision process will be oriented towards a definite goal, namely sustainable development; from which suitable indicators/criteria are derived (2) it will be clearly structured into four modules (I, II, III, and IV) for the assessment and evaluation of effects on selected goal-oriented indicators, the optimization of alternative plans, and the presentation of results in a userfriendly practice-oriented way; and (3) it will ensure long-term administration of the data base, considering the hydrologic input data; this feature offers among others the base for an effective flood management.

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DEUTSCHER VERBAND FÜR WASSERWIRTSCHAFT UND KULTURBAU (DVWK, written by R Merz and W Buck), 1999. Integrierte Bewertung wasserwirtschaftlicher Maßnahmen (Integrated evaluation of water resources measures) - DVWK Materialien 1/1999. Bonn: Gas und Wasser (in German)

Hydrodynamic-Numerical River Model Neckar in Connection with a GIS

Peter Oberle, Oleg Evdakov and Stephan Theobald

On request of the water management administration of the State of Baden-Württemberg a hydrodynamic-numerical flood model (HN-Model) was developed which is linked to a digital terrain model (DTM). The HN-Model was developed in the context of the “Integrating Concept for the Neckar Catchment Area” (Integrierende Konzeption Neckar-Einzugsgebiet, IKoNE, 1999). The HN-Model allows the simulation of flood scenarios in order to evaluate, e.g. the effects of civil engineering measures on the flood waves of the Neckar river. To determine inundation zones and boundaries respectively the results of a hydraulic calculation may be superposed with the DTM applying a Geographical Information System (GIS). Topographical information on the terrain was collected from various data sources and serve as basic DTM data. Aside from the topographical information flood-relevant spatial data records are digitized, e.g. flood marks, flood impact area, retention zones and legally defined flood area. Linkups to aerial photographs of different flood events complete the sets of spatial data files.

The model is to be expanded gradually on the entire navigable Neckar (about 200 km). Both, the HN-Models and GIS-applications are transferred to the water management administration with the goal of supporting the handling of flood-relevant problems (classification of legally valid flood areas, flood risk analysis etc.). The development of GIS-functionalities and user interfaces, which are aligned to specific requests of the users, the administration, is underway. Additionally, courses especially designed for the training of authorities are offered on a regular basis.

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Integrated Management Concept for the Neckar Catchment Area (Integrierende Konzeption Neckar-Einzugsgebiet, IKoNE; in German); URL http://www.ikone-online.de (last access: June 9th 2000)
Assessment of the impact of diking measures at the Elbe river

Martin Helms, Bruno Büchele and Jürgen Ihringer

The interdisciplinary research activities of the project ‘Morphodynamics of the Elbe river’, which is carried out at the University of Karlsruhe and collaborating institutes (German Federal Institute of Hydrology – BfG, FBTU Höxter - University of Paderborn, Federal Waterways Engineering and Research Institute – BAW), integrate various aspects of the hydrology, hydraulics, topography, morphology and groundwater dynamics of the river system of the Elbe. The application and the development of tools needed therefor are supported by the information techniques GIS and RDBMS. Taking part in the research programme ‘Elbe-ecology’ supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) the project provides informations about abiotic parameters along the water course between the czech-german borderline and the weir of Geesthacht (40 km upstream of Hamburg). These informations are necessary for ecological and socio-economical investigations and decisions concerning the river system aiming at a sustainable development of the River Elbe basin (BMBF (1995, p. 1)).

One of the goals of the project is the assessment of the impact of historical diking and actually discussed dike-shifting measures. The paper focusses on the hydrological aspect of this assessment and on its interfaces to other disciplines. It has to be emphasized that the overall impact of various measures along the river is considered. This is a prerequisite of further analyses in the decision-making process regarding dike-shifting measures and therewith an essential contribution to the development of a decision support system of the Elbe river.

1. Dikes at the Elbe river - historical background and actual discussion

Diking measures along the Elbe river began already in the 12th century. Since then the natural inundation area (at a discharge with a recurrence interval of 100 years) was reduced from 617200 ha to 83650 ha or to 13,6 % (IKSE (1996, p. 13-16)) . This corresponds to a loss of retention volume of about 1,4 billion cubic meters. A part of these diking activities took place during the second half of the 20th century: 69150 ha or 761 million cubic meters are concerned, mainly at the areas of tributary mouths of the Havel river and further downstream of the Elbe river (a total of 42500 ha or 567 million cubic meters).

These diking measures contributed to a changing flood situation along the Elbe river during the 20th century. An effect of decrease on flood peaks in the upper german reaches due to the installation of large reservoirs, especially in the czech part of the catchment, was compensated by an effect of increase resulting from the diking measures in the reach downstream the Havel mouth (see below).

The Elbe river is subject of an actual discussion of dike-shifting measures. Regarding the high ecological potential of the Elbe river and its floodplains, which is unique in Central Europe, dike-shifting measures at suitable locations would be favourable. On the other hand flood protection is needed or claimed for the agriculture, for settlements, plants, streets etc. along the water course. In this respect the evaluation of dike-shifting measures depends on the position (upstream or downstream) at the river.

A survey of sites of potential retention areas is represented in Fig. 5. These sites include the Havel river with its channel and six polders. This is the major part of the retention area that might be reactivated for
flood-protection. A significant effect may be assumed, since statistical analyses indicate that the flood situation changed significantly after the loss of this retention space. The other sites represented in Fig. 5 are those of discussed dike-shifting measures that were selected after a discussion with the responsible authorities. In comparison to the Havel area the total of these areas is not negligible.

The discussion of dike-shifting measures requires a decision support, especially concerning the overall impact of all or selected measures together.

Fig. 5: Gauges and sites of potential retention areas along the Elbe river

2. Hydrological analyses as a contribution to a decision support for discussed dike-shifting measures at the Elbe river

2.1. Identification of relevant processes

For a hydrological analysis under the mentioned aspect the most relevant hydrological processes have to be identified.

Processes of flow dynamics of flood events and their correct registration are fundamental.

In a first step the hydrometry and its uncertainties have to be investigated critically, since measurement errors in flow series might be enormous and even greater than the effect due to dike-shifting measures. This is especially valid for the Elbe river, which has an unstable river bed due to the fine grain size of its sediments.
Further, long-term changes in the runoff situation due to natural variability and anthropogenic impact (especially due to the installation of reservoirs in the Czech part of the catchment) must be taken into account.

Extreme flood events in the flow process have an occurrence probability that may be classified according to long-term statistics.

The hydrographs of these extreme flood events have a spatio-temporal development in the channel network of the catchment.

Finally the flow dynamics cause dynamics of water levels and inundation areas along the water course and therewith a retention of water in the floodplains of the Elbe river.

The spatio-temporal description and modeling of all these processes with their interactions and the interface definition regarding analyses of the process impact are essential in the context of the discussion of dike-shifting measures.

2.2. Hydrological analyses

*General analyses:*

The general target of the hydrological project part is the statistical analysis and the modelling of the flow process. The steps undertaken therefor contribute to the special targets regarding the investigation of the impact of diking and dike-shifting measures (see below).

As a base of the investigations flow and water-level series (daily means and monthly extremes of instantaneous values) at 10 gauges of the Elbe river and at four tributary gauges were collected and integrated into the data base of the project. The gauges are included in Fig. 5, except the gauge of Dresden at Elbe-km 55.6. The longest series are those of the gauge of Dresden (146 years).

With regard to hydrometrical errors and uncertainties and to runoff changes in history analyses of consistency and homogeneity of the flow series were necessary. Proposals of a plausibilisation of some of the flow series were worked out and are still subject of discussion with the responsible authorities. Trend and double mass analyses and other methods of homogeneity analysis indicated that the series are not homogeneous. In order to reduce bias effects in the statistical analyses the series were therefore divided into sub-series with equivalent lengths at the different gauges.

These series were then analysed by various methods of time series analysis, in particular of frequency analyses of extreme events. Therefor the hydrograph information was parametrized as independent annual series of maximal peak discharges of years and vegetation periods and of corresponding maximal discharges exceeded continuously during x days (see Fig. 6).
Cumulative density functions (cdf's) were selected and approximated to the series. From these cdf's discharges of interesting recurrence intervals may be determined as quantiles. Using a regression model with the regressors of the catchment area and the length of the river channel these quantiles - or statistical flood parameters - can then be regionalized as longitudinal sections along the Elbe river. An example is given in Fig. 7: lines represent longitudinal sections of two series of annual peak discharges investigated (1964-1995 - thin lines - and 1936-1995 - fat lines). The points represent the corresponding gauge values of the frequency analyses. The already mentioned changes in the flood situation along the Elbe river are reflected in this result. In the upper part the values of the series 1964-1995 are clearly lower than those of the series 1936-1995. It can be assumed that the installation of reservoirs during the 1950-ies/60-ies in the czech part of the catchment contributed considerably to this development. On the other hand the results of the two lowest gauges included in the analysis (Wittenberge and Neu Darchau) do not differ significantly between the two series. It can therefore be supposed that the damping effect observed in upper reaches was compensated at these gauges due to the effect of retention loss at the Havel mouth and downstream.
In addition to these methods of time series analysis with a stationary process consideration it is important to model the flow process under the aspect of instationarity or - in other words - in its temporal sequence. Therefor hydrological simulation models are applied and developed, including the following model types: shot-noise models, non-linear precipitation-runoff models, flow-routing models and conceptual models of reservoir simulation. Especially the two latter model types are important for the simulation of the impact of diking or dike-shifting.

Interdisciplinary collaboration within the project enables further analyses on the basis of the hydrological results. In respect of the investigation of the impact of diking or dike-shifting this is specified under point 9 of the next section.

Special analyses with respect to the impact of diking on the flow process:

These analyses have two main targets:

- **Quantification of the impact of diking measures during the second half of the 20th century at the reach downstream the Havel mouth.** The better understanding of the historical processes may contribute to the development of a complete longitudinal section of flood parameters of the period 1936-1995, which is not possible yet due to the lack of consistent time series in the reach between the gauges of Barby and Wittenberge. Further, the scenario of earlier dike buildings (before 1936)
may be simulated. Therewith the impact of very large flood events like those in the 1940-ies/50-ies may be assessed for the actual situation.

- **Assessment of the impact of discussed dike-shifting measures along the Elbe river on selected downstream sites** (e.g., city of Wittenberge). It has to be emphasized that the overall impact of several measures together (all measures together or scenarios of selected measure combinations) is assessed. The method is certainly not the optimum at single local sites, but it is the way that enables the multi-site simulation for the whole Elbe river. This simulation is thus a prior condition of local detail studies of dike-shifting in the context of the global situation at the Elbe river, since local studies need a hydrological input that may be modified by measures upstream.

Intending to meet these targets a concept is developed and presented in the following steps. It may be considered as the hydrological contribution to a decision support system regarding diking and dike-shifting measures (DSS - type 1). The ninth step concerns the interface definition to further disciplines or analyses, respectively. Therewith it is possible to couple the results to models of DSS - types 2 to 4.

1. **Identification of homogeneous periods regarding historical diking measures at the Elbe river** according to their documentation in the literature and to other informations, e.g., in IKSE (1996, p. 13-16) (see also section 1). This is necessary for the above mentioned quantification of the impact of historical diking measures. Further a period representing the status quo has to be identified for the impact assessment of actually discussed dike-shifting measures. For this assessment **scenarios of possible dike-shifting activities have to be defined** (all discussed sites or different groups of sites).

2. **Selection and classification of suitable historical flood events in comparison with long-term statistics** (see above). These events should show effects of diking or dike-shifting measures. Therefore events with peak discharges exceeding values with a recurrence interval of five years (according to the series 1964-1995) at the gauges of Dresden and Barby are selected. These events are further classified depending on their shape, since different effects of retention spaces can be expected for events with different shapes. The shape analysis - in comparison to long-term statistics - is carried out by the use of diagrams 'discharge vs. duration of exceedance' (see Fig. 8). Another important classification criterion is the occurrence time before (black lines in Fig. 8) or after (grey lines in Fig. 8) historical diking measures or during a transition period.
3. Diagrams like in Fig. 8 are further used for the identification of flood events with shape characteristics similar to the characteristics of long-term statistics of the above mentioned annual flood parameters: e.g., at the gauge of Barby the event of spring 1994 corresponds to flood parameters with a recurrence interval of 3 years according to the series 1964-1995. Using this diagrams the identified events may be scaled up to fictive, large and rare events (e.g., event with a recurrence interval of 100 years) representing approximately the properties of the long-term statistics.

4. A basic tool for the analysis of the impact of several measures of diking or dike-shifting together is a flow-routing model. Regarding the low flow velocity of the Elbe river the approach of diffusion analogy is justified. It is applied as a three-step linear model. Parameters - corresponding to those used in the flood-forecasting system ELBA used for the Elbe river - were provided by the German Federal Institute of Hydrology (BfG). The channel network of the modeling system includes all reaches of the Elbe river between the czech borderline and the weir of Geesthacht, as well as the lower tributary reaches. As an example Fig. 9 represents the reaches between the Elbe gauges Dresden and Barby. The application of the model on recent flow series was successful. It could be integrated into the hydrological modeling system ‘FGM’ – ‘Flussgebietsmodell’ (Ihringer, J. (1999)).
Fig. 9: System functions of the flow-routing model ELBA for various reaches of the Elbe river between Dresden and Barby. Model parameters were provided by the German Federal Institute of Hydrology (BfG - 1998).

5. The use of the flow-routing model alone already enables the impact quantification of historical diking measures at the mouth area of the Havel river and downstream. This may be realized by the routing of historical flood events with actual model parameters and by the comparison of routed hydrographs with measured hydrographs concerning their peak discharges, event shapes or running times. Moreover the difference hydrograph between measured and routed hydrograph can be considered, since it should reflect the temporal development of the historical retention effect. As an example the flood event of the year 1954 is represented in Fig. 10. The hydrograph of Barby is routed to the gauge of Wittenberge. Two routed hydrographs of this gauge are included in the figure. The difference between them depends on assumptions concerning the flow of the Havel.

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river. However, in any case a significant peak increase in comparison to the measured hydrograph gives an indication of the effect of retention loss in the mouth areas of the Havel river and of the Karthane river near Wittenberge.

Fig. 10: Impact of the retention loss in the mouth areas of the Havel river and of the Karthane river on the flood situation in Wittenberge - example: flood event 1954.

6. **Local simulations of retention are performed using a conceptual reservoir model** with an iterative solution of the discrete continuity equation of the reservoir. This module is already integrated in the FGM. Characteristic curves of the reservoir have to be determined. The relation volume versus water level can be found by the use of a GIS (ARC/INFO or ArcView): difference rasters between a digital elevation model and a water-level raster are calculated and summed up to the volume corresponding to the water-level raster. The water levels are determined by the use of hydraulic-numerical models (e.g., HEC-2). Fig. 11 represents the relation of the Havel mouth area. In this special case the discharge at the Havel gauge Rathenow has to be taken into account in addition to the water level. The use of hydraulic-numerical models is further necessary for the determination of the rating curve of the outlet of the reservoir (outflow versus water level). Two options are possible for the outlet: it may be uncontrolled, i.e. completely dependent on the rating curve, or controlled, i.e. adapted to the event characteristics. Using this module the hydrograph is transformed and therewith more or less damped.
7. The above mentioned modules are integrated into the system ‘FGM’ for a coupled routing-retention modeling. Therewith the essential event processes of historical flood events are reproduced. The result are verified at measured downstream gauges. Furthermore, events of ‘recent’ years (e.g., those of 1981 or 1988) are simulated under changed conditions according to defined scenarios of dike-shifting measures. The procedure consists of an interrupted routing to the site of retention, where the hydrograph is transformed using the reservoir model. Then the transformed hydrograph is routed to the next site and so on. Finally the hydrograph transformed by several routing and retention procedures is routed to a point of verification or impact assessment. Both, the verification and the impact assessment, are carried out by a comparison with measured hydrographs (see also point 5). Fig. 12 represents the flood event 1954 after its transformation at the Havel mouth area and its routing to the gauge of Wittenberge. The retention effect is quite evident. Remaining deviations between the measured hydrograph and the routed and transformed hydrograph probably result from an retention effect of the Karthane mouth area near Wittenberge, which was not yet included in the analysis.

Fig. 11: Retention capacity of the Havel river channel and adjacent polders depending on water levels and on discharges at the Havel gauge Rathenow.
Fig. 12: Hydrograph of the flood event 1954 after routing and transformation at the Havel mouth area in comparison with the routed hydrograph without transformation and with the measured hydrograph.

8. Simulated series are statistically evaluated. On the one hand measured series, which are subject to considerable hydrometrical uncertainty, shall be verified. At gauges with only shorter measured series or at non-measured points of interest simulated series shall be added. They can then be used as a contribution to the development of longitudinal sections of statistical flood parameters along the Elbe river. This is especially valid for the reach between the gauges of Barby and Wittenberge, where the development of longitudinal sections for a longer period (1936-1995) was not yet possible due to the lack of reliable flow data before 1961. On the other hand fictive scenario statistics shall be calculated. The impact of actually discussed dike-shifting measures in various combinations shall be assessed not only with regard to single events, but also to long-term statistics of simulated series in comparison with historically measured series. Another relevant scenario is the assumption that the dikes built in the second half of the 20th century existed already before (e.g., since 1936). This scenario may contribute to a long-term evaluation of the status quo.

9. The final step in a hydrological contribution (DSS - type 1) to a decision support regarding diking or dike-shifting measures is the definition of interfaces to other disciplines. This is necessary for a coupling with further DSS (types 2 – 4). The structure of an interface is schematically given in Fig. 13. It may be specified under various aspects of ecology or socio-economy (e.g., concerning flood protection). The lower right part of the figure shows cumulative density functions (cdf’s) of a frequency analysis applied to annual series of flood parameters. This analysis already includes ecological criteria, like the tolerance of interesting species or biocoenoses facing inundation duration or inundation frequency. The occurrence time of inundations, e.g., during the vegetation period, might also be included (see Fig. 6). In collaboration with the FBTU Höxter/University of
Paderborn and the Federal Waterways Engineering and Research Institute/BAW discharge values of the cdf’s - with an ecological relevance - are transformed into water-levels using rating curves or hydraulic-numeric models (e.g., HEC-2). This is shown in the upper right part of Fig. 13. Rasters of water levels are used for the determination of inundation areas corresponding to the discharge value (see upper left part of Fig. 13). This again is possible in a GIS (ARC/INFO or ArcView) by the calculation of a difference raster between this water-level raster and a digital elevation model, which is available at most of the reaches of the Elbe river basing on topographical maps with a scale of 1:10000. On the basis of the calculated inundation areas and changing areas due to an impact of dike-shifting an ecological assessment is possible, especially as a large-scale survey along the Elbe river. Regarding flood protection the inundation areas may further be coupled with damage functions.

