INCO-CT-2004-509158

NOSTRUM-DSS

Network on Governance, Science and Technology

for Sustainable Water Resource Management in the Mediterranean.

The Role of DSS Tools

Instrument: Co-ordination Action

Thematic Priority: INCO-MPC, Specific measures in support of international co-operation - Mediterranean Partner Countries (MPC)

Deliverable D5.5

Report on development and implementation of DSS tools in the Mediterranean Area

Due date of the Deliverable: 30/09/05	**Actual submission date: 26/09/05**
Start date of project: 1st August 2004	**Duration: 36 Months**
Organisation name of lead contractor for this deliverable: Fondazione Eni Enrico Mattei (FEEM) **(This deliverable has been realised by Environmental Software & Services GmbH (ESS), subcontractor of FEEM)**	
Revision:	
Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)	

Dissemination Level	
PU Public	**X**
PP Restricted to other programme participants (including the Commission Services)	
RE Restricted to a group specified by the consortium (including the Commission Services)	
CO Confidential, only for members of the consortium (including the Commission Services)	

Table of Contents

Executive Summary

This report describes the state of the art as well as underlying principles and concepts for the development and implementation of computer based decision support methodology and systems for integrated water resources management (IWRM) with special emphasis on the Mediterranean region.

The report is a contribution to Task C , Work Package 5 (Comprehensive Integrated Water Planning, Assessment and Sustainability Analysis), of the NOSTRUM-DSS work plan (see below).

The report first analyses the demand for DSS application by identifying the information needs and thus possible roles and contributions for a DSS in the water resources management domain.

It then provides a simple structure and terminology for decision problems, and discussion decision theory with reference to implementation in any water related DSS.

This is followed by a literature survey that looks into examples from the Mediterranean region, other European examples, and a global perspective. This clearly indicates that while there is a lot of information to be found on DSS development, ongoing and pilot projects and future plans, there are no examples of operational decision support systems for integrated water resources management in the Mediterranean region to be found yet.

The next section deals with practical implementation consideration, analysing the possible reasons for expectations and actual implementation of DSS examples, that also illustrate the basic elements of success and failure of DSS in general, and around the Mediterranean in particular.

Finally, a last section provides a short description of DSS theory and in particular the concept of satisficing that underlies many participatory approaches.

The descriptive part is followed by a selected bibliography covering water resources management and related DSS theory and applications.

NOSTRUM-DSS: Project Abstract

The Mediterranean basin is characterised by a strong heterogeneity of cultures, economies and societies which often implied problematic interactions. It is one of the areas where water resource scarcity and conflicts between different water users are more dramatic. The need and relevance for sustainable integrated water management strategies is therefore clear.

The great theoretical potential of DSS tools for helping policy makers to bring the principles of Integrated Water Resources Management (IWRM) into practice for managing socio-political conflicts over competing demands for water uses in different environmental situations seems to be not yet exploited. Various evidences suggest that their potential is often not exploited for various reasons, as lack of communication between scientists and policy makers. A need for reorientation of science to support policy making and for the adoption of multi-sectoral and multi-disciplinary approaches integrating socio-economic and environmental considerations is evident. NOSTRUM-DSS will address this gap approaching the analysis of needs expressed by stakeholders belonging to the various Mediterranean countries, directly involved in the CA activities and by fostering mediation between policy objectives and scientific knowledge to create an enabling environment for a more equitable and efficient water resource management in the basin. The main objectives are:

1. To establish durable links between scientific institutions, governments, NGOs, SMEs and other stakeholders and improve public awareness on water management;
2. To improve scientific knowledge and applied methodologies in IWRM;
3. To promote the development of suitable DSS tools built upon real needs of policy making in IWRM.

Ultimate aim of the Co-ordinate Action is to contribute to the achievement of improved governance and planning in the field of sustainable water management, by establishing a network between the science, policy, and civil society spheres, fostering active involvement of the relevant stakeholders in the different project’s stages, and through the development and dissemination of Best Practices Guidelines for the design and implementation of DSS tools for IWRM in the Mediterranean Area.

Objectives of Work Package 5:

- To develop a common framework for communication and analysis integrating sectoral and disciplinary approaches within the context of a sustainable development perspective.
- To analyse techniques and methods aimed at user-friendly DSS tools.
- To develop Best Practices Guidelines for the design, development and implementation of appropriate DSS tools for IWRM.
- To establish a long term network aimed at addressing capacity building and training needs.
- To facilitate dissemination of results and provide further co-operation opportunities between policy makers and researchers.

Task c of Work Package 5 focuses on “Interaction and integration of disciplines and methodologies: focusing on the integration of the different approaches and methodologies explored in the previous work-packages and with the specific aim to investigate the development and the implementation of DSS tools and their impact on decision making processes in the Mediterranean Area“.