Fig. 13: Example of the coupling of hydrological models and results to tools of other disciplines.

3. Outlook

The developed tools should enable the hydrological analysis of interesting aspects regarding flood statistics, flood protection, ecology and especially regarding the discussed dike-shifting measures. Since the tool development included an interface to other disciplines, the coupling to their tools will be possible. Therewith the hydrological analysis results may be evaluated under various aspects and a decision support is possible.

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We intend to present the results of the hydrological analyses in Fall 2000 at the ‘Magdeburger Gewässerschutzseminar’ in Berlin and at the ‘European Conference on Advances in Flood Research’ in Potsdam.

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Multi-objective Decision Support for Water Quality Management of the Rivers Oder and Lausitzer Neiße

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Abstract

Selecting management alternatives to develop the water quality of a river basin involves the consideration of political, economical, environmental, social, technological, and informational objectives. Applying multi-objective decision making methods to water quality management (WQM) tasks optimal compromise solutions between ecological and man-made management operations will be obtained. The goal of the present paper is to apply the decision support system (DSS) REH to WQM of the rivers Oder and Lausitzer Neiße. The special DSS REHSPROX was used to compute Pareto-optimal solutions for the DO balance of both rivers where contradictory goal functions for different management options are taken into consideration. In both cases, the DO balance of the rivers investigated follows the German water quality standard. The optimisation results show small effects of wastewater treatment according to the DO balance for both rivers but stronger effects on BOD. Finally, an estimation of optimal investment costs for enlargement or new construction of WWTPs along the courses of the rivers is discussed.

1 Introduction

Water quality management (WQM) on a river basin scale is very difficult and complex task. It requires mathematical models not only for different time horizons but also for different management strategies. The simulation models allow a process control related to special goals of water resources management. Most often the goal is a suitable control scheme which present a compromise between the available budget for prevention measures and an acceptable water quality. Therefore, water quality management strategies deal mainly with some form of operational cost minimisation of WWTP designed to meet river water quality and effluent standards. Then, management decisions were made by ranking of different scenarios resulting from simulation models (Saaty 1980, Lootsma 1988). These multiple contradictory goals requires decisions which are influenced by the dynamic characteristics of system compartments and their interrelationships, by the kind of anthropogenic actions onto the aquatic ecosystem to be managed. For this reason, water quality simulation models proved to be an indispensable assessment tool. The management procedure involves sampling of data, selection of appropriate and validated simulation models and, finally, decision analysis. Newer developments present results visualised by GIS.

On the other hand, a DSS may be seen as a development of water quality modelling and simulation procedures which give out (Pareto-) optimal control designs for conflicting goal functions of the water uses in a river basin. Rivers are polluted by various anthropogenic interactions within settlements, by agriculture, and by industries. Polluted water affect the...
ecosystem behaviour and various water uses, and risk human health. Therefore, WQM of rivers is usually achieved through legislation, by rules such as specific water quality standards, by effluent conditions, and by conditions of immissions. Most of the river water quality problems arise due to interactions between throughflow, discharged soluble and suspended matter, natural and man-made chemical substances and environmental influences from the catchment. From water quality simulation models statements on changes of important water quality variables and their socio-ecological significance can be obtained. Implementing a water quality model in an optimisation procedure optimal compromise solutions of goal functions can be computed. The goals of WQM are twofold. The first is to maintain water quality at desired levels corresponding to water uses. The second is to achieve the first goal with a minimum cost or maximum benefit to the human society concerned. Two concepts of control of aquatic systems are possible depending on the goals of WQM. The first concept is directed to get optimal river system states, while the second is focused to obtain a constant operating behaviour of WWTPs (Hokkanen 1997).

WQM is possible through actions that prevent pollution or change the level of pollution. The latter include wastewater treatment, storing of effluents, wastewater disposal on land, artificial in-stream aeration, low flow augmentation or various combinations of them. Controlling of non-point source pollutants is usually achieved indirectly. The alternatives appropriate for a particular situation depend on many factors. Selection of alternatives is only one step of the management decision process. More decisions are needed with regard to efficiency, capacity, location, and scheduling of implementation of the selected option. For river basins this decision process becomes more complex. Once assured that the water quality system operates correctly, it is also important that its operating cost are minimal or that it works in optimum time or whatever performance measure is chosen. While functional correctness is taken for granted, the latter quantitative properties will often decide the best operation of the WQM system.

In opposite of the widespread use of water quality simulation models for rivers only a few applications of DSS for solving water quality problems on a river basin scale exist (e.g. Hahn and Cembrowicz 1981; Cembrowicz 1984; Krawczak and Mizukami 1985; Gnauck et al. 1989, Ivanov et al. 1995). In this paper the DSS REHS PROX (Gnauck 1984) is used to compute an optimal DO-BOD balance for the rivers Lower Oder and Lausitzer Neiße. Dissolved oxygen, biochemical oxygen demand, the amount of wastewater quantity and costs of enlargement or new construction of WWTPs are taken into consideration. As a result, Pareto-optimal solutions are computed for different management alternatives.

Most often, different software tools are used for WQM. For example, they cover spreadsheet tools for data analysis, modelling software for simulation, optimisation software for decision analysis, graphical programs and GIS-tools to present results. The tools usually are disparaged or only loosely connected. The whole decision process is off-line and prone to frequent converting errors. Policy selection and decision making on a river basin scale would greatly benefit from integration of the operations of data analysis, modelling, optimisation and visualisation.

2 Decision support and optimal decision making on a river basin scale

Decision support for WQM means that a desired water quality state can be reached by different ways of management actions starting from an initial state. The desired or final state is described
by a number of conflicting criterias. Thus, a decision of a decision maker means a selection of one (subjective preferred) vectorial evaluated alternative of action chosen from a set of all objective allowable alternatives to reach the final state (Habenicht 1990). Ester (1987) distinguishes between multiple attribute decision making (MADM) problems and multiple objective decision (MODM) problems. In the first case the alternatives can be explicitly evaluated by discrete values of the goal functions. In the latter case the evaluation of alternatives is implicitly given by functionals and can change continuously in the domain of admissible solutions. In such cases an important feedback between optimisation and modelling procedures arises. Global goals how to find efficient compromise strategies and algorithms for determining efficient compromise solutions for MODM-problems are formulated by Peschel (1980). Simon (1960) and Steuer (1986) characterise multi-criteria decision making processes by four different phases. During the first phase (search phase) a system will be analysed for changes in the structure and the function. If the results of analysis are positive one or more decision making problems arise as a result from this first phase. The second phase (modelling phase) is characterised by formulation of the goal functions, by the directions of alternatives, by the modelling process and by the imbedding procedure of the simulation model into the optimisation procedure. The third phase (selection phase) is represented by choosing one alternative of action of the set of all alternatives. These special alternative has to be implemented into the system under consideration. The fourth phase is characterised by the decision making process. The decision making problem is represented by a set of alternatives which contribute to reach the different goals. For a given decision problem the set of allowable alternatives is defined by external (real) conditions.

Decision making processes are based on interactive decision support systems (DSS) with hierarchic structures (Gnauck 1987). Lewandowski and Wierzbicki (1988) classified DSS by simple software tools (e.g. data bases), by expert systems and knowledge based systems (recognition of special water quality situations) and by model based DSS. From the last classification type the decision maker gets support by using vector optimisation procedures or by multi-criterial selection procedures to generate and/or to select alternative ways of action (Habenicht 1990). In principle, DSS consist of four main components:

1. Component of communication (communication between the DSS and an user (e.g. decision maker)).
2. Component of model and/or knowledge base (formulation of the actual decision problem).
4. Component of visualisation (representation of management alternatives by GIS or other representation tools).

The computer-aided decision making process can be devided into three steps. Two of them are subjective parts and one is an objective part of the decision making process:

1. Formulation of the decision problem
   In this (subjective) part the decision variables and the contradictory goal functionals are defined.
2. Computation of proposals for decision making.
   In this (objective) part of decision making a set of efficient alternatives will be generated by multi-objective optimisation. The dominant alternatives are selected and stored in the result domain.
3. Actual decision making process.

This subjective part of the decision making process covers the computer-aided selection of a compromise by individual weighting of the goal functions by the decision maker.

Solving a decision problem three requirements have to be fulfilled (Hwang and Masud 1979, Chankong and Haimes 1983):

1. Each solution of the decision problem is an efficient alternative (problem of validity).
2. Each efficient alternative may be a solution of the optimisation procedure (problem of non-discrimination).
3. A solution of the decision problem is an efficient alternative, if it exists (problem of identification).

The application of optimality principles to WQM systems on a river basin scale is burdened with difficulties of fundamental nature (Saaty 1980; French 1988, Lootsma 1993). Three different ways of formulating water quality goal functions can be distinguished:

1. Formulation of water quality goals by means of natural sciences.
2. Formulation of the functioning of a water quality system and its socio-economic environment.
3. Formulation of environmental standards for WQM.

Decision making and search for a compromise is one of the main environmental concepts. In a wide sense, these problems are the basis of environmental systems analysis which are directed to the development of strategies for survival. Pareto-optimality will then characterised by concurrent goal functions of the living components, by alternatives of action, by consideration of multiple goals, by selection of one element of the set of all alternatives and by the individual weighting of one single goal related to the subjective preference of the decision maker. The decision making process is characterised by choice of one objective allowable kind of action related to a subjective valued compromise on partly satisfaction of the concurrent and conflicting environmental goals. That means, decision making for WQM is always a search for a compromise between contradictory goal functions. Consequently, for WQM (and also for environmental planning purposes) the analysis of a river basin is a summary of model building, simulation and scenario techniques in connection with optimisation procedures, game theoretical methods, knowledge and data based expert systems, and geo-referenced visualisation tools just like GIS. In search of all possible alternatives for controlling a dynamic system by restricting standards and socio-economic goals the use of computing facilities is essential.

The individual weighting of the goal functions by a decision maker provided by a number of consultants and experts often depends not only from the actually reachable water quality system states, but also from the responsibility of politicians. Planning and decision making is a process which is characterised by a mutual understanding of their respective contributions to the common decision task. For any politician it is an obligation and liberty to make decisions which may not correspond to recommendations from experts. The common platform assignment of expert work for river basin management should be economy and ecology since the basis for decision making relies on tax revenues, budgets and gratis services of the nature. Management issues belong to the categories of planning, design, or operation. In this context, experts are required to describe and to explain the legal, institutional, technological and
economic implications of the decisions computed by a DSS. On the other hand, experts are required to advise the decision scenarios and their validity for the WQM situation considered.

3 The DSS REH
One of the broadly described DSS is REH (Rechnergestützte Entscheidungshilfe) developed by Straubel and Wittmüß (1983). It summarises the following structure (Gnauck et al. 1989):

1. Preparation level:
General arrangements for computing, input of external process model parameters, input of parameters for optimisation runs.

2. Learning level:
Study of the time behaviour of the process model, investigation of the influence of different management strategies on the process model time behaviour in dependence of changing external parameters and of the performance of the goal functionals, learning how to choose a suitable management strategy by game theoretic methods.

3. Testing level:
Check for reachability of control targets related to the goal functionals, search for a special control (management) strategy to reach given targets within a chosen time horizon, computation of the decision domain (individual optima) of the goal functionals.

4. Optimisation level:
Computation of Pareto-optimal solutions by ranking the goal functionals, by relaxation methods or by computation of the set of all compromise points with decreasing a-priori knowledge of the decision maker.

The following optimisation procedures are implemented in the software package:
1. Numerical gradient approximation procedure
   (for concave or convex continuous problems).
2. Simulation of Darwinian evolution strategy
   (for non-concave or non-convex continuous and/or integer problems).
3. Mixed optimisation procedures
   (for non-concave or non-convex continuous and/or integer problems).
4. A thermodynamic method
   (simulated annealing).
5. Branch and bound procedures
   (to solve special problems).
6. Vector optimisation on graphs
   (for search of routes on state-dependent vectorial evaluated arcs).

The DSS REH works in an interactive dialogue form where no special requirements are necessary for the type of process equations and for the mathematical formulations of the goal functions. Time-dependent restrictions of the management variables in form of lower and upper bounds and other implicit formulated restrictions between state and management variables are taken into account additionally. The problems solved by DSS REH resulting in non-unique solutions of the given WQM problem. The common goal of such WQM procedures is to find out all values of control variables which are elements of a specific control domain. The non-uniqueness of the solutions is given by the differences between control variables and goal
variables primarily. The used version of REH combines modelling and simulation, optimisation and graphical output. A new version, but not yet available, of DSS REH includes GIS tools also.

4 Applications to the rivers Oder and Lausitzer Neiße

Most of the river water quality problems are related to the interactions between the discharged matter and river organisms. The primary mechanisms of conservative non-degradable wastes are transport and dilution while degradable waste concentrations are described mathematically by considering the natural transport and decay processes. Between biochemical oxygen demand (BOD) of the waste discharged and dissolved oxygen (DO) concentration at points downstream of discharge points exists a complex relationship. Since 1925 this relationship had become one of the main indicators governing river water quality. The simulation models used are extensions of the classical Streeter-Phelps model. This relationship was taken into consideration for the DSS REHSPROX governing river water quality. Other simulation models reflect the diffuse non-point pollution of river basins which has emerged in the last 15 years as a major, difficult to solve WQM problem world-wide.

4.1 Data material

The area of investigation is characterised by the river stretch of the Oder between km 542 and km 704, and the river stretch of the Lausitzer Neiße with a length of 197,7 km. Both rivers form the border line between Germany and Poland. The river stretch of the Oder was divided into 8 segments of different length in flow direction, while the Lausitzer Neiße was divided in 6 river segments. The following data taken from the years 1996 to 1998 are used for simulation and optimisation:

1. *River water quality data*: DO, BOD, water temperature;
2. *Data of WWTPs*: effluent DO, effluent BOD, discharge of wastewater;
3. *River morphometry and hydrology*: average depth, average width, average volume of segments, average flow velocity within each segment.

In table 1 some hydromorphological conditions for the Oder are given. The discharges of both rivers are influenced by temperate continental climate with high discharge rates during spring and low rates during summer. Water levels of the Oder vary between 84 cm and 778 cm at Hohensaaten-Finow water gauge (Sonnenburg 1993) which result in discharge variations from 111 m³/s up to 3.480 m³/s. All data are taken from monitoring programs of the Environmental Authority of the State of Brandenburg at Frankfurt/Oder or at Cottbus.
Along the investigated river stretches of the Oder and Lausitzer Neiße some WWTPs discharge their treated wastewater into the river. These discharges have impacts on water quality. In table 2 an overview on the WWTPs of the Oder river stretches under consideration is given. Especially the Oder river contributes mainly to the pollution of the Baltic Sea. Diffuse pollution causes decreasing effects of water quality additionally. In opposite of that, the Lausitzer Neiße river has a high ecological value for fish life and a low influences onto the Oder river. Therefore, the primary goal for planning of wastewater treatment capacities in the Lausitzer Neiße river basin will be the maintenance of a good ecological quality.

Table 2
WWTP along the investigated stretch of the Oder river

<table>
<thead>
<tr>
<th>WWTP</th>
<th>Number of river segment</th>
<th>Wastewater equivalent</th>
<th>Model WWTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEO</td>
<td>2</td>
<td>116</td>
<td>WWTP1</td>
</tr>
<tr>
<td>Eisenhüttenstadt</td>
<td>2</td>
<td>99</td>
<td>WWTP1</td>
</tr>
<tr>
<td>Frankfurt/Oder</td>
<td>4</td>
<td>120</td>
<td>WWTP2</td>
</tr>
<tr>
<td>PCK Refinery Schwedt</td>
<td>8</td>
<td>200</td>
<td>WWTP3</td>
</tr>
<tr>
<td>Schwedt Paper &amp; Carton</td>
<td>8</td>
<td>216</td>
<td>WWTP3</td>
</tr>
<tr>
<td>Schwedt Paper &amp; Carton</td>
<td>8</td>
<td>60</td>
<td>WWTP3</td>
</tr>
<tr>
<td>Haindl Paper Schwedt</td>
<td>8</td>
<td>183</td>
<td>WWTP3</td>
</tr>
</tbody>
</table>

For the Lausitzer Neiße tributaries and effluents of contribute to the organic load. In table 3 an overview on this situation is presented.
Table 3
Tributaries and WWTP along the course of the Lausitzer Neiße

<table>
<thead>
<tr>
<th>Tributary/WWTP</th>
<th>Number of river segment</th>
<th>Water/Waste-water input (m³/d)</th>
<th>DO (mg/l)</th>
<th>BOD (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Föhrenfließ</td>
<td>1</td>
<td>78.192</td>
<td>9,02</td>
<td>4,32</td>
</tr>
<tr>
<td>WWTP Forst</td>
<td>2</td>
<td>4.150</td>
<td>3,00</td>
<td>393,40</td>
</tr>
<tr>
<td>Malxe-Neiße-Channel</td>
<td>3</td>
<td>60.048</td>
<td>9,37</td>
<td>2,05</td>
</tr>
<tr>
<td>WWTP Guben</td>
<td>4</td>
<td>6.640</td>
<td>3,00</td>
<td>393,40</td>
</tr>
<tr>
<td>Schwarzes Fließ</td>
<td>5</td>
<td>79.488</td>
<td>12.80</td>
<td>5,43</td>
</tr>
<tr>
<td>Granoer Mühlenfließ</td>
<td>6</td>
<td>59.875</td>
<td>10,69</td>
<td>4,77</td>
</tr>
<tr>
<td>Lubsza</td>
<td></td>
<td>777.600</td>
<td>-</td>
<td>4,20</td>
</tr>
</tbody>
</table>

For both rivers investment costs of WWTPs are calculated in dependence from inhabitant equivalents.

4.2 The DSS REHSPROX

The Streeter-Phelps type model SPROX (Gnauck 1984) describing the DO-BOD relationship was imbedded into the DSS REH.

The DO - BOD interaction model equations are formulated as follows:

\[
\begin{align*}
\frac{d\text{DO}(i)(t)}{dt} &= - (K_2(T_W)+Q(i)/V(i))\text{DO}(i)(t) - K_1(T_W)\text{BOD}(i)(t) \\
&+ Q(i)/V(i)\text{DO}(i-1)(t-t_F) + K_2(T_W)\text{CS}(T_W) \\
&+ \text{DOE}(i)(t)\text{QE}(i)/V(i)\text{u}(i)(t)
\end{align*}
\]

\[
\begin{align*}
\frac{d\text{BOD}(i)(t)}{dt} &= - (K_1(T_W)+Q(i)/V(i))\text{BOD}(i)(t) \\
&+ Q(i)/V(i)\text{BOD}(i-1)(t-t_F) + \text{BODE}(i)(t)\text{QE}(i)/V(i)\text{u}(i)(t).
\end{align*}
\]

where t - time variable, DO - dissolved oxygen concentration (mg/l), BOD -concentration of biological oxygen demand (mg/l), K1 - BOD decay rate constant, K2 - reaeration rate constant for DO, Q - mean volumetric flow rate, V -mean volume of a river segment, TW - water temperature (°C), CS - saturation concentration of DO (mg/l), i - number of river segment, E - input of DO or BOD, tF - time of flow.

DO saturation concentration within a river segment is calculated as follows:

\[
\text{CS}(T_W) = 14.65 - 0.41022T_W + 0.007991T_W^2 - 0.0000474T_W^3.
\]

For the annual time course of water temperature TW(t) the following equation was used:

\[
\text{TW}(t) = 13.16 + 10.23\cos(2(t-213)/365).
\]

Because a one-dimensional model was used segmentation was done in longitudinal direction by river segments, where segmentation cuts are performed by river stretches with close to homogeneous characteristics. The global parameters describing DO-producing and DO-consuming reactions as well as pertinent hydraulic parameters (flow rate, flow velocity etc.) considered as constant for each segment. Segments are also determined by tributaries and essential wastewater inputs. Inputs of organic load are located at the beginning of a segment (if any), where a segment is considered as a continuous stirred tank reactor with complete mixing.
approximately. Water quality variables observed are given at the beginning and at the end of each segment. Then the output of the i-th segment will be the input of segment (i+1). According to the chosen model structure the goal functions were formulated as extremal values in dependence on the ecological and socio-economical standards. The optimisation results presented are valid for mean flow conditions. The model takes into account the inputs of constituents to the river from the drainage area, the transport of constituents along the river, physical, biological, chemical and biochemical reactions within the aquatic ecosystem, and also the basic load of constituents caused by the geological underground of the river bed and the drainage area.

The goal functionals for the DSS REHSPROX are formulated by the following expressions valid for all segments and all time steps:

$$\max_{i} \sum_{t} \sum_{i} DO(t), \min_{i} \sum_{t} \sum_{i} BOD(t), \max_{i} \sum_{t} QE(t) \text{ and } \min_{i} \sum_{t} \text{Costs.}$$

According to the German water quality standard for the DO balance (class II) of all river stretches and for all time periods the DO content must be > 6 mg/l and the BOD content must be < 6 mg/l. To get an information on the decision domain the individual optima of the variables under consideration are computed.

4.3 Results and discussion

The DSS REHSPROX was applied to both rivers. Because of higher importance only results for the Oder river are presented and discussed. Analogous results for the Lausitzer Neiße river are obtained. But they will not discussed in detail. On the basis of DSS REHSPROX two management alternatives for all river segments and all time steps are considered. The goal functions are symbolised by \(f_i(t)\): 

1. Efficient control of waste discharges from point sources.
   The goal functions are given by
   \(f_1(t)\) - average value of DO → Maximum,
   \(f_2(t)\) - average value of BOD → Minimum,
   \(f_3(t)\) - total amount of waste water discharged from point sources → Maximum.

2. Cost analysis for reconstruction of existing or construction of new WWTPs.
   The goal functions are given by
   \(f_1(t)\) - average value of DO → Maximum,
   \(f_2(t)\) - average value of BOD → Minimum,
   \(f_3(t)\) - total investment cost → Minimum.

To get some information of the domain of decision the individual optima of the goal functions are computed. The results are presented in table 4. It can be seen that the operation of wastewater treatment plants has only a little effect on the DO-BOD balance of the Oder river.
Table 4
Domain of decision for the DO-BOD balance of the Oder river

<table>
<thead>
<tr>
<th>Goal functional</th>
<th>mean DO (mg/l)</th>
<th>mean BOD (mg/l)</th>
<th>Investment cost (Mio DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean max. DO</td>
<td>9.89</td>
<td>1.99</td>
<td>471</td>
</tr>
<tr>
<td>mean min. BOD</td>
<td>9.89</td>
<td>1.99</td>
<td>471</td>
</tr>
<tr>
<td>min. IC</td>
<td>9.79</td>
<td>2.59</td>
<td>0</td>
</tr>
</tbody>
</table>

Figs. 1 and 2 show the behaviour of the DO-BOD interaction for the investigated part of the Oder river. Two scenarios are computed: Complete wastewater treatment (blue bars) and without wastewater treatment (red bars). It can clearly be seen that both concentration levels follow the German WQS class II for the DO balance (DO > 6 mg/l), BOD < 6 mg/l) for all river segments and all time steps.

Fig. 1 Mean minmax DO concentration profiles of segments of the Oder river
From fig. 1 can be seen that the minima of the optimised DO concentrations decrease with increasing river length for both scenarios. On the other hand, a slight decrease of the organic load result from complete wastewater treatment compared with the first segment. This is shown in fig. 2.
For insufficient wastewater treatment an increase of the load within the 8th river segment can be seen. From Table 4 and Figs. 1 and 2 result only small effects to the DO balance of the Oder river by effluents of WWTPs. The reason for this behaviour is that the Oder river has a relatively high throughflow (Hohensaaten MQ = 540 m³/s). Taking a mean BOD concentration of 2.1 mg/l at Widuchowa into consideration a yearly organic load of about 35,400 t BOD/y will be obtained. This load must be compared with a value of about 22 t BOD/y resulting from untreated wastewater. Furthermore, from Figs. 1 and 2 the influence of the tributary Wartha can be seen at segment 6.

Table 5 contains the Pareto-optimal results for different capacities of WWTP. It can be seen that the investment cost of 166 Mio DM is a turning point in the effect of wastewater treatment on the DO balance. After this mark no essential improvement of the water quality is observed from optimisation results. An increase of investment costs causes very small changes in the concentration levels of DO and BOD only. This is caused by the model WWTP2 which has only a neglectible effect to the optimal wastewater treatment compared with the other WWTPs.
Table 5
Pareto-optimal solutions for enlargement of wastewater treatment plants

<table>
<thead>
<tr>
<th>Capacity WWTP1</th>
<th>Capacity WWTP2</th>
<th>Capacity WWTP3</th>
<th>mean DO (mg/l)</th>
<th>mean BOD (mg/l)</th>
<th>Investment cost (Mio DM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9.79</td>
<td>2.59</td>
<td>0.0</td>
</tr>
<tr>
<td>0</td>
<td>25</td>
<td>0</td>
<td>9.81</td>
<td>2.53</td>
<td>20.5</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
<td>9.81</td>
<td>2.48</td>
<td>34.9</td>
</tr>
<tr>
<td>0</td>
<td>75</td>
<td>0</td>
<td>9.82</td>
<td>2.46</td>
<td>46.9</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>0</td>
<td>9.82</td>
<td>2.45</td>
<td>57.8</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>0</td>
<td>9.83</td>
<td>2.39</td>
<td>63.7</td>
</tr>
<tr>
<td>50</td>
<td>25</td>
<td>0</td>
<td>9.83</td>
<td>2.36</td>
<td>84.2</td>
</tr>
<tr>
<td>75</td>
<td>0</td>
<td>0</td>
<td>9.84</td>
<td>2.31</td>
<td>86.6</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>9.85</td>
<td>2.22</td>
<td>106.9</td>
</tr>
<tr>
<td>100</td>
<td>25</td>
<td>0</td>
<td>9.86</td>
<td>2.19</td>
<td>127.4</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>0</td>
<td>9.86</td>
<td>2.16</td>
<td>141.8</td>
</tr>
<tr>
<td>100</td>
<td>75</td>
<td>0</td>
<td>9.87</td>
<td>2.12</td>
<td>153.8</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0</td>
<td>9.88</td>
<td>2.09</td>
<td>166.0</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>25</td>
<td>9.88</td>
<td>2.07</td>
<td>268.4</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>50</td>
<td>9.88</td>
<td>2.04</td>
<td>336.9</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>75</td>
<td>9.88</td>
<td>2.02</td>
<td>406.4</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>100</td>
<td>9.89</td>
<td>1.99</td>
<td>471.0</td>
</tr>
</tbody>
</table>

The effects of all WWTPs can be observed within the last segment where the largest spanning width between the optimal values of the two scenarios can be seen.

5 Conclusions

The use of multi-objective optimisation procedures for WQM is an approach promising more theoretical understanding of complicated natural processes at the complex river basin level. From the study above comes out that the DSS framework REHSPROX is suitable for WQM of rivers concerning influence of point loading on DO balances of river segments. To evaluate the ongoing eutrophication process within the Oder and within the Lausitzer Neiße combined with restrictions of water uses the model equations must be enlarged by equations for the nutrient cycles (e.g. phosphorus and nitrogen) and suspended matter. Also mixing and instationary transport processes have to be included. The study of goal functions can be seen as a study of mechanisms of changes within a river basin, rather than a study of water quality as they are observable at a given instant of time, or at a given site and situation. Such study is far from simple, because there is no direct method to observe a goal function of a whole river basin or its subsystems. Up to now, it has not yet been distinguished which formulations of optimality are most appropriate for river basins, and how far different goal functions are equivalent. This is also a question of practical concern. The method of solution of the optimal problem depends on the formulation. In this context multi-objective optimisation, especially Pareto-optimisation...
is of growing interest to solve WQM problems. Game theoretic formulations of goal functions seem to correspond most closely to what is going on in nature. However, no solutions are available at present for situations remotely close to what is of interest from an ecosystems point of view. Therefore, orientor optimisation could be an outline for WQM and ecotechnological approaches in river basins. WQM problems and the design of WWTPs must be seen as a whole. Suitable informatic tools just like simulation models, optimisation procedures and visualisation tools should be used for WQM in a combined manner. This would be very helpful for a sustainable WQM in river basins.

References


A GIS-based Decision Support System for the Mapping and Assessment of the Ecomorphological Quality of Running Waters

Michael Haase1, Günter Barnikel1, Rainer Beuerle1,
Klaus Tochtermann1, Rüdiger Schaldach2

Abstract

For the management of surface water resources a wide variety of spatial information has to be taken into account. These management tasks can only be performed economically by using a Geographical Information System (GIS). Commercially available GIS usually only provide a set of broad applicable functions (i.e. logical ANDs like the intersection of polygons) which are not specifically designed for selected user groups (i.e. river authorities). Additional functions can only be implemented by programming the GIS which in turn can only be performed by specially trained experts. Against this background the Ministry for Environment and Traffic (UVM) of the state of Baden-Württemberg has contracted the Research Institute for Applied Knowledge Processing (FAW) in Ulm in order to implement a GIS-based toolbox which is to be used by the river authorities (Gewässerdirektionen) in the state of Baden-Württemberg.

A main module within this toolbox is concerned with the mapping and assessment of the ecomorphological quality of running waters. This module is primarily based upon the standard which is defined by the working group of the federal states on water problems in Germany (Länderarbeitsgemeinschaft Wasser, LAWA) on this issue. However it has been adopted to special requirements in the state of Baden-Württemberg. Based upon the potential natural state of a selected river the current state of the ecomorphological quality parameters can be registered and evaluated along the course of the river making use of the spatial representation of this information in a GIS and assessing it via graphical user interfaces. The user interacts with the system via digital maps which are provided by a GIS. The current state of individual sections of the river or even the entire river regarding its ecomorphological quality is automatically computed from these registered parameters and will be presented in thematic maps and parameter bands to the user. On the basis of these results an interdisciplinary planning staff may then work out detailed plans where and how to improve the overall ecomorphological quality of a river. Last not least the system may be used to monitor the effects of the realizations based on these activities on the overall ecomorphological quality of the river.

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2 R. Schaldach, Technische Universität Braunschweig, Institut für Geographie und Geöökologie, Langer Kamp 19c, D-38106 Braunschweig, E-Mail: r.schaldach@tu-bs.de
1 Introduction

Determining the ecomorphological quality of running waters is a complex task which needs to take a variety of spatial information into account. The algorithms and procedures for carrying out this evaluation are well defined (LAWA 1999 a, b). In addition new requirements might arise from special local settings.

GIS are capable of handling and analyzing these large and complex data sets. Low cost GIS (i.e. ArcView from ESRI) which comprise an interface to a programming language are of special interest in this context. This enables software developers to implement new functions into the GIS framework which meet special user requirements regarding user interfaces and analysis procedures. The FAW currently implements a module under the application framework of ArcView for the determination of the ecomorphological quality of running waters. In addition to the definition of problem oriented databases and user interfaces this task comprises the implementation of rules for determining the ecomorphological quality of running waters. These rules can either be coded using a programming language or may be defined in a knowledge base. The latter allows for easy changes in case the evaluation procedures change over time. This paper discusses ways of handling these problems and gives examples for the use of such a system with field data.

The remainder of the paper is set out as follows: Section 2 gives an overview about the framework the system is embedded into. A general overview about the procedures and objectives for mapping and assessing the ecomorphological quality of running waters is presented in section 3. A set of relevant data is described in section 4 which have to be compiled in order to meet the information requirements resulting from the procedures and objectives described in section 3. In section 5 examples for using a software system for determining the ecomorphological quality of running waters are presented. Section 6 introduces a knowledge based system for determining the ecomorphological quality of running waters including tests with field data. The paper ends with a summary and a list of literature which has been cited in the text.

2 System Overview, Framework

The system is embedded into the Environmental Information System Baden-Württemberg (UIS BW). Figure 1 depicts the components of the system (Mayer-Föll et al. 1998).
The UIS BW is composed of so called "Base Systems" which provide basic data (e.g. geographic data, measurement data, land register data and metadata - data about data - provided by the environmental data catalogue UDK) and systems which provide specific information about the environment. The latter are subdivided into base components which mainly provide information to officials in charge and higher level components which provide relevant information to executive officers.

The information system for surface waters (GewIS) which is part of the systems for water, waste, former waste deposits and soil (WAABIS) provides means for accessing information about surface waters. On behalf of the Ministry for Environment and Traffic Baden-Württemberg the FAW is currently developing a GIS-based toolbox (GIS-GwD) (Haase et al. 1999 a, 1999 b, 2000) as part of the GewIS system which is designed for the use by the river authorities in the state of Baden-Württemberg. The main objectives of these developments are

- to provide an easy access to spatial data,
- to accelerate the working process with spatial data and
- to enhance the quality of processing spatial data

in order to support the officials in charge of the river authorities. ArcView under the operating system Windows NT was chosen to be the common platform for these developments. This GIS is in operation at all sites of the river authorities.

Michael Haase, Günter Barnikel, Rainer Beuerle, Klaus Tochtermann and Rüdiger Schaldach: A GIS-based Decision Support System for the Mapping and Assessment of the Ecomorphological Quality of Running Waters
The project GIS-GwD is subdivided into three main areas of interest which are:

- surface waters (e.g. planning tools for the enhancement of the ecomorphological quality of running waters),
- groundwater (e.g. hydrogeological monitoring) and
- special requirements resulting from the "Integrated Rhine Program" (e.g. ecological flooding of flood protection schemes (LfU 1999)).

Against this background two different tools for mapping and assessing the ecomorphological quality of running waters were implemented into this tool box. These tools are implemented differently and make use of different parameter sets for the assessment of the ecomorphological quality of running waters. They also offer different means for analyzing the data which have been entered into the system.

A main basis of both tools forms the digital network of running waters which allows to georeferentiate the compiled parameters including facilities along the course of the river. Other main sources of spatial information are the WAABIS systems and the spatial information and planning system RIPS (Müller 2000).

3 Mapping and Assessing the Ecomorphological Quality of Running Waters

The evaluation process for the ecomorphological quality for running waters will always take place on the local scale. Therefore, first of all the officials in charge have to decide about the section of a selected river which is of interest for further analysis. This procedure on one hand includes the definition of a section of the river being of interest which might actually be a part of the river or even the entire river. On the other hand the extension of the flood plain of this section has to be identified which is of interest for the following analysis.

The analysis itself is a feedback procedure taking changes of the state of the river over time into account. This procedure consists of the following four basic steps (Schaldach et al. 2000a):

1. Determination of the potential natural state of the river which mainly depends on the regional petrography and morphology.
2. Compilation and evaluation of the present state of the river according to the potential natural state of the river which was defined in the previous step.
3. Definition of actions which improve the overall ecomorphological quality of the river and realizing these concepts along the course of the river.
4. Monitoring of the actions which were realized in the field and restarting with step 2.

All information which is collected during this procedure has a spatial attribute. It therefore is collected, stored, analyzed and presented using GIS functions. Almost every information is
referenced to the river course. The digital georeferenced river network forms a main basis for the compilation and analysis of data. This river network has been derived for the scale 1 : 10,000. A second major data source is the digital topographic map, which is displayed in the background in order to assist the official in charge while compiling the relevant data or for presenting results in maps.

4 Relevant Information

Which information is relevant for the determination of the ecomorphological quality of running waters? The Länderarbeitsgemeinschaft Wasser has defined an extensive set of parameters which need to be evaluated along the course of the river (LAWA 1999 a) for determining the ecomorphological quality of running waters. Table 1 lists a subset of these parameters which are of interest.

<table>
<thead>
<tr>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Management</td>
</tr>
<tr>
<td>State of the Banks</td>
</tr>
<tr>
<td>Water Power Plants</td>
</tr>
<tr>
<td>Floodplain Usage</td>
</tr>
<tr>
<td>Groins</td>
</tr>
<tr>
<td>Discharge Regulations</td>
</tr>
<tr>
<td>River Bed Structures</td>
</tr>
<tr>
<td>Closed Channel Segments</td>
</tr>
<tr>
<td>Flood Protection Structures</td>
</tr>
<tr>
<td>Bank Vegetation</td>
</tr>
<tr>
<td>River Bank Strips</td>
</tr>
<tr>
<td>Discharge Points</td>
</tr>
<tr>
<td>Intake Points</td>
</tr>
</tbody>
</table>

Table 1: Examples of parameters of interest for the determination of the ecomorphological quality of running waters

In figure 3 two different methods for compiling parameter attributes are compared. On the left hand side of this figure graphical user interfaces for the compilation of vector data are presented. Point and line features are differentiated here. As an example for compiling data for line features the graphical user interface for the parameter "Line Management" has been chosen. The user interacts with the system by pointing out the start- and endpoint of a river reach with a unique attribute (i.e. meandering) on a digital map like the one depicted in figure 4. Here the river course including the river length at equally spaced intervals of a thousand meters distance values is depicted with the topographical map presented in the background. Depending on the scale the user is currently working in he is able compile data at any detail down to a resolution of a meter. After having chosen the river reach with a unique parameter
attribute a graphical user interface like the one depicted here will pop up. Here the user is asked to enter the parameter attribute value. In addition the start- and endpoint of the selected river reach are presented in this dialog. The user may change this selection at any time. In case two sections should overlap the system automatically corrects the sections involved according to the latest input so they do not overlap any more. The interaction of the user with the system for compiling data of point features (e.g. Water Power Plants) is similar to the one described for line features in this paragraph. It only differs by the fact that the user just picks one point with the mouse on the digital map along the river course, where the point feature is located (e.g. Water Power Plant). All defined parameter attributes are directly presented in the digital map to the user according to a predefined legend.