Related activities

More than five years ago (April 2000) the Federal Institute of Hydrology (BfG) organized an international workshop on Decision Support Systems (DSS) related to water management in Europe: http://elise.bafg.de/?3469 . A lot of progress in this field has been achieved, also taking into account cross sectoral and cross bordering aspects, especially since the EU WFD came into force, but also as a consequence of recent high-water events and other tasks. In Germany the Federal Ministry of Research and Education (BMBF) funded different projects working on this topic. But still the use of DSS and related methodological aspects have to be brought forward from research to daily planning practice. The workshop wanted to focus on user and developer experiences concerning methodological, operational and organizational aspects of decision support systems for integrated river basin management.

The idea of the workshop is not to present mere project results, but condensing experiences and ideas in a creative and open workshop atmosphere. The workshop wanted to address these key issues, grouped into user and developer experience as listed below:

User experience

- Does the DSS address your management tasks with the right scope and scale?
- How do you embed “your” DSS in organizational structures and decision making processes
- How is the knowledge, lifecycle management and the maintenance of a DSS organized in your administrational environment?

- Is the DSS in use generally accepted or even part of legal planning procedures?

Developer experiences:

- Which methodologies for model integration have been proven by themselves?
- Which software engineering aspects of model integration are important to discuss for further developments
- Which features of User Interface design for policy support with complex scientific applications would you prefer to develop in future?
- Tell about the DSS development process: goals, roles, conflicts, methodology, knowledge engineering

Workshop results:

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 eco-morphological 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.

Decision Support Systems: concepts and terminology

There is no single accepted definition of what constitutes a Decision Support System (DSS) in the technical literature. The discussion is reminiscent of the AI field in the late 70s and mid 80s, here authors have provided rather enthusiastic descriptions and very optimistic predictions and future use and impacts. What happened to expert systems and many AI technologies seems now to be repeated with the DSS catchword.

While there is no agreement what exactly or even minimally constitutes a DSS, and many descriptions show a lack of understanding if not wilful abuse of terminology for apparent marketing purposes within science as a rather pliable social construct, many description share a few common traits as the examples below demonstrate:

“A decision support system (DSS) is both a process and a tool for solving problems that are too complex for humans alone, but usually too qualitative for only computers. Multiple objectives can complicate the task of decision-making, especially when the objectives conflict. As a process, a DSS is a systematic method of leading decision-makers and other stakeholders through the task of considering all objectives and then evaluating options to identify a solution that best solves an explicit problem while satisfying as many objectives as possible to as high a degree as possible” (Westphal, K. 2000). Westphal claims: “A DSS is much more comprehensive than traditional methods of decision-making in water resources management. Rule curves, one common traditional method, are discrete and confined to specific conditions, while a DSS can be adapted to any conditions. DSS recommendations are based on scientific data and models and can account for all stakeholder objectives, cause/effect relationships, risks, costs, and reliability, whereas traditional decision processes have had difficulty aggregating all of these considerations. DSS programs are adaptable; they are custom-designed for specific systems to help achieve system-specific management objectives. And because a DSS is a reproducible method of decision-making, its results are defensible to stakeholders and regulatory agencies. A DSS is capable of aggregating all competing objectives to identify the best strategy--that is, a strategy that is truly optimal. Moreover, as a process, decision support techniques involve the decision-makers in defining the problems and the objectives. This gives the stakeholders the knowledge that their values are important, and they can see that their qualitative and quantitative input is being used.”

"Decision support system" is defined as an approach or methodology for supporting decision-making. It uses an interactive, flexible, and adaptable computer-based information systems especially developed for supporting the solution for a specific non-structured management problem. It uses data, provides an easy user interface, and can incorporate the decision maker’s own insights. In addition, a DSS usually uses models and is built (often by end users) by an interactive and iterative process (evolutionary prototyping process). It supports all phases of decision-making and may include a knowledge component. Finally, a DSS can be used by a single user on a PC, or it can be Web-based for use by many people at several locations" (Turban et al. 2001).

To quote a water specific attempt at definition from Hahn and Engelen, (2000): "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 (1999). 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 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."

Simonovic (1998) writes: "A decision support system (DSS) is often useful where problems are poorly structured and where a significant portion of the effort in making a decision is used to generate information, leaving precious little time to consider "big Picture" issues. A DSS does not replace a decision maker. Rather, it places the decision maker at the centre of the decision-making process so that information and timely assistance can be effectively utilized. As such, a DSS should allow people to combine personal judgment with the results of analysis. A DSS typically consists of databases, modelling tools, and documentation on the decision making process. All of this information is organized according to the needs of the users within a software application. The resulting DSS may include geographical information systems (GIS), modelling tools to analyze unique scenarios, artificial intelligence techniques for accessing information in a timely manner, and decision analysis techniques for assessing tradeoffs among alternatives. Decision support tools are applications or programs that offer the resources necessary to make a decision. The tool does NOT make the decision. Instead, a decision support tool provides the necessary information in a timely manner so that a person can make a qualified judgment."

In summary, a DSS is computer based, including hardware, software, and data; it must assist in making non-trivial decisions, but beyond that, there is little agreement. Analysing the literature, the overwhelming number of cases that claim DSS status refer to relatively simple information and model systems that focus on problem representation and in most cases, WHAT-IF type scenario analysis.
A considerably smaller group addresses optimization tools with usually a strong Operations Research and mathematical programming focus.

The basic functions of a DSS include:

1. Identify and structure the problem, and define a consistent preference structure in terms of criteria, objectives, and constraints.
2. Design alternatives that provide solutions to the problem as posed.
3. Select preferred solutions from the set of alternatives based on the preference structure.

The main elements of a decision include the design of promising, feasible alternatives and the subsequent selection of a solution (alternative) from a set of alternatives thus generated or identified. This decision process is based on:

1. A set of **Alternatives,** which can be discrete and pre-existing, or generated on demand;
2. A set of **Criteria** describing each of the alternatives; criteria can be qualitative or quantitative, cardinal, ordinal or nominal.
3. **Constraints** describing acceptable lower or upper bounds on any one of the criteria; only a solution that meets all constraints is deemed a feasible alternative and subsequently considered.
4. **Objectives** or objective function(s), expressed in terms of the criteria that should be minimized or maximized by the selection.
5. A **preference structure** that defines the relative importance of different criteria in contributing to the objective function, and the different importance of different objectives in an overall evaluation.

The choice or selection project can be dynamic (in time) or static, include spatial properties, and use dynamically generated attributes (from simulation models or on-line monitoring) in the analysis.

There are several basic decision oriented processes that DSS tools can support:

1. **Classification, estimation**. Given contextual or anecdotal information, an estimate for an unknown or its classification is derived by inference. The method is first order logic, the implementation a backward chaining rule-based expert system. Given a target concept, a set of rules guides the user to a best estimate or classification for the variable or symbol sought. Examples are the estimation of model parameters, complex estimates using cascading heuristics (e.g., the arrival time of a pollutant plume from an accidental spill and consequent shutdown procedure for bank filtrate intakes for drinking water supplies) or the classification of an event given limited information (e.g., the level or severity of a drought and its effects on agricultural production and the corresponding mitigation measures). Typical example are an EIA procedure for water resources development projects (http://www.ess.co.at/EIA), or numerous elements in quantitative risk analysis and assessment: http://www.ess.co.at/RISK.
2. **Operational advise** in real-time. The same basic principle holds for operational or tactical advice in real-time, e.g., for emergency management. These systems are referred to as IC3 (Intelligence, Communication, Command, Control). Any set of formal, consistent guidelines or operating procedures can be implemented as rules, and processed to provide decision support in the form of operational instructions in a dynamically changing context with asynchronous information flow. However, real-time may also span days and weeks rather than minutes and hours, e.g., to control a multi-step procedure like an EIA process. The method is again based on rule-based expert system, but combining forward-chaining with backward chaining, so that the inference engine runs continuously in real-time and considers time or time derived variables (absolute time, simulated time, elapsed time, etc.) among the decision criteria. Typical examples are technological and environmental emergency management systems (http://www.ess.co.at/HITERM/) or on-line distance learning and technical training (http://www.ess.co.at/A-TEAM) for emergency management.
3. Multi-criteria **Ranking and Benchmarking.** Given a set of objects each described by multiple attributes or criteria (e.g., watershed characteristics, slopes, soils, land-cover, agricultural management practices, rainfall patterns) the system supports the interactive ranking of the set by any or all of the criteria in any arbitrary combination, in this example, for erosion, sediment yields, and turbidity. The objective is to establish a rank-order by dynamically generated, derived criteria the user defines interactively. An example from regional planning is http://www.ess.co.at/NOE/Edemo.html. The benchmarking concept introduces a context for evaluation, and relative positioning of objects in relation to known

reference cases rather than isolated and in more difficult to interpret absolute terms in the absence of general standards that can be used as constraints.