The second way of compiling data is depicted on the right hand side of figure 3. The parameters are grouped here to form parameter groups (i.e. River Bed Dynamics and Flood-plain Dynamics). The parameters are compiled along the river course in a fixed raster (i.e. 1000 m). Copy functions are implemented for the user’s comfort. Therefore the user only needs to change the attributes of parameters within the river section which is currently selected according to the attribution of the previous section. Using this dialog the user may work his way back and forth along the river course and edit any of the attributes which were previously entered. Due to cartographic complexity these attributes are not presented to the user on the digital map right away.

After the user has finished his data compilation work he is interested in viewing and analyzing these data. For this purpose a band graphic generator has been developed for generating user defined band graphics. The graphical user interface for the definition of such a band graphic is depicted in figure 5.
Fig. 2: Toolbox for assessing and mapping the ecomorphological quality of running waters

The user may subsequently select the parameters to be displayed in the band graphic from a list of parameters including blank lines ("Leerzeile") to visually form parameter groups. The sequence of the selected parameters which are displayed in the listbox on the right hand side of the dialog determinates the setup of the band graphic. In addition the user may select a scale for the presentation of the band graphic and a reach of the river which is going to be presented in this view.
1. Compilation of Single Parameters

1.1 Linear Features:

1.2 Point Features:

Fig. 3: Different GIS-based methods for data compilation

Fig. 4: GIS-based data compilation for single parameters
Fig. 5: Definition of parameter bands

Fig. 6: Example of a parameter band derived from the settings depicted in figure 5

A band graphic which is generated based upon this definition is presented in figure 6. Hot links are implemented which enable the user to dynamically change back and forth between the digital map and the band graphic views by locating a point along the course of the river or defining a location in the band graphic via mouse clicks.
6 Rule-based Evaluation of the Ecomorphological Quality of Running Waters

Fig. 7: Components of a rule-based evaluation of the ecomorphological quality of running waters based upon the ecosystem management decision system (EMDS)

We have chosen the ecosystem management decision system (EMDS) (Reynolds 1999 a, b) as an application framework for the knowledge based decision support for the enhancement of the ecomorphological quality of running waters. The system is comprised of the following three components which are depicted in figure 7:

- ArcView for data input, storage of spatial data and spatial analysis of data,
NetWeaver (Knowledge Base) as a system for storing, entering and maintaining the knowledge-base and

an Assessment System for managing and performing analyses (Interface / Inference Machine) on the geographic data stored in ArcView using the knowledge-base which was defined using NetWeaver. The results in turn are retransferred to ArcView for further spatial analysis. The link to ArcView is managed via a FTab object.

The main reasons for not coding the rules in a procedural language (e.g. Avenue, Visual Basic) are:

- Using a procedural language the user needs to know how to program or employ a contractor who is doing the programming work in order to maintain the analysis procedures.

- The knowledge base can be fairly easily extended by users who do not know how to program in order to enhance the evaluation procedure. The implementation of rules may be easily verified by the user using the NetWeaver system.

- The knowledge base can be subdivided into modules which simplifies the maintenance process of the particular knowledge base for the user.

There are several different ways for encoding facts and relationships which represent knowledge, i.e. semantic networks, object-attribute-value triples, rules, frames and logical expressions (Harmon and King 1985). Knowledge representation in NetWeaver is based on object-oriented fuzzy-logic networks that offer several significant advantages over the more traditional rule-based representation. Compared to rule-based knowledge bases, NetWeaver knowledge bases are easier to build, test, and maintain because the underlying object-based representation makes them modular. The modularity of NetWeaver knowledge bases, in turn, allows designers to gradually evolve complex knowledge bases from simpler ones in small, simple steps. Modularity also allows interactive knowledge base debugging at any and all stages of knowledge base development, which expedites the development process. Finally, fuzzy logic provides a formal and complete calculus for knowledge representation that is less arbitrary than the confidence factor approach used in rule-based systems and much more parsimonious than bivalent rules (Reynolds 1999 b).
Fig. 8: Semantic rule network for the example of integrated flood protection schemes

Figure 8 depicts the logical network for determining the natural flood protection index for a river section. This coding is based upon the definition of the following discrete categories for reasoning (Schaldach 2000 b):

\[
\text{rating} = \begin{cases} 
1, & \text{complete redesign of river section} \\
0, & \text{minor changes with respect to the present state of the river section} \\
-1, & \text{preserve the present state of the river section} \\
-0.5, & \text{no data available}
\end{cases}
\]  

(1)

In the following section the network for integrated flood protection schemes will be explained in order to illustrate the semantics of coding rules (Schaldach 2000 b) using NetWeaver:

- **Left hand side of the network**
  In order to ensure in case the section of the river under consideration lies in a build-up area (Auenutzung = f) that any flood protection schemes herein are protected this section will be assigned an overall rating of "-1" for the left hand side of the network.

  If the floodplain of the particular river section is not used as a build-up area the evaluation of the retention potential has to be taken into account. In case the retention...
potential has not been changed (= 1) the rating of the retention is defined as "-1". If the retention potential has been slightly changed or there has been an obvious change to it (is in 3,4) the rating of the retention is defined as "-0.24". And finally if the retention potential has been changed completely (= 7) the rating of the retention was defined to be "1". No data values are assigned a rating of "-0.5" automatically.

The overall rating of the left hand side of the network is computed via a fuzzy AND which is defined as a truth value (rating) of the AND node as follows:

\[
\text{AND}(t) = \min(t) + \left[\frac{\text{avg}(t) - \min(t)}{\min(t) + 1}\right]/2
\]

\(t\): set of truth values (ratings) of the AND node’s antecedents

Table 2 shows the evaluation matrix resulting from these rules.

<table>
<thead>
<tr>
<th>AND</th>
<th>Retention</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>-0.24</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Auenutzung = f</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>-1</td>
</tr>
<tr>
<td>Auenutzung != f</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>0.4756</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>-0.3125</td>
</tr>
</tbody>
</table>

Table 2: Evaluation matrix for the left hand side of the network depicted in figure 8

- **Right hand side of the network**

In case the floodplain of the particular river section is either a conifer or poplar grove, grassland, arable land, a build-up area or a combination of arable land and build-up areas the rating of the land usage (is in b,d,e,f,g,h,i) is defined as "0". In case this floodplain of the river section under consideration is a deciduous forest including brushwood areas or a wet land area (is in a,c) the rating of the land usage is assigned the value "-1". No data (= z) is assigned a rating value of "-0.5".

- **Cumulative rating using a fuzzy OR**

Both networks are combined via a fuzzy OR which is simply the maximum of the rating values (truth values) calculated for both networks for an instance. Taking into account the definition of the categories in (1) this evaluation procedure produces no-conservative ratings with a strong tendency for the redesign of the particular river sections.
Fig. 9: Results obtained from a rule based network for the evaluation of integrated flood protection schemes

The data basis for a practical test of the system was supplied by the Gewässerdirektion Südlicher Oberrhein / Hochrhein (GwD So/Ho 99) for the Brädbach. The catchment of the Brädbach is located at the eastern rim of the Black Forest. The Brädbach has a total length of about 17 km and is a tributary to the Breg which in turn tributes to the Danube.

Figure 9 depicts the results of the rating process for the evaluation of integrated flood protection schemes. The results shown in this figure are based on two different environments. The one in the background shows the evaluation within a stretch of the river in a coniferous forest. The second one in the foreground envisages the results for a relatively small section of the river along arable land in the flood plain. The red color symbolizes segments of the river which are rated “0”. Thus minor changes with respect to the present state of these river sections are to be realized. Those segments which are attributed with a green color are rated “-1”. These sections should be preserved with respect to their current state.
7 Summery and Further Enhancements

A GIS-based decision support system for the mapping and assessment of the ecomorphological quality of running waters on the basis of ArcView is presented in this paper. The system is currently being developed.

Examples for the practical use of the system are presented. Experiments with a knowledge base for the rating of river sections with respect to the ecomorphological quality of these sections are currently carried out. For this purpose the ecosystem management decision system was chosen as the software basis. Examples of results derived with this system and a self-constructed knowledge base are given in the paper.

A first version of the system will be completed by the end of the year 2000. It will include functions for data compilation and aggregation as well as for data presentation in maps and parameter bands. A knowledge based rating mechanism in order to determine the ecomorphological quality of river sections (i.e. the one described in section 6) can be easily integrated into the system later on.

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A Spatial Modelling Tool for Integrated Watershed Management: Lessons Learned from the EU-Project MODULUS

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Abstract

An important amount of new knowledge and material has been obtained from the many research projects carried out in the EU-DG12 Environment and Climate programme. However, little effort has gone into making this scientific material available as part of practical planning or management tools for public policy makers at the regional level. In a two year project, MODULUS aims to develop a generic spatial Decision Support System for integrated environmental policy-making at the regional level. Models from past or ongoing EU-projects are integrated that represent the physical, economic and social aspects of land degradation and desertification in Northern Mediterranean watersheds. The individual models operate at very different temporal and geographical scales. At the most detailed temporal scale, processes taking few minutes are represented, and, at the most detailed geographical scale dynamic models running on top of raster-GIS layers are implemented. The MODULUS DSS is developed as a very interactive, transparent and (geo)graphical instrument. It runs on PC machines under Windows NT and makes extensive use of Active X and COM component technology. In order to demonstrate its generic applicability the MODULUS DSS is applied to two case regions: the Argolidas (Greece) and the Marina Baixa (Spain). In the presentation we will dwell on the many lessons learned in trying to bridge the gap between fundamental research and integrated policy making.

1 Introduction

In the past decade, as part of its successive Framework Programmes, the EU has sponsored major research efforts in the domain of land degradation and desertification in Mediterranean watersheds. This research has generated large amounts of data, methodologies and models that have been instrumental in getting a much better understanding of physical and human causes and effects of these problems in Southern Europe. Based on the work carried out, many of the research projects made ‘scientifically based’ suggestions and recommendations, on ways to slow down, stop or reverse the process of land degradation. However few of the measures proposed found their way to the policy makers and got to be implemented. Hence, from a practical policy making point of view, little use was made of the studies carried out. This is in part due to the fact that much of the research was carried out for scientific reasons and with the purpose of better understanding the processes causing the problems. This type of research
tends to be very sectorial and in depth, rather than integral and multi-faceted in nature. It may produce outputs which are extremely valuable in their narrow disciplines, but too specific and disconnected for the policy maker who needs a broader view on the problems that need a solution. With a view to boost the policy use of material developed for scientific purposes, the MODULUS project poses the following scientific question: *Can existing research material, obtained from different complementary research projects, be integrated and made useful to policy makers?*

2 Methodological Approach

The methodological approach of MODULUS is clearly focussed on the integration of research material that is or will become available from other EU Environment Programme Research Projects. The guiding principle in this integration effort is the fact that the resulting model should be useful for environmental decision and policy making in the Northern Mediterranean generally and in two pilot regions in particular. To that end MODULUS principally builds upon the research results obtained in 4 on-going or past projects: EFEDA, ERMES, ModMED and ARCHAEOMEDES, and to a lesser extent MEDALUS. These projects have been selected among those carried out in the DG 12 Climate and Environment Programme because of the complementarity of the research carried out.

2.1 The EFEDA project

The EFEDA project (See for example: Burke et al., 1998) examined the interaction between the types of land surface and hydrological change associated with desertification and meso-scale climatic impacts. EFEDA developed methods and models to investigate the interaction between the land surface and climate processes within the context of changing surface properties. One of the main outputs of research was the PATTERN ecosystem model, developed to investigate the impact of climatic variability and climatic change on surface and subsurface hydrology and plant ecology (Mulligan, 1996, 1998a). The model is a tightly coupled hydrology and plant growth model developed for semi-arid environments. It incorporates all of the major hydrological fluxes as well as ecological processes of germination, growth, biomass partitioning, death and competition for up to three plant functional types at any one time. It includes a rainfall, storm and weather generator in addition to the tightly coupled hydrology and growth model that forms its core. The model was originally designed as a cellular slope model applied at the 100m² scale. It was later coupled with a GIS and applied to the whole Guadiana catchment (Castilla La Mancha, central Spain) for analysis of the impact of land use and climatic change on groundwater recharge.

2.2 The ERMES Project

As part of the ERMES project (See for example; Oxley et al., 1998) multi-scalar models have been developed concerning the effect of changing land-use patterns on vegetation cover, erosion risks, water run-off and infiltration, changes in ground water and channel flows, and evapotranspiration. The models developed capture the effects of various processes of water
flow and storage as a function of biological activity that operate in the system. These are very small-scale processes involving the water storage capacity and permeability of the soils as a function of the vegetation cover, slope, soil type, aspect and detailed spatial and temporal pattern of rainfall. This allows to represent at more aggregate levels the behaviour of successive scales of sub-basins within a catchment, and to represent the complex impacts of land-use on the channel flows at local and large scales, as well as on the recharge rates for ground water, and the stability and fertility of soils within the catchment.

2.3 The ModMED Project

Although the focus of the ModMED project (See for example: Legg et al., 1998; ModMED, 1998) is on the study and modelling of natural vegetation dynamics; hence on the biological and ecological processes characterising land covered by freely colonising and growing plant species, there is awareness that the space available to natural vegetation enabling the recovery of spontaneous plant cover is largely dependent on socio-economic dynamics. Where human pressure is increasing, loss of biodiversity and the complete destruction of habitats occurs, but, where old types of land-use practices are abandoned, new re-colonization and succession takes place restoring the dominance by shrubs and eventually forest species. In turn, this can lead to the loss of some ancient communities of grass- and shrub-land vegetation with a high biodiversity and conservation value. Although these processes are increasingly understood, the timing of the related landscape changes and the biological mechanisms behind such changes (species dissemination, establishment and competition) still need to be studied to a more satisfactory extent. ModMED addresses these problems by integrating three different levels of ecosystem analysis: individual plant, plant community, and landscape. A modelling environment has been developed consisting of hierarchically nested modules operating at different spatial and temporal scales.

2.4 The ARCHAEOMEDES Project

The ARCHAEOMEDES Project (See for example: Leeuw, 1998) investigated how the changing socio-natural dynamics of Southern Europe (urbanisation, agro-industry, infrastructure) relate to the problems of degradation and desertification in the area. Its central themes were: (1) the definition of the various levels of structuration which drive the dynamics involved, (2) the investigation of the ways in which the dynamics at these various levels articulate, (3) the development of decision-support models of these dynamics which facilitate the investigation of alternative scenarios for the future, and (4) the development of ways in which to map these dynamics in geographical time-space. The project used a combination of fieldwork, analysis, interpretation and modelling focussed on the relationship between the social dynamics responsible for perception, decision-making and action and the natural dynamics which sometimes are subject to human action and at other times trigger and constrain it. The phenomena are investigated at four spatial scales, each representing the interaction between two levels of structuration ranging from the European to the individual scale.

From the above short project descriptions, it may be clear that there is both complementarity and overlap between the projects selected: the complementarity should permit to come to an
integral model covering the essential physical, ecological, economic and social processes related to degradation, while the overlap should permit selecting the most appropriate and compatible model-components among the alternatives available.

3 MODULUS: a Spatial Modelling Tool for Integrated Environmental Policy-making

3.1 Choice of the Pilot Regions

MODULUS is to develop models and a Decision Support System with a high level of generic applicability in the Northern Mediterranean region. Applying the system to two pilot regions will test the adaptability and transferability of the system. Early in the project, the Marina Baixa (Spain) and the Argolid (Greece) were selected based on the following scientific and pragmatic considerations:

1. Policy relevance. MODULUS promotes a dynamic and integral approach to water management, desertification and land degradation. From the many sites where EU Environment Programme projects have been carried out, we selected two urbanised coastal watersheds where physical, natural, and socio-economic processes have been studied. Sites also, were the consequences of human practices (crop rotation schemes, irrigation, abandonment of agricultural land, return of natural vegetation cover, tourism and urbanisation) on the aquifer (depletion, pollution, salt intrusion) and on slope dynamics has been documented and modelled.

2. Data availability. MODULUS does not include an intensive data acquisition programme, rather it should work to the extent possible with existing data. For both regions selected sufficient high quality data, including GIS data, are readily available to validate and run the integrated models.

3. Model availability. MODULUS integrates existing models, methods and knowledge. It allows for the reformulation (aggregation and simplification) of existing models. But, as little as possible new models should be developed. In both sites ERMES and ARCHAEOMEDES have carried out combined research and model development in an effort to pool up to date understanding of the linked natural and socio-economic dynamics. EFEDA and ModMED have been involved in predominantly natural dynamics, and have, as a consequence, been able to come up with more easily ‘portable’ insights and models.

3.2 Policy makers

The development of DSS systems is an expensive and time consuming exercise, only to be undertaken if real problems exist that require a lasting surveillance of the system and regular interventions in order to bring it back on course. The only way to assure that the DSS will be effectively used for policy and planning exercises is to involve the end-users during its development. From the start, they should get the feeling that the end-product is useful in solving their problems in ways that make intuitive sense to them (see for example: Holtzman, 1989). In MODULUS the intended end-users are regional planners and policy makers, defined as: high-level technicians actively involved in the design and evaluation of regional public
policies. They perform policy work of a formal/analytic nature in support of the administrator or politically appointed person whose role it is to implement policies.

MODULUS intended to involve the end-users in the project right from the start, but, we ran into two problems, which forced us into rethinking the practical implementation of this aim:
1. In both pilot regions selected, as would have been the case in most other pilot regions, the past scientific work has been carried out for research purposes and not for policy making strictly speaking. Hence, little attention has been paid to involve local or regional policy makers in the work. As a result, MODULUS needed to find and contact its own end-users and convince them of the usefulness of yet another research project. This process took more time and effort than expected.
2. In some northern EU-countries a long tradition exists of involving scientifically trained technicians in the policy preparation phase. Other countries are still in a phase of setting up the institutional frameworks within which these people are or will become active.

As a consequence, and in order not to slow down the technical work, we decided to define temporarily a ‘virtual’ policy maker and ‘typical’ policy problems, to be replaced by real policy makers and their policy problems at a later stage. At the same time extra effort was put into the search for ‘life’ policy makers.

3.3 Policy problems, policy levers, and policy indicators

From the fieldwork carried out in the pilot regions as part of ARCHAEMODES and ERMES, a preliminary list of policy issues --policy problems, policy levers, policy indicators and policy criteria-- has been established. This list has been helpful in selecting and adapting the models considered useful for integration and in focussing the discussions with the actual policy makers. However, the policy issues mentioned in the preliminary lists very strongly focus on the short term: the actual economic activities, production practices, and immediate water management problems. It is precisely the strength of model based systems to explore the decision space and search for development alternatives that are beyond the immediate concerns and imagination of stakeholders, politicians and planners. Although most of these alternatives might turn out to be totally unacceptable or undesirable, some will be worth further analysis and evaluation, and all of them are calculated on the basis of a coherent set of assumptions, represented in the same equations and rules of the models. Hence, if we work from the assumption that ‘good’ socio-environmental policies are to be evaluated from a broader perspective and that they have to increase the level of sustainability of the region, then, we should define indicators and criteria that fit in broad categories including for instance: environmental quality, human welfare, resource availability and cost of policy implementation.

4 ‘Research Models’ versus ‘Models to support Policy Making’

Despite the fact that the terms ‘integrated’ or ‘integral’ model are widespread in the scientific literature, and despite the fact that the use of integrated models is strongly advocated in ‘disciplines’ such as Integrated Assessment (see for example: Gough et al., 1998), very few
recipes or procedures for model integration are available from the literature. Hence, model integration seems more an art than a science at this moment.

The integration of models is clearly a multi-criteria and multi-objective problem. We believe that problems need to be solved that deal with the end-use, scientific, and technical aspects of the integration. Although we treat them here separately, it is clearly understood that this sub-division is rather artificial:

4.1 End-use integration

In his review of the models developed as part of projects in the field of desertification under EU framework III and IV, hence, including all of the projects concerned in MODULUS, Mulligan (1998b) discusses a number of important differences between ‘Research’ models and ‘Policy models’. Both are foremost tools developed to simplify reality in order to understand it better. The former are developed to push ahead scientific understanding. They are process oriented, and are developed to build, test and extend research hypotheses. The latter are output oriented and meant to explore, understand, and anticipate the consequences of policy interventions in complex ‘real world’ systems. As to their use there should not be a difference between both types of models, and policy makers should be able to work with the most up to date knowledge about the way systems work. However, there are a number of practical considerations that differentiate them. Mulligan mentions among others:

- Research models are mostly complicated models which are computationally demanding and hence are much more time consuming than what is wanted for interactive, explorative policy exercises;
- Research models are often developed to understand processes that take place at geographical and temporal scales that are not relevant to policy makers. Policy makers will typically be interested in time scales expressed in years, not in seconds or centuries, and spatial scales covering a typical political, administrative, or management unit;
- Research models are typically data demanding. Often they will require field data specifically collected to run the model. Policy models can usually not afford this time and resource consuming luxury and should run on the basis of existing data material;
- Research models are models for experts, generating a type of output that is of immediate interest to the expert. The output is not compatible with the language and concepts that are of concern to the policy maker. Often, minor adaptations to the output generated by the models and a state of the art graphical user interface could bridge part of this gap, but they are rarely being applied;
- Research models are difficult to validate. This reflects their level of sophistication. Validation is a prerequisite for models if they are to be used in a policy context.

This list reinforces the point made earlier that research models are not automatically usable for policy purposes, and that often important adaptations need to be made to research models in order to use them for policy purposes. For MODULUS, the key end-user requirements of the Decision Support System and its integral model can be summarised as follows (see Chapter 4 by Mulligan and Reaney in Engelen et al., 1999):

(a) All processes. The MODULUS model must adequately represent all of the important processes necessary to provide the required output;
Scientifically proven. The process descriptions within the MODULUS model should be well known and scientifically proven. It is better to have a well understood, proven but crude process description than an innovative but poorly documented and less proven description. The model results have to be robust, reliable and accurate;

(c) Scale. The MODULUS model must operate at a regional scale and must provide information at a sufficient level of spatial detail (resolution) to reflect the scale of variation in the most important environmental and human variables;

d) Time horizon. The MODULUS model must be a dynamic model, operating at time scales and temporal resolutions which are relevant to the policy end-user. It should realistically represent the autonomous dynamics of the system modelled as well as the time scales involved in the policy preparation and implementation phases;

(e) Routine data. The MODULUS model must be sufficiently simple to run from routinely measured data. Routinely available data may include data collected by government or intergovernmental agencies such as the EU;

(f) Scenario based. The MODULUS model should provide easy to understand scenarios which the user can be taken through. These may be for environmental changes, anthropic impacts, and management options;

(g) Output centered. The MODULUS model must be output centered. It will be judged mostly upon the quality of its output and less upon its scientific or technical innovative character. It should provide appropriate results using indicators or variables that directly interface with the policy implementation process rather than more abstract scientific or technical variables;

(h) Interactive. The MODULUS model must be fast, responsive and interactive and should cater for a very short attention span. A response time of 15-60 minutes per simulation-run covering a period of 20-30 years should be aimed for. Clever models, fast algorithms, and efficient code will be required to achieve this.

The key trade-offs are between accuracy (of the data and of the model process representation) and simplicity (of models and of data). The model must have sufficient spatial and temporal detail and sufficient model complexity to accurately represent the processes but must achieve this over large areas in a fast and responsive manner with a minimum of data. From the above, it will be clear that this is not automatically achieved on the basis of research models, rather that important adaptations to the models are required before they are effectively integrated. In this respect, MODULUS has developed solutions at three levels: straightforward integration when the model represents the process adequately and efficiently, and when the interactions with other component models is possible; models are adapted if only minor repairs or reformulations to the model, its algorithms or code are required to have it perform its tasks more appropriately; finally rebuilding is considered when the model need major repair and adaptation in order for it to fit in the modelling scheme.

4.2 Scientific integration

The 4 projects described earlier in this paper where deliberately selected on the basis of the complementarity of the research carried out. And, from a preliminary analysis it was concluded that the potential for integration was real. From the 4 projects models were available in different stages of development: some models where fully finished and had been validated
and tested against real world data, while others were still in an early development phase. The models were evaluated on their conceptual and technical merits as well as their scientific novelty. A ‘typical’ scientific evaluation would also have considered the performance of the models in terms of realistically representing the processes for which they are developed, and their capacity of generating validatable output. However, most of the models available from the 4 projects where not sufficiently operational to permit the latter type of analysis.

As a result most of the evaluation has been focussed on the role models could fulfil as component sub-models in the integrated context of the MODULUS model. The following criteria where taken into consideration for the selection and evaluation:

- **Time scales and temporal dynamics.** Only dynamic models are considered. Models have to span a strategic time horizon (10-20 years) and operate at appropriate (simulation) time steps reflecting the real world processes and decision-making time frame (1day-1year). With a view of simplifying or aggregating the model, the effect of increasing or decreasing the time step on the performance of the model is a criterion;

- **Spatial resolution and spatial dynamics.** Only spatial models or models that can be spatialised are considered. Models have to be applicable to a relatively large regional entity and operate at an appropriate spatial resolution reflecting realistically the real world processes, the spatial variability across the region, and the individual geographical entities subject to decision and policy making (1ha-1000km²). With a view of simplifying or aggregating the model, the effect of increasing or decreasing the spatial resolution on the performance of the model is a criterion;

- **Compatibility of scientific paradigms.** Models are considered that from a scientific/operational point of view can be integrated. Thus, the basic assumptions and constraints on which the models are developed are evaluated. Most of the models available in MODULUS are spatial, dynamic, non-equilibrium models that are solved by means of simulation. Hence, little problems with clashing scientific paradigms were detected;

- **Models that fit the total integration scheme.** Models are considered that fulfil a task within the MODULUS integration scheme which is not dealt with by any other (sub-)model. They compute a subset of the total set of state-variables and exchange the necessary information among one another at the right temporal and spatial scale during the calculation;

- **Level of sophistication.** The models considered are in most cases simplified version of ‘the ultimate’ or ‘the best available’ models. In order to fit in the integrated scheme, and to be at the right level of abstraction, models need to be simplified and need to be striped of details that are not directly relevant to the problems at stake. The value of the integral model is as good as the weakest element in the web of linked sub-models. Hence, it is better to improve this weakest element rather than to add details to the other sub-models.

The analysis of the models against the selection criteria lead us to conclude that an integral MODULUS model consisting of the models mentioned, would be a grid based model running at a spatial resolution of 1 ha (100 by 100 meters) and at a temporal resolution in the order of 1 week to 1 month. The output generated with this model would suffice for most relevant policy questions in both case regions. A spatial resolution of 1 ha would be appropriate for the majority of the processes represented. A large amount of GIS data are available at this resolution, and it allows for the inclusion of models running on irregular (administrative) areas if the borders of these areas are redrawn to coincide with the edges of cells. The errors thus made are minimal. As for the temporal resolution, the choice of a monthly or weekly time-step
is not appropriate for a number of the models. In particular, KCL’s PATTERN model (see for more details Chapter 4 by Mulligan and Reaney in Engelen et al., 1999) requires a much finer time step (minutes or hours). As a result, the decision was made to develop a model running at an hourly time step. While the simulation is stepping through time, sub-models are invoked as required. Information that needs to be exchanged is aggregated over days, weeks or months as required.

4.3 Technical Integration

As most research models nowadays are also computer models, the problem of technical integration is very much a hard- and software problem. From a computer science point of view, integration of models has become very much a problem of software component integration. Software components are pieces of software that are designed for re-use: ‘a coherent package of software artifacts that can be independently developed and delivered as a unit and that can be composed, unchanged, with the other components to build something larger’ (D’Souza and Wills, 1999). The ideal software-component is platform independent and can be plugged into a software system like a plug into a socket.

Clearly, the typical user of a modelling shell or Decision Support System (DSS) would be served best if he could compose, exchange and re-arrange sub-models as easily as Lego building blocks and develop his model from a set of exchangeable and interchangeable Model Building Blocks (MBB). Such Model Building Blocks can be more or less complete models varying from simple mathematical operators, such as Multipliers or Adders, to rather sophisticated and nearly complete models consisting of coupled mathematical equations performing a number of sophisticated calculations. A Model Building Block represents a part of a model: an action or process. MBB’s may simply represent sources of information (i.e. entered from file or by the user), other will transform information as it passes through them, and still other will simply serve to communicate, in a synthetic manner, the outputs of the model to the user.
We realise that MODULUS will not develop the ultimate methodology or library containing a set of easily pluggable Model Building Blocks. More development time would be required to achieve this goal. But in MODULUS the question of re-use is posed: from different EC projects partners have their existing models, written as monolithic applications in whatever programming language they master. Rather than re-coding this material in yet another programming language to develop yet another monolithic application, MODULUS has chosen to integrate the material on the basis of a state of the art component technology. The constraints of time and budget, the availability of ready to use modelling material, as well as the objective to produce a running system applied to two case regions made us decide to attack the problem from a rather practical angle. The focus of the work carried out under the heading ‘technical integration’ therefore is on the evaluation of the usability of the existing component technologies, rather than on the development of new standards, functional specifications and technical designs.

5 The MODULUS model

Screening the available models against the End-use integration and Scientific integration criteria has allowed deciding on a scheme for an integral MODULUS model, consisting of component sub-models (see Figure 2). This integration scheme has the great merit of covering an important part of both the natural and the socio-economic system. From an initial analyses it was concluded that sufficient data are available in both pilot regions to run the integral model, and that the sub-models produce and exchange the appropriate information required in the integration scheme. This in itself is a remarkable result, since each of the models has been developed within different research contexts and with different purposes in mind. However, one should not interpret this to mean that model integration is a straightforward and easy
process. On the contrary, it requires a very careful examination of every aspect of every sub-model that is affected by the integration. It may be clear that this is the work of specialists working in a team, and it is to wonder whether this process can ever be made into an operational procedure not requiring the involvement of the model developers.

**Figure 2:** The MODULUS model integrates a number of components (shown as boxes). Each component consists of a model developed as part of EFEDA, ERMES, ModMED or ARCHAEOMEDES. For each component the available models (named after the projects they have been developed in) have been ranked. The models ranked first have been implemented first. The arrows in the scheme represent the main links between the sub-models only.

Each of the models included in the scheme is dynamic and spatial. The typical spatial resolution at which the integral model runs is the 1ha grid. The role of the individual models in the connection scheme can be summarised as follows:

- **Weather:** (EFEDA, PATTERN Weather & Storms model, available as a C++ MBB). This model runs daily. It calculates for each day the time of sunrise and sunset and the average solar radiation map at the top of the atmosphere between sunrise and sunset. The average solar radiation is then corrected for the slope and aspect of each cell. The average temperature per cell is updated monthly. Further the model generates for the day a detailed time series (expressed in minutes and bucket-tip times) for precipitation for the study areas based on data from at least 1 AWS weather station.
Figure 3: Air temperature in the Argolid at ground level. The mean monthly temperature at sea level is derived from a 30-year climate scenario. It is spatialised and corrected for altitude and local deviation from the mean temperature as measured by local weather stations.

- **Hydrology & Slope processes:** (EFEDA, PATTERN Hydrology & Slope processes model, available as a C++ MBB). This model runs daily, but integrates internally over bucket-tip times. This model deals with the soil hydraulic properties and calculates the water budget. It calculates the interception, infiltration, soil moisture, transpiration, soil evaporation, overland flow, surface recharge, and erosion.

Figure 4: Soil moisture in the Argolid in the winter (end of December)
Natural vegetation: (ModMED, RBCLM2 Community model, available as a PROLOG MBB). This model runs once a month. It represents the processes of growth, succession and decline of the natural vegetation at the community level. It calculates the leaf area index, the vegetation cover fraction, and the rooting depth. The natural vegetation model is a rule based model, applied to each individual cell of the case regions. It is supplemented with a cellular seed diffusion model, which produces a seed biomass maps, which links the community level cells at the landscape level.

Crop Growth: (EFEDA, PATTERN Plant Growth model, available as a C++ MBB). This model runs daily. It represents the processes of growth of commercial crops and calculates the leaf biomass, root biomass, leaf area index and the vegetation cover fraction.

Aquifer: (ARCHAEOAMEDES, 2 versions of the aquifer model are retained: the Agricultural University of Athens-ModFlow model and the IERC-Aquifer model. The ModFlow model is available as a FORTRAN MBB, while the IERC model is available as a POWER BASIC MBB). Due to the very complex and discontinuous nature of the aquifer in the Marina Baixa, the aquifer model is only applied in the Argolid region. This model represents the depletion, recharge and pollution of the aquifer. It calculates the aquifer water height, salt concentration and the fluxes between cells. The ModFlow-aquifer model runs monthly and on a spatial resolution of 500 by 500 m. The IERC-Aquifer model is intended to run daily on a 1ha or 1km resolution.
Fig. 6: The main watershed modelled in the Argolid and the location of the Aquifer within. The Aquifer is modelled by means of a ModFlow model at a 500 by 500m grid, which runs on a monthly basis. The volume of the aquifer is represented.

- **Catchment:** (ERMES, Catchment model, available as a POWER BASIC MBB) This model runs on a daily basis. It represents the river, canal, and water reservoir system, and the water quality of the surface water. It calculates the river flows per stream order, the sinkhole flows, the catchment recharge flows, and the river PO₄ and NO₃. The model runs on irregular shaped, natural defined areas –the catchments and sub-catchments.

Fig. 7: Catchment stream orders for the Argolid watershed.

- **Crop type decision:** (ARCHAEMEDES, Decision making model, available as a POWER BASIC MBB). This model runs on a yearly basis. It is a rule based model representing the crop-choices made by farmers as a function of changing physical, socio-economic and institutional conditions and circumstances. It is applied to each 1ha cell and calculates the crop type, crop water requirements, water source, presence of boreholes, borehole depth, pumping capacity, air mixer deployment and the total yearly long term exploitation costs.
Figure 8: Crop types in the Argolid.

- **Pumping:** (Extracted from work done in ARCHAEOMEDES by IERC, available as a POWER BASIC MBB). This model runs twice daily. It is a rule based model representing the farmers decision to switch on the water pumps and start the irrigation. It is applied to each 1ha cell and calculates the pump status, volume to be pumped, extraction from the canal, volume of frost water, frost water salt concentration, irrigation water volume, irrigation water salt concentration, and the total yearly short term exploitation costs.
Figure 9: User-interface of the MODULUS system. The user gets access to the individual sub-models (Model Building Blocks) by means of the systems diagram (shown in bottom left). He can run simulations and select any combination of maps on the display.

- **Land Use:** (GEONAMICA Constrained Cellular Automata model, available as a C++ MBB). This model runs yearly. It is a cellular automata based model which allocates in a detailed manner (1ha grid) the land claims resulting from demographic changes, as well as the dynamics in the agricultural and non-agricultural part of the economy. The allocation methodology will take into consideration the activity specific attractiveness of cells in terms of their suitability, zoning regulations and accessibility to the road transportation infrastructure.

The model presented heavily relies on GIS data. As an input it requires some 25 GIS layers (raster maps, mostly at 100 meter resolution), and it updates at every simulation time step some 50 output maps. All the output maps are simultaneously available to the user. Hence, during the simulation he can watch the evolution of the modelled region by means of any combination of the 50 mapped variables. Some of the output maps represent a final output variable of the integral model, but most maps are generated or updated by an MBB to serve as an input to another MBB.
Although it is expected that the integration will eventually lead to a scientifically acceptable model, this does not mean that the end-use usability of the integral instrument is automatically guaranteed. The first tests performed showed that a single run of the integral model for the entire Argolid region, consisting of 239385 * 1ha cells, took nearly 12 days. In this test the sub-models were running at the appropriate time step (1 minute – 1 year), for a period of 30 years, and at the spatial resolution which is considered minimally required for the soil and slope models (namely the 100 m grid). It goes without saying that a model which takes this much time to perform a single simulation run is not a very practical tool for policy making. It looses all of its explorative capabilities as well as its role as a communication tool. Since then, a lot of effort has been put into reducing the execution time. A simulation run now takes some 2 hours.