4. **Complex Optimization**. In the previous cases the set of alternatives were supposed to be given. If we have a model or set of models describing a complex system, we can generate any number of alternatives, and apply the above elements to identify a bets, most desirable solution, and in fact design it automatically to meet all constraints and minimize or maximize the objective functions. Since large, complex system are usually non-differentiable unless simplified considerably, and all observation are highly uncertain (especially in the risk analysis domain) we extend the set of criteria by elements of Gestalt and measure similarity in term of distance in a N dimensional behaviour space. The underlying methodology is a hybrid of several heuristic methods, including Monte Carlo, stochastic hill-climbing, linear and dynamic programming, and evolutionary algorithms to make the search procedure more efficient and avoid computability issues of combinatorial explosion. However, for large systems, the method is very compute intensive, which is the price for a detailed and more realistic model description (coupled, dynamic, spatially distributed, non-linear).
5. **Discrete MC Optimization**. This is an implementation of the reference point methodology of multi-attribute theory. Its basic advantage is simplicity, the use of a minimum set of assumptions, so that it lends itself to interactive use. Here we use the N dimensional geometry of the behaviour space (defined by the set of alternatives) to define measures of achievement (the objective function) given the distance of any alternative from utopia, or a user-defined reference point. The implicit normalization of the criteria (dimensions) to the interval between nadir and utopia as a degree of (possible) achievement makes it possible to use an effective strategy without eliciting complicated weights or preferences from the user. The method first partitions the search space into dominated and non-dominated alternatives (i.e., generating a Pareto-optimal sub-set) always depending on the user's choice of the criteria to be considered, and any constraints specified.

To quote from a commercial supplier of decision support or engineering consulting: http://www.riverside.com/services/waterresources/dss.asp):
"Decision Support Systems allow decision makers to analyze hydrologic data, run hydrologic simulation models, run basin water allocation models that represent water rights, and study the effects of potential decisions. RTi designs a DSS to access or display hydrologic data in an easily accessible manner, to model interactions between water law and dynamic hydrologic conditions, and to determine the ability of the river system to meet future demand based on operational and administrative use of storage. Often these DSS allow users to simulate and evaluate various "what if" scenarios for river operation alternatives. Operational plans addressed by a DSS include the improvement of water use efficiency, exchanges between water users, the construction of new reservoirs or enlargement of existing facilities, the development of augmentation and replacement plans, as well as the development of additional beneficial uses, such as minimum stream-flow and alternatives for protection of endangered species."

Applications for real-time Decision Support Systems in the water domain that Riverside quotes include:

- Hydrologic forecasting for flood or drought conditions
- Reservoir operations and forecasting
- Hydropower operations simulation and optimization
- Water supply and delivery management
- Water resources data management
- Soil moisture and snow-pack assessment and forecasting
- Water rights modelling
- Inter-agency coordination

Other, DSS related sources of information include:

DSS books:	http://dssresources.com/books/dssbooks.html
DSS glossary:	http://dssresources.com/glossary/dssglossary1999.html

IWRM: decision problems and information requirements

The report deals specifically with DSS development and the less common application to integrated water resources management. The application domain has a strong influence on the applicable technology, as the information requirements of the water resources planning and management processes define scope and necessary or desirable functionality of a useful DSS. Water resources problems all revolve around the same common issues: not enough or too much, at the wrong place or time, of insufficient quality, or too costly.

The primary purpose of water resources management is, consequently, to provide water where and when needed, with the quality required, which includes to control floods and mitigate droughts as external events of extreme inter-annual variability of natural water supply, i.e., precipitation.

This seemingly simple objective has a number of closely related components that can be organised in terms of instruments or technologies (the selection and implementation of these instruments lead to the decisions that must be made and, we presume, supported by a DSS) that can be used to achieve the objectives.

Supply and demand

The primary objective is meet demand, that is to achieve a supply over demand ratio as close to one as possible. This, however and notably, has to components:

- Supply of water from different sources;

- Demand for water for different purposes.

Thus, the central objective is to bring demand and supply in line, also considering issues of sustainability in particular when tapping fossil (and thus non-renewable) water resources like deep groundwater, or when using fossil (and thus non-renewable) energy in providing water, for desalination, pumping or treatment.

Classical instruments of water resources management on the supply side (and thus, possible decisions to be taken) include

- Tapping of springs
- Well and well fields exploiting groundwater which includes pumping at a cost
- Inter-basin transfer, which, however, is always a local solution at the expense of another location and thus just a relocation of problems, current or future;
- Desalination as an energy intensive but, as far as feed-water is concerned, near unlimited source;
- Water harvesting, i.e., usually small scale collection and storage systems for local precipitation based on impervious surfaces, most commonly roofs.

In all of these cases, the possible decision issues involve questions of if, where, how much, and how, that is using which technology which in terms defines investment and operational costs.

Once water is available in the system, it has to be distributed to reach points of demands from where is initially supplied. This includes natural and man made channels, pipelines, networks of pipes, and structures that control the flow.

The probably most notable and also much discussed technology for water resources management are dams and reservoirs. While they obviously do not contribute to the primary water supply, they dampen natural variability of supply to provide stored water during otherwise dry periods. Costs are obvious in the construction and maintenance of dams and reservoirs, as well as water losses due to evaporation and seepage. Due to their side-effects such as land requirements leading to relocation of people and often subsequent watershed degradation, effects on water quality both within the reservoirs and downstream due to modifications of the flow patterns and sediment and nutrient transport, as well as the risk of dam breaks with are low frequency but very high risks events, large dams have an increasingly bad reputation as a brute forward engineering solution.