6 Using the MODULUS model and Decision Support System.

The use, role and usefulness of models and Decision Support Systems in policy making has been the subject of a rich scientific debate and literature, and extreme views have their advocates. In this paper we do not have the room to dwell on this discussion. However, inherent in the aims of the MODULUS project, is the somewhat positivistic view that the use of scientific models can improve the policy making process. More in particular, MODULUS adheres to the view that better informed policy makers are better equipped to make better policies that bring the systems they are to manage on a path towards sustainability. Thus, the prime role of the models and the Decision Support Systems is awareness building and education, rather than the decision-making act itself. The models therefore should give an adequate and truthful representation of the real world system, and the policy maker should be enabled to work with the models in a well-structured, well-guided and flexible manner. A well-designed user-friendly interface should enable to structure the policy exercises carried out with the model. The same interface should increase the transparency of the model and the DSS as much as possible: at any point in time, the user should have access to the background information required to understand the processes in the model he is working with and the numbers they generate. Without this information, the model becomes a black box and no learning takes place. The user can try out policy interventions in his system (which he selects from a predefined Policy Options Window). He can test the robustness of the system and his policy interventions if the system is subjected to scenarios (which he can select from a predefined Scenarios Window). Finally, he can see how his policy interventions and/or scenarios in terms of indicators (which are shown in an Indicator Window) affect the system. This way the impact of interventions can be tested and tuned in an interactive session between the policy maker and the modelled system and catastrophes can perhaps be avoided in the real system. Such an explorative approach, we believe, contributes to the design of actions to pilot the system past the worst and hopefully towards the most desirable future possible.

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SimCoast, a fuzzy logic, rule-based expert system for coastal zone management

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SimCoast™
Fuzzy Logic Expert System for Integrated Coastal Zone Management

Uncertainty and Risk:

Professor Jacqueline McGlade,

How to incorporate uncertainty and risk into decision-making.

Policy-makers and planners continuously have to make decisions in the face of varying degrees of uncertainty and risk. SimCoast is an intelligent soft computing system designed to address these problems explicitly. Here we look at how fuzzy logic and expert systems - two of the fundamental approaches within SimCoast - can be used to improve decision-making in relation to conditions of high levels of uncertainty, subjectivity in data and inexact reasoning.
1 Introduction

In most of today's institutions there is a belief that the effects of an intervention can be predicted. This supposition occurs because most existing resource and economic planning models allow managers to simulate, or in a crude way, anticipate the future. But this implies not only that all the interactions within the system are adequately understood, but also those processes that will direct its forward evolution. This assumes that all future states are contained within the dynamical description of the present system.

Unfortunately, this is generally not the case.

For example, the inner dimensions of a planning model that included all possible future states would contain so much working detail that in practice it could not be developed. Secondly, the outer dimensions would have to reflect the fact that complex living systems are open and hence have significant exchange of materials across their boundaries. Remarkably, most planning decisions have ignored these two issues, concentrating instead on a highly restrictive view of what is actually happening. Thus in many parts of the world we see situations where researchers and planners have been forced unremittingly into a role where they are trapped by their own knowledge. They might think they know what the system is doing, but rarely do they know why or even how it is doing it.

In areas outside policy and planning, researchers have learned to cope with such problems. One way has been simply to use error bars when estimating variables. But errors can derive from uncertainties in a wide range of processes and objects, e.g. in the instruments themselves, calibration, design, lack of skill and general confusion about the theoretical foundations of particular measurements. When a problem becomes more and more complex, simple inexactness cannot fully describe the situation, and uncertainty must be dealt with explicitly.

Uncertainty is not merely the spread of data around some arbitrary mean, known with confidence, but rather a systemic form of error that can swamp an otherwise easily calculated random counterpart. Achieving certainty then, even in a quantitative science, relies largely on managing the different sorts of uncertainty affecting performance. Because uncertainty cannot be removed it has to be clarified.

The errors associated with data points represent the spread, i.e. the tolerance or random error in a calculated measurement. Confidence limits refer more to risk; for example, in a risk analysis of future scenarios resulting from different policies, confidence limits are reflected in estimates when they are qualified as optimistic, neutral or pessimistic. An assessment based on historical estimates of some quality or resource thus acts as a qualifier on the numbers used and on the spread of data points. An assessment represents unreliability and relates to our knowledge about the processes involved, whereas the spread represents inexactness and relates to our knowledge of the behaviour of the data.

Another important concept is ignorance; this is a measure of the gaps in our knowledge. These gaps may simply be anomalous results that are exposed when a new advance in understanding occurs or simply reflect the maturity of the subject.

The boundary of ignorance is very difficult to map; one approach has been to assess the pedigree of a quantity (see below). This describes the state of art of a particular field from which the quantity derives. For example, in the case of theory of relativity, there was a progression from an embryonic field in 1905 through to the 1950s when experimental results had corroborated the theory and all but cranks had accepted it. Resource management on the other hand relies on data that are highly qualitative and heterogeneous. Well-structured theories, common in many branches of science, are conspicuous by their absence.

In the table below, colleague consensus describes the social strength of the paradigms in which the information is cast, and hence the way that knowledge has and is being built about a particular subject.
<table>
<thead>
<tr>
<th>Pedigree score</th>
<th>Theoretical structures</th>
<th>Data</th>
<th>Peer acceptance</th>
<th>Colleague consensus</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>established</td>
<td>experimental</td>
<td>total</td>
<td>all but cranks</td>
</tr>
<tr>
<td>3</td>
<td>theoretical model</td>
<td>historic/field</td>
<td>high</td>
<td>all but rebels</td>
</tr>
<tr>
<td>2</td>
<td>computer models</td>
<td>calculated</td>
<td>medium</td>
<td>competing schools</td>
</tr>
<tr>
<td>1</td>
<td>statistical procedures</td>
<td>educated guess</td>
<td>low</td>
<td>embryonic field</td>
</tr>
<tr>
<td>0</td>
<td>definitions</td>
<td>uneducated guesses</td>
<td>none</td>
<td>no opinion</td>
</tr>
</tbody>
</table>

Thinking that we can make exact predictions under highly complex circumstances is thus likely to be premature; leading those involved in decision-making towards a misdirected sense of concreteness in overall policy judgement.

Worse still is the fact that the credibility of science is also at risk because of the dilemma of uncertainty and responsibility. Neither can be eliminated, nor indeed would it be desirable: managing uncertainty in the context of responsibility cannot be sidestepped. Unfortunately, many of today’s institutions have been developed to undertake planning and policy development from the standpoint of determinacy rather than complexity.

One of the major difficulties in coastal zone management is that it requires an interdisciplinary approach, involving fields of varying states of maturity and with very different practices in their theoretical experiments and social dimension. Planners and policy-makers often find themselves having to use inputs from research areas with which they are potentially unfamiliar, thus making it difficult to apply the same sensitivity and quality of judgement as they would do in their own fields of expertise.

The result is a dilution of quality control on the planning process and a weaker quality assurance of results.

Scientists have tended to develop a healthy prudence about passing judgement on the results of others in areas outside their own expertise, with the result that any interference in others’ fields is discouraged. Unfortunately, in an interdisciplinary policy-related area such an approach rapidly becomes counterproductive, because criticism, the lifeblood of science, does not properly occur.

The problems created in policy-related research by uncertainty are increased by its societal dimension. Here research is judged by the public, including bureaucrats, on its performance in sensitive areas such as the economic returns on foreign aid, returns from the exploitation of natural resources, the dumping of hazardous wastes, the dangers of oil spills or environmental pollution. All involve much uncertainty, as well as inescapable social and ethical aspects, so simplicity and precision in predictions or even setting safe limits are not always feasible.

Yet policy-makers tend to expect straightforward information to use as inputs into their own decision-making process. In such circumstances, the maintenance of confidence amongst policy-makers, planners and the community becomes increasingly strained, with the researcher often caught in the middle.

The problems become manifest at several levels, the simplest one being the representation of uncertainty in only qualitative estimates. Any advisor knows that a prediction such as a “one in a million” chance of a serious accident or health incident should be hedged with statements of many sorts of uncertainty so as to caution any user as to the reliability of the numerical assertions. But if these were all expressed, policies would become tedious and incomprehensible, and if omitted then the same policies could convey a certainty unwarranted by the facts.

_H. Bottrell and K. Morris:_
_SimCoast, a fuzzy logic, rule-based expert system for coastal zone management_
Besides low-frequency hazards, there are also problems relating to higher probability events such as the failure of an investment/development programme, diffused hazards such as the long-term usage of chemicals or possible large scale environmental perturbations such as global warming. The dilemma is that any definite advice is liable to go wrong: a prediction of danger will appear alarmist if nothing happens in the short term, whilst reassurance can be condemned if it retrospectively turns out to be wrong. Thus the credibility of research, based on the supposed certainty of its conclusions, is endangered by advice given on inherently uncertain issues.

But if the researcher prudently refuses to accept vague or even qualitative expert opinions as a basis for quantitative assessments, and declines to provide definitive advice when asked, then research itself is regarded as obstructionist, not performing its public functions and its legitimacy is called into question.

It is not surprising then that most policy and planning institutions have been unable to respond in a locally adaptive way; in many cases the organisations are suffering from a chaotic mixture of hierarchical, non-hierarchical, academic and industrial research modes.

A major component of integrated coastal zone management must therefore be to create new settings in which to evaluate evidence from a broad array of sources, so as to provide clear and explicit guidelines for analysis and public action. SimCoast aims to resolve many of the ambiguities concerning data, knowledge and information in the decision-making process by using fuzzy logic within a rule-based expert system and help to generate data for an analytical approach to for multi-objective decision-making known as issue analysis. The combination of different methodologies in this way represents an example of an intelligent soft computing system.

2 Intelligent soft computing systems

In fact intelligent soft computing systems are now employed to address many practical issues such as control and consumer electronics (e.g. auto-focus cameras), decision support in medicine (e.g. computer-assisted management of child birth, automatic interpretation of brain activity, intensive care monitoring) and business and finance decision support (e.g. credit rating, stock market analysis and forecasting, direct marketing). An important goal of such systems is to simulate one or more forms of natural intelligence e.g. learning, knowledge and skills, expert behaviour, adaptive and evolutionary strategies.

Three key intelligent systems techniques are now generally available: neural networks, expert systems and genetic algorithms. Interactions between these techniques and approaches such as fuzzy logic and qualitative multivariate data analysis can be built into intelligence systems to provide even more power. For example, we find that fuzzy logic is used heavily in expert systems to handle uncertainty and imprecision in the knowledge and data; expert systems combined with neural networks are used to provide the explanatory capability lacking in neural networks; neural networks are used in neuro-fuzzy systems to learn about hidden patterns within data sets to generate membership functions for a fuzzy logic system; and issue analysis combined with an expert system is used to allow rigorous analysis of multivariate qualitative data for setting policy priorities.

The design of the interrelationships between the different forms of knowledge gathering, analysis and interpretation is highly flexible in SimCoast so that a wide variety of users can exploit its structure and operation. The design concepts themselves have been rigorously tested as separate elements as well as part of a combined system to ensure that if there are non-unique solutions to problems, their effects can be qualitatively told apart. The basic building blocks of the system include: the use of fuzzy logic to identify the elements within a system, the creation of linkages through fuzzy-logic rules.
3 Fuzzy logic

In our everyday life we continually provide descriptions of entities, events, processes and issues, using imprecise, linguistic phrases which are understood clearly, e.g. pollution levels are getting worse, fish are becoming scarcer. One way to utilise such qualitative, linguistic or imprecise information is to adopt a fuzzy logic approach to system characterisation, using fuzzy sets. Developed by Zadeh (1965), fuzzy set theory follows the principles of conventional set theory with one major exception: in conventional set theory elements are divided into two categories i.e. those that belong to a set and those that do not. The conventional, non-fuzzy or crisp set, thus maintains a clear difference between elements which are members and those which are not. In fuzzy set theory, the linguistic variables are context-dependent variables whose values are thus words or sentences, for example oil spill size (small, medium, large); age (young, middle age, old) etc. The range of possible values is known as the universe of discourse. Elements within the universe of discourse are assigned a grade of membership between 0 and 1, although in some cases the membership functions can be single values, or singletons.

Initially, all input variables are converted into fuzzy variables using membership functions- a process known as fuzzification. The shape of the membership function (e.g. a simple vector, S-function, triangular, trapezoid) is optimised through successive observations and may differ depending on the application and the need to capture different levels of uncertainty. For example, in an area where oil spills ranging in size from $10 \text{ – } 100 \text{ km}^2$ have been observed, the fuzzy set “about 50km $^2$” can operate over the entire range of 0 to 100 km$^2$. The membership value decreases progressively from 1 to 0 as the distance from the set point (50 km$^2$) increases; thus at the 25km$^2$ position, the membership is 0.5. In conventional set theory, this point would have been assigned a membership value of 0.

Fuzzy set theory thus allows lesser points to be recognised within the universe of discourse which may signify other key attributes, e.g. heterogeneity in growth due to nutrient status. It also allows uneven observation of ecosystem components to be taken into account. For example, given sufficient time and access to a school of fish it would be possible to assign it to a particular crisp set of school sizes e.g. 100, 200, 300 etc. However, it is more likely that even with repeated observations, the observer would only be able to provide an estimate of the size of the school in the field; in this case a fuzzy set can be created e.g. where “100” = 50 – 149, “200” = 150 – 249, “300” = 250 – 349 etc. so that a fish school estimated to contain 120 fish is assigned to the fuzzy set 100, a school of 210 assigned to fuzzy set 200 and so on. The measure of the observational uncertainty in assigning a particular school to a particular crisp set is thus taken into account. This situation is akin to one where it is difficult to assign sets in the first instance, e.g. as with ecological trophic groups where membership can change due to migration or omnivory. In this case the trophic groups are placed in a fuzzy set from the start, and this can then also include observational uncertainties.

Uncertainty in the basic definition of a set or the observation of it can be further captured through the spread, shape and overlap with adjacent fuzzy sets through the manipulative operations of union, intersection and fuzzy relationships. The union operation, when applied to two fuzzy sets both of the same universe of discourse, is equivalent to a connective OR: the operation of union is indicated by the sign $\cup$. For example, in the fuzzy sets describing oil spill size, sets linguistically named small and medium can be defined. Applying the principle of union to the sets small and medium creates a small OR medium set.

In a similar manner, the operation of intersection when applied to two fuzzy sets of the same universe of discourse is equivalent to a connective AND; the operation of intersection is indicated by the sign $\cap$. By the application of the operation of intersection to the fuzzy sets small and medium describing oil spill size, a new small AND medium set is created.

Hedges are used to emphasise (e.g. to reflect the phrase very, as in very large) or de-emphasise (e.g. to reflect somewhat) the fuzzy shape of the set. The two common ones are intensification (i.e. use the square of an expression) and dilation (i.e. use the square root). Finally, to extract a crisp out value for practical needs, defuzzification is undertaken e.g. using the centroid or the maximum value of the set.
4 Expert systems

An expert system is a computer-based system that contains specialist knowledge in a given area and is able to use the stored knowledge to solve problems or make inferences/deductions that would normally require human expertise. In simple terms, to build an expert system, the necessary knowledge is obtained from one or more experts and encoded into a computer system. A typical expert system contains a knowledge base, which holds the expert knowledge, an inference engine, which decides how the knowledge in the knowledge base should be used and a user interface, for communication with the user.

In the development of SimCoast the representation of knowledge is based on logic using syllogisms and sets. [There are many texts on expert systems to which the reader should refer in order to gain a clear understanding of the way in which premises are used and conclusions drawn.] Inferences are then made to derive new knowledge or information. A variety of methods of inference are used within SimCoast depending on the pedigree of the area and theories to derive knowledge. These include:

deduction: logical reasoning in which conclusions must follow from their premises
induction: inference from the specific case to the general
intuition: no proven theory. The answer just appears, possibly unconsciously recognising an underlying pattern. Expert systems do not implement this type of inference yet, although a neural net will always give the best guess for a solution
heuristics: rules of thumb based on experience
generate and test: trial and error. Often used with planning for efficiency
abduction: reasoning back from a true conclusion to the premises that may have caused the conclusion
default: in the absence of specific knowledge, assume general or common knowledge by default
autoepistemic: self-knowledge. This is always context-sensitive
nonmonotonic: previous knowledge may be incorrect when new evidence is obtained
analogy: inferring a conclusion based on the similarities to another situation

The knowledge collected via these methods can be represented in a number of ways, for example trees, graphs and lattices.

Although not explicitly identified, common-sense knowledge may be a combination of any of these types. It is the type of reasoning that people use in ordinary situations but that is very difficult for computers. This is the reason why a fuzzy rule-based logic system for common-sense reasoning (see below) has been used as the overall basis for SimCoast.

Induction can also be used to infer new rules and rediscover known rules. Once knowledge about a new rule is gained, it must be checked to see if it is compatible with similar rules. SimCoast has a rule model pattern of similar rules that it knows about and tries to fit the new rule into its rule model. The metaknowledge of SimCoast is of two types; metarules which then tells how the rules are to be applied and a rule model type of metaknowledge which determines whether the new rule is in an appropriate form to be entered in the knowledge-base.

Rules are long-term knowledge as they do not normally change during expert systems handling and processing of information. In a rule-based expert system, such as SimCoast, determining if the new rule is in the correct form is verification of the rule. Determining that a chain of correct inferences leads to the correct answer is called validation. The general format for rules is:

\[(1) \quad \text{GIVEN} \ <\text{feature}> \ \text{AND} \ <\text{activity}> \ \text{THEN} \ <\text{effect}>\]
In crisp systems, the variables for the rules (1) and (2) are either true or false. In fuzzy systems, the variables are words or sentences. Thus fuzzy, expert systems can operate with the same natural language phrases which experts use in practice.

Reasoning under uncertainty is the crucial issue that was addressed in the development of SimCoast, mainly because of the heterogeneity of the information to be utilised and its pedigree. As indicated above, different types of errors can contribute to uncertainty:

- ambiguity
- incompleteness
- incorrectness
- false positive (i.e. accepting a hypothesis when it is not true)
- false negative (i.e. rejecting a hypothesis when it is true)
- imprecision (i.e. how well the truth is known)
- accuracy
- unreliability (if the measuring equipment supplying facts is unreliable the data are erratic)
- random
- systematic (introduced via some bias)
- invalid induction
- invalid deduction

Unfortunately even experts are not immune to making mistakes, especially under uncertainty. Different theories of uncertainty attempt to resolve some or all of these errors to provide the most reliable inference. But for example, in contrast to the other errors in the list, the last two are errors of reasoning. This can be a major problem in knowledge acquisition when the experts' knowledge must be quantified in rules, because then inconsistencies, inaccuracy and all other possible errors of uncertainty may show up.