Water demand is traditionally described by sector, primarily agriculture, industry, and domestic, with tourism playing an increasingly important role with a very high per capita demand and high quality requirements. Agricultural water demand is usually dominant around the Mediterranean, and in fact world wide, with roughly two thirds to three quarters of all water being used in agriculture, primarily irrigation. However, increasing urbanisation and industrialisation change these relations, albeit slowly.

The primary decision issue in water demand and use is its efficiency: how much water is needed and used to obtain one unit of useful output, whether it is a ton of rice, a tone of steel, or a happy tourist. To satisfy useful demand usually more than one technology with different efficiency, but also different investment and operating costs, can be used.

Irrigated agriculture provides some obvious example, where the differences in water use between traditional flooding and electronically controlled drip irrigation can easily amount to an order of magnitude, but so will the differences in investment and operating costs.

Another closely related aspect of water demand is the complexity introduced by demand versus consumptive use: while demand defines the amount a user wants to extract from the distribution system, consumptive use describes the fraction that is, from the water resources system point of view, irretrievably lost, that is consumed. The rest is returned as return flow, and in principle, subject to quality constraints, again available for downstream use.

A typical example of non-consumptive use would e hydropower generation, a typical example of consumptive use would be cooling water the fully evaporates in a cooling tower. Most forms of water use are somewhere in between with a variable share of consumptive use.

This return flow is the source of local re-use and recycling, i.e. water that can be used more than once on its way from precipitation to the ocean. Since water use normally goes hand in hand with some level of water pollution, this introduced the issues related to waste water treatment and purification. Treatment here refers to water treatment after the source of pollution and before return flows enters the distribution system again, purification refers to treatment just before use, typically in drinking water but also for industrial process water where quality requirements can be high as well. Obviously, water pollution limits the potential use of water for different purposes, including environmental use or somewhat less anthropogenic, its effects on the aquatic ecology.

How much treatment and purification where is a classical decision problem, where investment and operating costs have to be related to the usually social costs of downstream pollution.

Costs and benefits

Different uses of water have very different cost-benefit characteristics. If water where indeed treated as an economic good only and consistently, as the Dublin Principles or the EU Water Framework Directive 60/2000/EC advocate, market forces should lead to a convergence of cost-benefit ratio at the margin, subject to the constraint of unequal spatial distribution of the initial supply and variable transportation or provision costs.

In reality, water is treated both as a social good, that society provides to its members at a nominal fee or for free, and a semi-economic good: even in the latter case what is charged for by public or private utilities under a public concession is not the intrinsic value of water, but the cost of providing it.

The Dublin Statement:

Scarcity and misuse of fresh water pose a serious and growing threat to sustainable development and protection of the environment. Human health and welfare, food security, industrial development and the ecosystems on which they depend, are all at risk, unless water and land resources are managed more effectively in the present decade and beyond than they have been in the past.

Five hundred participants, including government-designated experts from a hundred countries and representatives of eighty international, intergovernmental and non-governmental organizations attended the International Conference on Water and the Environment (ICWE) in Dublin, Ireland, on 26-31 January 1992. The experts saw the emerging global water resources picture as critical. At its closing session, the onference adopted this Dublin Statement and the Conference Report. The problems highlighted are not speculative in nature; nor are they likely to affect our planet only in the distant future. They are here and they affect humanity now. The future survival of many millions of people demands immediate and effective action.

The Conference participants call for fundamental new approaches to the assessment, development and management of freshwater resources, which can only be brought about through political commitment and involvement from the highest levels of government to the smallest communities. Commitment will need to be backed by substantial and immediate investments, public awareness campaigns, legislative and institutional changes, technology development, and capacity building programmes. Underlying all these must be a greater recognition of the interdependence of all peoples, and of their place in the natural world.

In commending this Dublin Statement to the world leaders assembled at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in June 1992, the Conference participants urge all governments to study carefully the specific activities and means of implementation recommended in the Conference Report, and to translate those recommendations into urgent action programs for **Water and Sustainable Development:**

Concerted action is needed to reverse the present trends of over-consumption, pollution, and rising threats from drought and floods. The Conference Report sets out recommendations for action at local, national and international levels, based on four guiding principles.

Principle No. 1 - Fresh water is a finite and vulnerable resource, essential to sustain

life, development and the environment.
Since water sustains life, effective management of water resources demands a holistic approach, linking social and economic development with protection of natural ecosystems. Effective management links land and water uses across the whole of a catchment area or groundwater aquifer.

Principle No. 2 - Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels
The participatory approach involves raising awareness of the importance of water among policy-makers and the general public. It means that decisions are taken at the lowest appropriate level, with full public consultation and involvement of users in the planning and implementation of water projects.

Principle No. 3 - Women play a central part in the provision, management and safeguarding of water.
This pivotal role of women as providers and users of water and guardians of the living environment has seldom been reflected in institutional arrangements for the development and management of water resources. Acceptance and implementation of this principle requires positive policies to address women’s specific needs and to equip and empower women to participate at all levels in water resources programs, including decision-making and implementation, in ways defined by them.

Principle No. 4 - Water has an economic value in all its competing uses and should be recognized as an economic good.
Within this principle, it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price. Past failure to recognize the economic value of water has led to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources.

Water management objectives

Ideally, the objectives of integrated water resources management are derived from, or at least compatible with, these principles.

If there is enough renewable water available to satisfy all demands, the only objective is to do so at minimal cost. However, as soon as demands exceeds supply (a dynamic and spatially distributed constraint), water resources management must use one of the possible strategies, usually in some combination:

1. Increase supply – provide more
2. Increase efficiency of use – do more with less

3. Decrease demand – want less

All three strategies, usually in combination, can be used to re-align supply and demand.

- Increasing supply is rational if the cost of the increased supply is less than the benefits of the additional useful demand that can be satisfied;
- Increase efficiency of use is rational if the cost of alternative technologies is less than the benefits of the additional useful demand that can be satisfied;
- To decrease demand is rational if neither supply increases nor increases in the efficiency of use (which in fact also decrease selected demands) are technically or economically feasible.

Management of demand can use two basic strategies:

- Allocation rules, based on historic water rights or explicit preferences of sector or regions, priorities due to upstream or downstream location, water compacts;
- Economic incentives such as (usually differential) pricing, or outright subsidies.

Overall management objectives for an integrated system could be to maximise the global supply/demand ratio (including environmental demands), reliability of supply, or the overall cost/benefit ratio for the water resources system (should be a river basin, i.e., a hydrographic unit) subject to maintaining constraints (including water quality) on sustainability. This, in the most simplified interpretation and strict conservationism would imply not to use any non-renewable resources.

However, there rarely are the institutional structures or market mechanisms in place to indeed consider an entire river basin as one entity for integrated management with common objectives. In addition, the different uses of water are not subject to the same economic valuation: while uses for the agricultural, industrial, and tourism sectors can be compared on largely if not purely economic grounds based on benefits generated per unit water input, both the domestic sector and the environmental uses of water (e.g., maintaining minimum flow and quality for aquatic life, sustaining wetlands) defy comparable valuation.

Distributional effects, i.e., costs and benefits to different interest groups, economic sectors, regions within a river basin or even countries along an international river introduce a considerable number of often conflicting objectives. Additional objectives include intra- and inter-generational equity, access to water, and related sanitation issues relevant for public health.

Therefore, no obvious, generally acceptable a priori objective function and preference structure can exist for any even moderately complex river basin, which invariable leads to multiple criteria and multiple, conflicting objectives. This moves the decision problem from the realm of science and engineering necessarily to the policy domain.

Literature Review: theory and implementation

A simple, naive query to the Google Internet search engine with the keywords: "**DSS tools, water, Mediterranean**" yields approximately **57,000** entries which simply demonstrates that the topic of considerable interest. A similar search with a global scope (without the limiting Mediterranean search term) yields a staggering **552,000** hits, approximately ten times as much. Searching for DSS alone, just to indicate orders of magnitude, yields about 7,500,000 documents.

Further restricting the search to documents that also refer to "integrated water management" rather than water in general, still results in **17,900** documents.

Not surprisingly, the NOSTRUM-DSS projects itself leads the listings together with OPTIMA (http://www.ess.co.at/OPTIMA) and ongoing INCO-MPC project also dealing with optimization for sustainable water resources management around the Mediterranean, the MedAqua project (http://www.medaqua.org), various NOSTRUM-DSS partners, and the OPTIMA project (http://www.ess.co.at/OPTIMA).

However, when following the links, they by and large announce future activities; examples of results, system implemented and working in day to day practice, are extremely rare. Also, the terminology is used very liberally if not inflationary: what is called a DSS is, in most cases, at best a simulation model for interactive scenario analysis. Where optimization is involved, it usually addresses only a very specific, narrow and well defined issues such as reservoir operation or maintaining groundwater levels, far from the aspirations of integrated water resources management.

The Mediterranean region

While there are numerous projects dealing with water resources around the Mediterranean, and equally many claims of practical DSS methodology, very few if any examples of operational systems in day to practice can be found.

Most references refer to future results and their possible applications and impacts. Many are simple plans without even an operational demonstration prototype. Also, as is common on the web, many project home pages contain mostly dead or empty links, and have never been updated after their initial conception and installation.