The major quantitative way of dealing with uncertainty has traditionally been through probability theory. Classical probability, which was first proposed by Pascal and Fermat in 1654, also called a priori probability, deals with ideal systems. In such systems all numbers occur equally, so an experiment or trial involving tossing a die a number of times, will generate a number of equally possible events. When repeated trials give the same result the system is said to be deterministic.

An event is a subset of the sample space. A certain event is assigned probability 1 and an impossible event assigned probability 0. Mutually exclusive events have no sample point in common, e.g. a computer cannot be both working correctly and not working correctly at the same time. The corollary means that the probability of an event occurring plus it not occurring is equal to 1. These axioms, devised by Kolmogorov, refer to the objective theory of probability.

In contrast to the a priori approach, experimental probability or a posteriori probability, defines the probability of an event as the limit of a frequency distribution. The idea is to measure the frequency at which an event occurs for a large number of trials and from this induce the experimental probability.

Next there is subjective probability. This deals with events that are not reproducible and have no historical bias on which to extrapolate, such as drilling an oil well at a new site. However, a subjective probability by an expert is better than no estimate at all and is usually very accurate (or the expert would not be an expert for long). A subjective probability is actually a belief or opinion expressed as a probability rather than one based on axioms or empirical measurement. In the real world events tend to compound each other; so it is important to be able to be able to separate those events that really are pairwise or stochastically independent. For the remainder, the effect on calculating the mutual independence of events is to enormously increase the number of equations that need to be satisfied. In this case the additive law is applied.
Beliefs and opinions of an expert play an important role in expert systems, even though they cannot be explicitly described mathematically and the relative frequency method is impossible to apply.

Finally there is conditional probability, which describes the fact that events which are not mutually exclusive influence one another. Knowing that one event has occurred may cause us to revise the probability that another event will occur. In this instance the generalised multiplicative law is used. The conditional probability states the probability of event A given that event B occurred.

The inverse problem is to find the inverse probability which states the probability of an earlier event given that the later one has occurred. This type of probability often occurs where symptoms appear and the problem is to find the most likely cause. The solution to this problem is given by Bayes’ Theorem.

Bayes’ Theorem is commonly used for decision tree analysis in the social sciences and the method of Bayesian decision-making is also used in an existing expert system PROSPECTOR (Duda and Reboh 1979) to decide on favourable sites for mineral exploration. PROSPECTOR achieved a great deal of fame as the first expert system to discover a valuable molybdenum deposit worth $100m.

Prospecting is an obvious activity where it is appropriate to use Bayesian approaches for decision-making under uncertainty. Initially, the prospector must decide what the chances are of finding fresh water. If there is no evidence, either for or against water being present, the prospector may assign the subjective prior probabilities for or against water as both 0.5. With no evidence, an assignment of probabilities, which are equally weighted between possible outcomes, is said to be made in desperation. This term does not mean that the prospector is (necessarily) in desperate need, rather it is the term for unbiased prior assignment.

If there is a survey there may be some information to help make a decision. However surveys are rarely 100% accurate. The test may be false positive or false negative. Using the conditional and prior probabilities an initial probability tree can be constructed; and from this a set of expected pay-offs can be calculated at each event node, so that the overall best action can be determined.

The decision tree is an example of hypothetical reasoning or “what if” type situations. By exploring alternate paths of action, the paths that do not lead to optimal payoffs can be pruned.

Reasoning about events that depend on time is called temporal reasoning and it is something that humans do very well. However, it is difficult to formalise temporal events so that a computer can make temporal inferences. Yet it is just such systems which could be most useful in determining policies and planning options.

Different temporal logics have been developed, based on different axioms (Turner 1984). The different theories are based on the answers to such questions as whether time is continuous or discrete? is there only one past but many futures? If the temporal reasoning is best dealt with using probabilities, e.g. for weather, storms, epidemics, a Markov chain process can be used.

A Markov chain process is defined as having the following characteristics:

- having a finite number of possible states
- the process can be in one and only one state at a time
- the process moves or steps successively from one state to another over time
- the probability of a move depends only on the immediately preceding state.

In integrated planning it is also important to consider the different temporal scales over which changes are likely to occur, and the possibility of history playing a key role in determining the future possible states. To achieve this, SimCoast is constructed as an inference net (see below).

So far we have only dealt with probabilities as measures of repeatable events. However in many instances the events or contexts are unique. In such a case the probability should be interpreted as the degree of belief, and the conditional probability is then referred to as the likelihood. It is thus important...
in determining the likelihood of some event occurring that the degree of uncertainty in the evidence is understood.

For example, suppose a householder discovers a source of oil under their property; at this stage it is not known for certain that there is oil under any other property. Conclusive evidence would be to drill a test well, but this is expensive, so the partial evidence is considered:

- other people in the neighbourhood found water
- there is some black ooze on the property but this could be due to local oil dumping
- a stranger came to the door and offered the householder $20m to buy the house because of the view.

Based on this partial evidence, the householder may decide the likelihood of oil under their property is rather high, but in analytical terms the perception of that probability has become magnified. So one way to counteract this very human effect, is to use piecewise functions that separate the probabilities of each piece of evidence leading to a particular conclusion. Evidence can also be combined using fuzzy logic, as described above.

5 Inference nets

SimCoast involves the use of inference nets. For real-world problems the number of inferences required to support a hypothesis or to reach a conclusion are often very large. In addition many inferences are made under uncertainty of the evidence and rules themselves. An inference net is thus a good architecture for expert systems that rely on taxonomy or knowledge.

The basic idea in SimCoast is to encode the experts' knowledge of different models into the system. The data for each model are organised as an inference net, where nodes can represent evidence to support other nodes which represent the ideas or hypotheses of other experts. Each model inside SimCoast can be encoded as a network of connections or relations between evidence and hypotheses. Thus, an inference net is a type of semantic net.

Observable facts, such as the type of subsurface geology obtained from field exploration comprise the evidence to support the intermediate hypotheses and groups of intermediate hypotheses are used to support the top-level idea. Certainty factors are used in this process because experts often find it difficult to specify posterior probabilities or likelihood ratios.

SimCoast is not a purely probabilistic system because it uses fuzzy logic and certainty factors for combining evidence. SimCoast uses both logical combinations i.e. AND and OR nodes, as well as weighted combinations using likelihood ratios.

The weighted combinations are also examples of plausible relations. The term plausible means that there is some evidence for belief. Other terms such as impossible also have a clear meaning. For example:

- impossible: evidence definitely known against
- possible: not definitely disproved
- plausible: some evidence exists
- probable: some evidence for
- certain: evidence definitely known supporting

SimCoast is able to create partitioned semantic nets to enable the user to group portions of the net into meaningful units. Partitioned semantic nets were developed by Hendrix (1979) to allow the power of predicate calculus such as quantification, implication, negation, disjunction and conjunction. The basic idea is to group sets of nodes and arcs in abstract spaces which define the scope of their relationships.

The important aspect of this is that most inference nets have a static knowledge structure; i.e. the nodes and connections between them are fixed in order to retain the relationships between nodes in the knowledge structure. However, SimCoast has been designed to allow a dynamic knowledge structure.
either with no fixed connections between rules or via changes in the probabilities associated with each node.

Probability theory as it is used in parts of SimCoast can be considered as a way of capturing and reproducing uncertainty. However in the context of integrated planning much of what happens is based on human belief rather than the classic frequency interpretation of probability. To address this, the expert system allows inexact reasoning i.e. where the antecedent, the conclusion and even the meaning of the rule itself is uncertain to some extent.

The main area where this plays a key role is in the weighting of rules; in SimCoast rules are weighted and combined according to their certainty factors; the problem addressed here is that one piece of evidence might give one value, whereas ten give another. The expert system should not then fire on the basis of only one piece of evidence. Certainty factors are a special case of the Dempster-Shafer theory which deals with inexact reasoning (Gordon 1985) but are only used in certain areas of SimCoast for the following reason.

A fundamental difference between the Dempster-Shafer theory and probability theory is the treatment of ignorance. Probability theory distributes an equal amount of probability even in ignorance. The Dempster-Shafer theory does not force belief to be assigned to ignorance or refutation of an hypothesis. Instead the mass is assigned only to those subsets of the environment to which the user wishes to assign belief. Any belief that is not assigned is considered nonbelief. Belief that refutes an hypothesis is disbelief, which is not nonbelief. Thus the difficulty for integrated planning occurs with normalisation, whereupon the system ignores the belief that a process being considered does not exist.

In many situations ignorance and belief are purely used, quantified and reasoned using natural language in which many words have ambiguous meanings. This is why SimCoast has been constructed as a fuzzy logic rule-based expert system.

### 6 Fixed Rulebase Fuzzy logic

Fixed Rulebase Fuzzy Logic (FRFL) has been developed from fuzzy set theory as a means of coping with those decision processes involving imprecise data. Obviously if rigid mathematical relationships between component parts of the system can be defined, then analyses and subsequent decision making can be undertaken with relative certainty of the outcome. However, in cases where such prior understanding is not possible, or a variety of views exists, and a realistic assessment of the decision outcome is required, the task is considerably more difficult to describe in quantitative terms.

A technique is thus needed which is capable of utilising qualitative, linguistic or generally imprecise information. The FRFL technique demonstrates this ability. As described above the manipulative operations that can be used include: union of fuzzy sets; intersection of fuzzy sets; and fuzzy relationships.

In fuzzy logic, as in conventional logic, the functions AND, OR and NOT are used to combine the fuzzy variables in the premise (the IF part of a rule). Examples of such inputs are normal, abnormal, high, low, very low. Fuzzy rules use the same natural language terms as experts, making it possible to develop an heuristic rule set.

An example of a simple fuzzy rule set would be:

- **IF** television sound is too loud AND background noise is low
- **THEN** reduce the volume

- **IF** water is too hot OR water is too cold
- **THEN** adjust the cold water.
Fuzzy rules with single premise and a single consequent have the inference form:

IF X is A
THEN Y is B

or more simply

IF A
THEN B

where A and B are fuzzy sets which are known in advance, X and Y are crisp or fuzzy measurements from the outside world or the outcome of another fuzzy rule in the inference net. Given the values of X and Y, fuzzy inference process is used to deduce the extent a rule will activate or the ‘belief’ in the conclusion of the rule.

The two common methods used for fuzzy inference are the max-min inference and the max-product inference. The max-min inference yields a clipped output fuzzy set, whereas the max-product preserves the shape of the output set. When the rules have multiple premises as in many rule-based systems, the induced fuzzy sets depend on whether the premises are joined by an AND function or an OR function.

In SimCoast, as in other practical systems, after fuzzy inferencing, a crisp out value for the outside world is produced, e.g. to activate a device or to write to a data file. The process of doing this is known as defuzzification. Two forms of defuzzification method are commonly used: the centroid and the maximum method, both of which are available in SimCoast. The numerical results from this process then form the inputs into the issue analysis.

7 Issue analysis

Many of the problems encountered in setting policy in the coastal zone is that activities and features interact in such a way as to create positive and negative feedbacks amongst themselves. Each set of interactions has its own measure of impact on different targets such as biodiversity or tourism, so intercomparisons have to be made on the basis of some common scale. For example, a large oil spill could have a large, short and long term negative effect on fishing in that it could reduce a coral reef to below a level where it could regenerate itself: on a scale of -5 to 5, a numeric value of -5 might thus be assigned to this particular set of interactions.

However, given that the impact of different processes will alter according to the distance between processes along a transect, it is important to also be able to derive an interaction matrix between coherent zones. For example, if there is logging in an upland area that could lead to significant amounts of siltation in the intertidal zone and leading to a negative effect on artisanal fishing, the interaction matrix should contain a negative entry. But the actual value would depend on the terrain, surface geology, inclination and run-off, and precipitation. These can all be examined using numerical modelling, but the interactions between them may not in fact be obvious.

In addition institutional structures will also have a moderating effect on the values in the interaction matrix. For example in some parts of the world it is clear that emergency contingency plans exist to respond to oil spills; in the absence of such a capacity the impacts could be much larger.

Given the problems of planning in such a complex environment it is clearly necessary to provide policy and decision-makers with tools to identify the dominant processes, activities and issues that are likely to have a significant impact on the whole system.

The basis for realising such an goal within SimCoast has been to create an intelligence tool that combines the outputs of the fuzzy logic expert system, as described above, with an analytical tool designed to extract patterns from multivariate, qualitative data i.e. issue analysis.
Once the individual interaction terms between activities given the particular features of a transect zone with respect to a set target or issue have been identified and quantified via the expert system it is essential to examine the importance of them in terms of their relative influence on each other. An eigenvector analysis can be used to achieve this (see *A technical overview of an eigenvector analysis*). In short, this approach produces a weighting of impacts of different sectoral activities in terms of targets (e.g. biodiversity, fisheries, shipping, oil and gas exploration) given the biophysical and socio-economic features and processes characteristic of a particular area and a set of sectoral activities across the transect.

This impact list reflects all the intra- and inter-sub-zone interactions, and can be used as an indication of where and on what activities policy changes and plans need to be based and prioritised. Given that different communities are likely to have different perceptions of what the issues, problems and needs are, a similar exercise can be repeated by various peer groups and the results compared.

The calculations of the solutions of eigensystems can now be easily done on a PC using standard routines in packages such as Numerical Recipes or IMSL.

In SimCoast the following procedures are followed. The fuzzy logic expert system calls up the rules that link the activities with each other given

- the socio-economic and bio-physical features within each transect zone
- the distance away from the primary zone where the activity is occurring with respect to the various targets (e.g. biodiversity).

Uncertainty or risk is explicitly dealt with inside the fuzzy logic of the system; however it is also possible to attach a probability density to the values. If the distribution is significantly skewed or non-normal then the operator can transform the data before deriving a set of normalised values to be fed to the issue analysis.

The rules are used to create a set of normalised values of the effects of each activity on itself and each other within each zone, even if the activity occurs in another transect zone. The values then make up a symmetric $n \times n$ matrix, which becomes the input data for the SVD. As explained briefly above the analysis attempts to seek out the patterns in the variance in the data that explain the relative importance of each activity with respect to zone and target. The results are then displayed both on the final transect screen and as output tables and graphs.

Given the targeted user community for SimCoast the system initially gives only the first dominant eigenvectors as these will enable policy-makers and planners to see the relative impacts of the various activities. However it is always possible to examine the entire structure of all the eigenvectors in the extended tables given within an option of SimCoast.

**References**


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*H. Bottrell and K. Morris:*

*SimCoast, a fuzzy logic, rule-based expert system for coastal zone management*
A technical overview of an eigenvector analysis and its use in SimCoast™

Analytical overview

A matrix $A$ made up of $n \times n$ elements is said to have an eigenvector $x$ and a corresponding eigenvalue $\lambda$ if

$$ A \cdot x = \lambda \cdot x $$

This equation can be written in the following form

$$ (A - \lambda I) \cdot x = 0 $$

where $I$ is the identity matrix. The general theory of simultaneous linear algebra shows that there is a non-trivial solution if and only if the matrix $(A - \lambda I)$ is singular i.e.

$$ \det | A - \lambda I | = 0 $$

The determinant on the left-hand side of this equation can be expanded to give an $n$th order polynomial, as

$$ a_0 + a_1 \lambda + ... + a_{n-1} \lambda^{n-1} + (-1)^n \lambda^n = 0 $$

This last equation is called the characteristic equation of the matrix $A$ and will have $n$ roots which are the $n$ eigenvalues of $A$. Corresponding to any eigenvalue $\lambda$, the second equation has at least one non-trivial solution $x$. It is evident that if there is a solution of the second equation then $k \cdot x$ is also a solution for any value $k$. It is convenient to choose this multiplier so that the eigenvector has some desired numerical property; such vectors are called normalised vectors. The most convenient form of normalisation which is used is that the sum of the squares of the moduli of the vector components is equal to unity.

Root searching of the characteristic equation is usually a very poor computational method for finding eigenvalues. There exist many different standard methods including the Jacobi and singular value decomposition (SVD). The first involves plane rotations designed to destroy the off-diagonal matrix elements. Accumulating the product of these transformations gives the eigenvectors and the final matrix the eigenvalues. The method is extremely robust for real, symmetric matrices (the input covariance matrix is real and symmetric). SVD decomposes matrix $A$ such that:

$$ A = U \cdot W \cdot V^t $$

where $U$ is an $n \times n$ column orthogonal matrix, $W$ is an $n \times n$ diagonal matrix and $V^t$ is an $n \times n$ orthogonal matrix transpose). In this case the eigenvalues are given by the diagonal elements of $W$ and the eigenvectors are given by the columns of $V$. 

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Expert:
View each rule as it is fired by the expert system. The current rule is highlighted with a brown bar.

View summary of rules fired for a given Feature/Activity/Target combination.
**Expert:**
Highlight any rule in the rule summary list to view its contribution to the total effect for the given Feature/Activity/Target combination.

Highlight other rules to view their contribution to the total effect.
**Results Grid:**
Review de-fuzzified (i.e. crisp), normalised results from the expert system.

Review size and confidence values for the key Features and Activities.
Results:
View Results screen derived from the principal component analysis executed on the de-fuzzified, normalised results from the expert system for the current run.

Save the last run?
Results:
Use the last run as the base for the next run?

Select another run to compare to last run, or use as base for the next run.
Management and visualization of dynamic environmental data

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Abstract

Geographical information systems (GISs) generally employ a two-dimensional framework that is suitable for many applications. However, the natural environment is constantly changing and this requires a more dynamic way of handling such data. For instance, land-use may change from season to season or from year to year. Environmental media such as the oceans and the atmosphere, complicate matters further as processes that occur within them vary through three-dimensional space and through time.

Conventional GIS use the x and y dimensions alone to display spatial data in map form at any one time. This paper describes a GIS system that handles time or depth visualization of a feature in addition to mapping the feature as a horizontal map. This treats time or depth as a dimension rather than an attribute, which is a prerequisite to effective multidimensional visualization and analysis (Raper and Livingstone, 1995).

The STEM (Spatio-Temporal Environment Mapper) has been developed for LOIS (Land-Ocean Interaction Study), a UK research project investigating features and processes in the coastal zone. STEM is a GIS data viewer fronting a database containing the highlights of LOIS. This paper demonstrates STEM's powerful ability to visualize environmental data in a novel and truly multi-dimensional way, an extension of the underlying database structure. An insight into the LOIS data integration process is provided and future options for integration (use of metadata) and visualization (displaying attribute values in perspective) are discussed.