Some examples of more current and active projects include:

Decision support for water resource management: an application example of the MULINO DSS (Mysiak, J., Giupponi, C., Fassio, A., 2002)**.**
MULINO is an EU RTD project, funded under the FP5-EESD program. It aims at providing a Decision Support System (DSS) targeted at solving decision problems in the

management of water resources. Through the integration of socio-economic and environmental modelling techniques with geographic information system (GIS) capabilities and multi-criteria decision aids, the MULINO-DSS aspires to be an operational tool which meets the needs of European water management authorities and facilitates the implementation of the EU Water Framework Directive. The application-driven approach to developing the MULINO-DSS combines the scientific background of the consortium members with local knowledge and decision support needs, expressed by five user groups. The diversity of cultural, socio-economic and environmental characteristics of the case studies requires that the tool is capable of a common approach to different decision cases but also flexible enough to adapt to the specific objectives and constraints of a given decision problem. The DPSIR framework (Driving forces – Pressure – State – Impact – response) has been chosen as the overall conceptual framework of the DSS. A demonstration of the first MULINO-DSS prototype is presented through an application example in the Vela catchment that belongs to the Venice Lagoon Watershed (north-east Italy). The decision act refers to the choice among alternative actions (public works) for the improvement of Vela's water quality.

OPTIMA: Optimization for Sustainable Water Resources Management (Fedra, 2005; Fedra and Harmancioglu, 2005) Within the Framework of a FW6 sponsored INCO-MPC project, OPTIMA, a simulation based water resources planning and optimization system is being developed and applied in case studies in Cyprus, Turkey, Lebanon, Jordan, Palestine and Israel, Tunisia and Morocco. The model system addresses both quantity and quality, water demand and supply, surface and groundwater, water technologies and efficiency of use, allocation strategies, costs and benefits. A web based client-server implementation supports distributed use and easy access, and a participatory approach involving local stake holders for multi-criteria optimisation and decision support (http://www.ess.co.at/OPTIMA).

The optimization uses heuristics and concepts of genetic programming, based on a realistic, detailed, dynamic and distributed representation of the individual river basins. The underlying dynamic (daily) simulation model describes the water resources systems at a basin scale including the groundwater system for conjunctive use. The model covers the physiographic and hydrological elements, but also aims to represents the institutional and regulatory framework, and the socio-economic driving forces. The primary optimization identifies sets of non-dominated pareto-optimal solutions in heavily constrained scenarios; these are the basis for an interactive discrete multi-criteria selection with the participation of end users. The multi-criteria approach covers global and sectoral demand and supply balances, reliability of supply, access, cost and benefits, including environmental and social aspects. Arbitrary penalty functions can be used for the valuation of violation of standards and missing targets, both shortfalls of supply as well as excess (flooding or pollution).

The overall aim of OPTIMA is to develop, implement, and critically evaluate, an innovative, scientifically rigorous yet practical approach to water resources management intended to increase efficiencies and to reconcile conflicting demands. Based on the European Water Framework Directive (2000/60/EC) as conceptual framework the approach equally considers economic efficiency, environmental compatibility, and social equity as three pillars of sustainable development. OPTIMA is extending classical optimisation and mathematical programming methodology in several respects:

- Using full-featured dynamic and distributed simulation models and genetic programming as the core to generate feasible and non-dominated alternatives. Water technology alternatives including their cost structure, and long-term hydrometeorological data are primary inputs;
- Extending the set of objectives, criteria and constraints through expert systems technology to include difficult to quantify environmental and social dimensions;
- Putting specific emphasis on local acceptance and implementation through the inclusion of stake-holders in an interactive, participatory decision making process carefully embedded in institutional structures, using a discrete multi-criteria reference point methodology;
- Adding comparative evaluation and benchmarking across the set of local and regional case studies in seven countries, namely Cyprus, Turkey, Lebanon, Jordan, Palestine, Tunisia and Morocco around the Southern and Eastern Mediterranean as the final step of analysis to identify generic examples of best practice.

The optimisation approach is conceptually simple. We use the full complexity of the simulation models to retain their distributed, non-linear and dynamic features deemed essential for the problem. We then split the optimisation into two steps: in a first step, we identify a set of feasible, non-dominated solutions using a large, inclusive set of criteria and options expressed as combinations of decision variables. The decision variables can represent structural changes, alternative allocation rules, different efficiencies through alternative technologies, and changes in demand patterns. Alternatives are generated by a Monte-Carlo approach embedded in a heurist driving framework that uses concepts of genetic programming including the “re-combination” of parameter sets of successful trial runs. The set of alternatives are tagged with their expected effects in terms of selected performance criteria, so that after a failure, violating one or more constraints, we can select alternative values for the decision variables using these heuristics. Once a solution that meets the constraints is found, we explore its local neighbourhood in parameter or decision space using a stochastic hill climbing method. Populations of feasible solutions are developed around major structural alternatives, which are then used as the starting points for the next round of generating alternatives with modified constraints.