1 Introduction

The natural world is an ever-changing environment. From sub-second rates through to geological timescales there are interactions between many environmental components including atmospheric, terrestrial, riverine, marine and geological. It is becoming increasingly important to understand the processes behind these changes in order that anthropogenic effects on the environment can be better managed (UNEP, 1995). Central to this is the storage, access and visualization of all environmental data, to facilitate improved understanding of the data and better predictions through modelling (Peuquet and Qian, 1997).

Many environmental studies have concentrated on either local or broad-scale environmental patterns and processes over either relatively short or long timescales (Stafford et al., 1994), often limited to one environmental component. To understand the processes in the environment and to effect better management, it is now becoming more important to integrate all of these factors and provide a more holistic view of the environment (NERC, 1994; UNEP, 1995).
Therefore, there is a requirement for this to be reflected within the software tools used to handle environmental data. Integrating the data and tools also avoids duplication of effort and provides a more cost-effective way of managing such data (Ehlers et al., 1990). Strebel et al. (1994) suggest that for environmental information systems to be of any real use, a major challenge is to integrate disparate data sets (collected with varying instrumentation / experiments of varying structure) and archive them effectively. A further challenge is to adequately represent data with three-dimensions or more.

This paper describes a system developed to store, access and visualize environmental data using the four dimensions of x, y, z and time, using a generic data model. The system, the Spatio-Temporal Environment Mapper (STEM), was initially developed within the Land-Ocean Interaction Study (LOIS). LOIS is a multi-disciplinary research programme within the United Kingdom Natural Environment Research Council (NERC) studying the fluxes of materials in the coastal zone, from river catchments, through estuaries, the continental shelf and beyond (NERC, 1994). Two objectives of LOIS were to integrate all the disparate environmental data within a geographical information system (GIS) and to publish the data on CD-ROMs. STEM was developed to satisfy these objectives and is included on the ‘LOIS Overview CD-ROM’, published at the beginning of 1999. The Overview CD is not only a ‘shop window’ to the highlights of LOIS data and model output, but is also a tool to visualize and present scientific data to facilitate effective coastal zone management.

The remainder of the paper will describe the reasons for developing the system and the generic principles underlying the system, concentrating on the multi-dimensional visualization and integration of environmental data.

1.1 The Challenge

There were a number of challenges encountered whilst developing the STEM. These challenges will be explained and discussed in this paper and include:

- To extend the capabilities of what might be considered a traditional 2D GIS by the two additional dimensions of depth and time. The representation of time, in the context of database design and visualization, has been one of the major challenges facing GIS developers. It is accepted that databases for many GISs have been designed to represent static situations, not change. This feature may be inherited from representations used in cartography (Peuquet and Qian 1997, Pfaltz and French 1994).
- Ensuring that the system design was science-led rather than technology-driven.
- To design and produce a generic system that was applicable to many diverse environmental applications within NERC.
- To integrate a diverse range of environment data measured with different instruments and within different environmental media. These data are measured at many different scales and temporal resolutions.
- To provide a user-friendly system that would allow scientists to explore their own data in conjunction with related environmental data.
1.2 Overview of Data

The LOIS Overview CD-ROM holds much diverse environmental data and model results. LOIS ran for six years (1992-1998) and involved some 250 scientists, producing an immense amount of multidisciplinary data of various types and formats. There are some 39 different types of data, or features, which include river, marine, and intertidal monitoring sites, river catchment, marine ecosystem and sea-level change model results, boreholes, and remotely sensed images. Additionally, it features ancillary data such as place names and geology and land cover maps. To complement these, approximately 450 attributes have been measured at these feature types such as metals, nutrients, microcontaminants, invertebrates, foraminifera, ostracoda, and other physico-chemical determinands. Much of these data vary through time as can be seen in Figs. 1 and 2.

The range of temporal scales implicit in the data is large – every 15 seconds in the case of marine cruises, through to 1000 year intervals for a sea-level change simulation beginning in the Holocene period. Similarly, depth measurements range from millimetre accuracy in boreholes through to 1800m depths at the continental shelf edge, while planimetric scales range from intertidal monitoring sites covering a single beach, to hydrodynamic model output spanning the British Isles and North Sea.

Now that the scene has been set in terms of challenges and data, the system development will be briefly outlined, followed by an analysis of the data integration processes feeding into STEM and STEM’s visualization capabilities.

2 An Overview of System Development

Environmental information systems have advanced significantly during the past decade. Improvements in computing technology and contemporary development tools such as Microsoft Visual Basic, combined with object libraries and controls have provided developers with a powerful suite of tools for building flexible information systems. Today, scientific users demand a high standard of software product whether they are developed by large software houses or smaller bespoke developers. They require simple to use, clear and well presented geographical interfaces, powerful query and search capabilities and access to a myriad of datasets.

Equally, the users and to some extent developers should be able to conceptualize the data at a logical level whilst not concerning themselves with the complexity of the data model's physical implementation. For example, a programmer does not need to know any of the table names or their relationships in the underlying database to make full use of it.

Attempting to meet these requirements, and to some extent demonstrating to the user community what can actually be achieved, has been the responsibility of a small development team based at Plymouth Marine Laboratory (PML) and the Institute of Hydrology (IH).
2.1 Systems Design Philosophy

Traditionally, software development projects within NERC have been undertaken in isolation. Many of these projects, however, share three essential components: mapping/data visualization, data storage/retrieval and data loading. Developing such software independently causes duplication of effort resulting in higher development and maintenance costs (Pressman, 1994). The need to produce an integrated system for the LOIS programme and the problems associated with uncoordinated software development between projects, provided a good opportunity to revise our software development plan. It was identified that the majority of our software products would benefit from a generic modular development strategy. Large, monolithic software products that have not been developed in a well-designed modular way usually lead to systems that are extremely complex and often become nearly impossible to understand (Pressman, 1994). Each of the essential components, mapping and data visualization, data storage and retrieval and data loading should be designed and implemented as discrete parts.

2.2 Generic Data Storage and Retrieval

To understand and model the environment, large volumes of diverse data are required that vary in both space and time. These data must be effectively stored and managed so that relationships between datasets can be explored. In order to achieve this it has been the aim of the development team to design and implement a generic data model called the Water Information System (WIS). The name WIS in the context of STEM is somewhat misleading because of its direct association with water. WIS is a generic data model capable of holding many types of data even if they are not environmentally related. WIS only retains this name for historical reasons.

One of the key drivers behind the WIS data model has been the need to store numerous data types that vary in both space and time. WIS is a generic data model that can be implemented in virtually any relational database management system (RDBMS) (Moore, 1997).

2.3 The WIS Logical Database design

The logical database design provides a simple conceptual model that helps users and developers to visualize how their data are stored. It allows the user to record the history of any object, or feature as it moves through space and time (Moore, 1997). Descriptions of features and the events observed at them are recorded in terms of properties or attributes. Thus, to store river water quality data, an individual monitoring site might be classified as a feature and the variables which describe or are observed at the site, such as its position, the site name, a unique reference number, river flow, pH values and so on, would be its attributes.

One of the significant advantages of the WIS data model is that all attributes or properties are assumed to be potentially time and depth variant. Even positional properties may form a time series. For example, although a land based river monitoring station has a grid reference that is unlikely to change, marine and airborne sampling campaigns are conducted from a base that is constantly moving.
Unlike many GIS systems, the WIS data model does not have a predefined concept of a map or thematic layer. WIS stores objects, properties, and relationships as discrete entities. A map layer is a function of mapping/visualization software. For example, a map layer could contain several different features or object types.

This is the conceptual view of the data model. Fig. 3 provides a pictorial view of the WIS logical data model. The model holds data in a cube that is comprised of individual cells.

The three axes of the cube represent features (where observations are made), attributes (what has been observed) and time (when the observations are made). Each cell contains a value (or values depending on the attribute’s data type) of an attribute describing a feature at some moment in time. For example, one cell might contain a real value representing the rate of flow in the river Thames at Kingston on the 20th May 1993. Listed below are the key properties of the WIS cube:

- Any attribute may be observed at any feature;
- A feature may have any number of attributes;
- Any number of values may be recorded for an attribute over time at a feature;
- The values may be recorded at fixed or random time intervals;
- The data model does not distinguish between spatial and temporal data;

The significance of the cube is that it provides a completely generic data independent structure around which to build equally generic tools for data visualization, analysis, retrieval and data loading.

3 Data Visualization and Mapping

One initial important design decision was to develop a system that is freely distributable. Consequently many commercially available mapping systems could not be used. This, coupled with the lack of time and depth based systems meant that a completely new mapping package was required. The target audience for the CD-ROM ranged from schools and universities through to government agencies and industry. A second requirement, therefore, was that it was easy to use. The mapping component of STEM has been developed using a combination of Visual Basic, Windows API and OpenGL, which enabled the rapid development of a user-friendly graphical user interface.

3.1 Querying the database

Data are accessed via a query wizard that guides the user through the query procedure. At each stage SQL queries are made to the database to retrieve the relevant information for the user. After choosing a selection area on the map, the user may choose up to five feature types within a query. This means that the user may, for instance, retrieve chlorophyll data for a number of features, including river monitoring stations, marine monitoring stations, intertidal monitoring stations and so on. This is scientifically important when investigating the transfer of materials...
between different environments. The next stage in retrieving data is to select the attributes that are required. Again, a maximum of five may be selected, which is useful when comparing parameters, e.g. nitrate versus salinity. The user then specifies what time range is required.

When displaying data on a map that varies through time, it makes little sense to plot every value on the map at the same time. Later data may mask out earlier data and in a marine environment where the media will have moved in the intervening period the map will be misleading. A solution to this is to aggregate the data into periods of time (Kraak and MacEachren 1994). At present, STEM enables the user to aggregate in terms of years, quarters, months, weeks, days and hours. This will be modified in the future to accommodate timescales that are more closely related to natural events, such as seasons and tidal cycles. At this stage data varying with depth or height is treated in a similar manner. It is necessary to aggregate the data in terms of depth/height groupings. This can be achieved in terms or percentiles of the maximum depth or by a user specified interval.

At the end of the query all attribute data throughout the time and depth ranges are retrieved into one map layer. Due to memory limitations the number of time periods is currently restricted to 200 time slices and depth grouping to 100 intervals. The data are aggregated into a statistical array associated with the map layer. Any time/depth combination may be chosen for display. This means that one STEM map layer may represent the equivalent of up to 100,000 (200 times x 100 depths x 5 attributes) of what might be described as conventional GIS map layers. Some complex depth/time queries may take several minutes within STEM, but when you consider how long it would take to create 100,000 layers in many current commercial applications, the advantages are clear. Most datasets are not as comprehensive as this and may only contain some depth aggregates at certain time periods. It should be noted that although statistics are calculated for each aggregate the full dataset is also retrieved and stored within the layer, including every measurement recorded within the specified time and depth ranges. Once the data have been loaded the user may view and compare attributes through the full time and depth sequences.

### 3.2 Time and depth bars

There are several ways in which the time and depth dimensions are visualized within STEM. The main access to these dimensions is afforded through the time and depth bars that appear below the map window. The time bar (Fig. 4a) represents each of the time periods selected in a query. Initially, the data displayed on the map shows the first period. The user may then select any of the segments in the time bar to change the display. The segments are coloured according to the mean value for all sites in that query. Hence, the time bar itself provides a useful summary of temporal variations in the dataset, e.g. seasonal variations in river quality data. Colours in the time bar and points displayed on the map may also represent other statistics, including measurement frequency, minimum, maximum and standard deviation. The depth bar (Fig. 4b) behaves in a similar fashion and switching between the two dimensions is relatively seamless, via an icon on both bars. A future adaptation will be to combine both bars into a 2D grid that shows all of the aggregates simultaneously (Fig. 4c).
3.3 Time series or depth plots

The second method is to produce time series or depth plots of the data. This is achieved by simply clicking on a site in the current map layer. Up to five sites and five attributes may again be compared within the graphing tool (Fig. 5a). The graphing tool enables the direct comparison of attributes either through time and depth or against other attributes (Fig. 5b). In the latter case, only data that is coincident in terms of depth and time are plotted. It is also possible to display the full time or depth series in addition to the calculated statistics.

3.4 Animation

A further method, which applies to both point and raster data, is that of animation. An animation tool (Fig. 2) allows the user to control the speed, direction and extent of the animation. Animation of point data (e.g. concentrations of atrazine at fixed sites) may result in pulsating proportional symbols on the map or fixed-sized symbols that vary in colour during the animation. Alternatively, if more than one attribute has been retrieved it is possible to animate bar charts at each site, allowing a comparison of all parameters throughout the time sequence. Raster animations may include a set of remotely sensed images or the results of a model run. At present, only one map layer may be animated at a time. A future requirement is to extend this so that many layers may be animated simultaneously. This will be useful when comparing the results of two models, e.g. a river model running into an estuarine model.

3.5 Profiles and perspective view

Depth is also visualized through depth profiles and perspective views (Fig. 6). Depth profiles are achieved by drawing a transect on the map and then performing an interpolation through depth (Fig. 7). It is hoped that the perspective view tool will soon be extended to incorporate all environmental data rather than simply an elevation surface.

3.6 Integration and dictionaries

Many of the scientists involved in LOIS acquired data for their own purposes, using their own instrumentation and possibly in different units, e.g., the marine scientists often measure using moles while the hydrologists use g/l. Some of the instruments used were intercalibrated, but unfortunately not all. All other identical attributes were converted to the same units.

Integration was also afforded by the development of an ‘integration wizard’. This differs from the query wizard in that the user initially selects an attribute rather than a feature type. The appropriate feature types to include within the query are determined behind the scenes. Within the query wizard the attributes are grouped into dictionaries (e.g. physical, chemical), while the integration wizard groups attributes into topical themes (e.g. nutrients, metals, microcontaminants, biology). This is more suited to the user who wishes to find an attribute in their field but does not necessarily know where (or at what feature) they have been measured. It is possible to include individual attributes in more than one topic and in the future STEM will enable the user to change the topics and dictionaries according to their own preferences.
The techniques, outlined in this section, provide some new tools for the scientist investigating their data. It is now very simple to compare attributes through time and across scientific disciplines, by graphing and animations. The benefits of this will hopefully become apparent as STEM is used in the scientific and academic communities.

4 The Future

The size of some of the databases used with STEM is continually growing. With this expansion, the need for guidance through the database will increase. Users will always ask fundamental questions of the data such as ‘What data exist?’; ‘Are they of use to me?’; ‘Can I see a sample?’; ‘Is this what I really want?’; ‘How do I get them?’ (ESRI, 1995). Presently, the size of STEM’s database is not too large for the user to answer those questions with simple exploration. However, there will come a time soon where the database is sufficiently large for such exploration to become an unrewarding and laborious process. Given this situation metadata issues will become important in future development.

Metadata is “designed for description of the contents of a dataset” (Goodchild, 1998), or data about data. Facilities for metadata storage and query are essential for such large databases and data to be transferred across distributed networks (users want to know about the data before transfer to ascertain its suitability for use).

The use of metadata can already be seen in STEM. The time and depth bars form a summary of the data (aggregated by average, measurement frequency etc.) at each period or interval, guiding the user to the most interesting datasets before seeing them in full. Alternatively, point data can be interrogated to give information about attributes measured there. Finally, the query interface provides an overview by listing feature types, attributes at those features, and the time and depth ranges for those attributes.

This is metadata, but in insufficient detail. Various standards for metadata have been drawn up, such as that of the Federal Geographic Data Committee (FGDC) and the European Spatial Data Infrastructure (ESMI). The FGDC standard is the most widely adopted, though to differing levels of rigidity. It covers seven categories of metadata - Identification Information, Data Quality Information, Spatial Data Organization Information, Spatial Reference Information, Entity / Attribute Information, Distribution Information and Metadata Reference Information. STEM should be able to cover these categories, whether through an extended query wizard or an additional module accessed prior to data query. Flewelling and Egenhofer (1999) suggest a hybrid solution of metadata coupled with representative subsets of data. Subsetted data can provide information about the data values themselves that metadata cannot capture.

Other future issues include:

- Constant updating of the database in real time. This might include data telemetered from remotely deployed moorings or river monitoring stations.
- Expanding the statistical and analytical capability of STEM.
• Running STEM over a distributed network. This would enable a more corporate data and information strategy to be realized.
• Distributed database management – ensuring that any local versions of the database are updated if any changes, such as calibration of data, are made to the centrally maintained database.
• Visualization issues such as the animation of lines and polygons and the animation of environmental data within a 3D representation. Also there will be experimentation with alternative time representations, such as the space-time cube.
• Enabling STEM to run within an Internet browser.

5 Conclusion

The LOIS Overview CD-ROM has now been published and has demonstrated a GIS capability that incorporates time and depth. Environmental data can now be stored, accessed and visualized in a novel way that treats time and depth as valid dimensions within the system. We feel that STEM can now be used for all types of environmental data and indeed any other data which can be referenced in terms of time and space, e.g. crime/health statistics or house prices. A number of novel visualization methods have been developed and as STEM is used in the scientific community we hope that it will lead to discoveries about environmental data that were either not possible previously or took a long time to achieve. The main enabling factor in this is the integration of multi-temporal, multi-feature data in STEM, representing what may be hundreds of thousands of ‘layers’ in most conventional GISs.

The modular and generic nature makes the system suitable for expansion, including further visualization techniques, the addition of specialist scientific/analytical components and the progression into a fully functional corporate system. The system is already moving towards this goal and is being used by environmental institutes/companies in the United Kingdom.

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References


Figures

Fig. 1 Time series plot of alkalinity at a river monitoring station.

Fig. 2. Results for chlorophyll provided from the European Regional Seas Ecosystem Model (Allen 1997). An animation tool provides the user with control over display and animation of the model results. The clock in the centre of the control shows progress through the time sequence.

Fig. 3. The WIS logical data model. The WIS cube.

Fig. 4 a) The STEM time bar, note how the values change throughout an annual cycle.
   b) The STEM depth bar.
   c) A possible 2D grid combining the time and depth aggregates within one display.

Fig. 5. a) Graph showing a time series for alkalinity and chromium dissolved for two different sites.
   b) Graph showing an attribute versus attribute plot for alkalinity and manganese for three different sites. Note how the three sites plot within different regions of the graph.

Fig. 6. A perspective view of the East Coast of England, showing elevation and bathymetry.

Fig. 7. An interpolation of chlorophyll profiles at the Hebridean shelf edge.
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