The approach then uses a discrete multi-criteria methodology to identify the optimal solution given a reference point in performance space. The default reference point is utopia, and we normalise the performance space for all criteria as a degree of achievement in the interval between nadir and utopia. The last step of defining reference points step is done interactively, with the actors and stakeholders or their proxies involved: criteria can be excluded or included (which leads to different sets of non-dominated alternatives), constraints moved, and different reference points defined to immediately see the consequences of each such preference structure, expressed in natural units for all constraints, and learn about trade offs and possible solutions.

The primary objective of the methodology is to contribute to better policy and decision making for resource management at the basin scale. The basic elements are reliable data and information, exploiting modern information technology, an integration of qualitative and quantitative tools for rational and scientifically based design and analysis of options and alternatives, and the support for wide participation in the decision making process. DSS based on optimisation technologies are a central element of operations research, and an established technology in water resources research. Their practical applicability for complex problems, however, is limited by the fact that efficient optimisation requires a sometimes gross simplification (usually based on linearization) of the problem to arrive at an optimal solution with guaranteed convergence. A secondary problem is that the formalisation and related abstraction and simplifications make assumptions and results difficult to understand and communicate, which hinders broad participation in the decision making process and thus often generates barriers to the actual implementation of technically optimal solutions. Brute forward numerical optimisation, based on simulation modelling can retain a sufficiently detailed, realistic description. However, the combinatorial explosion of alternatives makes an exhaustive search of the decision space impossible for even moderately complex problems.

An alternative is the introduction of domain specific heuristics in a multi-tiered approach, using rule-based expert systems, and genetic algorithms, which can make the search much more efficient than traditional methods. Iterating between different levels of aggregation and representation, evolutionary strategies and local stochastic gradient search, a screening level approach and the use of evolutionary concepts of good enough rather than optimal can lead to efficient solutions even for very complex and large-scale problems.

This innovative approach to the optimisation of complex, non-linear, distributed and dynamic systems is embedded in a framework of interactive, participatory decision support based on a secondary layer of discrete multi-criteria optimisation. The reference point approach simplifies the expression of preferences and trade-offs, which can be expressed directly in natural terms and units. The method supports interactive, exploratory use and aims at easy integration in the planning and policy making process. The tools primarily provide a framework for structured, rational discourse facilitating the participation of all major institutions, actors and stakeholders in water resources management with a common, shared and sound information basis.

An Integrated Assessment Framework for Water Resources Management: A DSS Tool and a Pilot Study Application (Fassio, Guipponi, and Mysiak)

(http://ideas.repec.org/p/fem/femwpa/2004.122.html) Decision making for the management of water resources is a complex and difficult task. This is due to the complex socio-economic system that involves a large number of interest groups pursuing multiple and conflicting objectives, within an often intricate legislative framework. Several Decision Support Systems have been developed but very few have indeed proved to be effective and truly operational. MULINO (Multisectoral, Integrated and Operational Decision Support System for Sustainable Use of Water Resources at the Catchment Scale) is a project funded under the Fifth Framework Programme of the European Research and the key action line dedicated to operational management schemes and decision support system for sustainable use of water resources. The MULINO DSS (mDSS) integrates hydrological models with multi-criteria decision methods and adopts the DPSIR (Driving Force – Pressure – State – Impact – Response) framework developed by the European Environment Agency. The DPSIR was converted from a static reporting scheme into a dynamic framework for integrated assessment modelling (IAM) and multi-criteria evaluation procedures. This paper presents the methodological framework and the intermediate results of the mDSS tool through its application in a pilot study area located in the Watershed of the Lagoon of Venice.

A DSS for water resources management under uncertainty (Pallottino, S.; Sechi, G. M.; Zuddas, P.,2002) In this paper, the authors present a scenario analysis approach to perform water system planning and management under climatic and hydrological uncertainty. A DSS with a a graphical interface allows the user a friendly data-input phase and results analysis. Different generation techniques can be used to set up and analyze a number of scenarios. Uncertainty is modelled by a scenario-tree in a multistage environment, which includes different possible configurations of inflows in a wide time-horizon. The aim is to identify trends and essential features on which to base a robust decision policy. The DSS prevent obsolescence of optimizer codes exploiting the standard input format MPS. Obtained results show that scenario analysis could be an alternative approach to stochastic optimization when no probabilistic rules can be adopted and deterministic models are inadequate to represent uncertainty. Moreover, experimentation to a real water resources system in Sardinia, Italy, shows that the DSS can be easily used by practitioners and end-users**.**

WaterStrategyMan: The goal of the WSM project - "Developing Strategies for Regulating and Managing Water Resources and Demand in Water Deficient Regions" is the study of the differences between quantity and quality dimensions in water management and the development of alternative options and long-term scenarios, through the establishment of a broad framework on the existing knowledge on IWRM practices, while highlighting of the importance of regionalization and the relevant cultural context. Methodology, tools, guidelines and protocols of implementation will be developed that will enable decision makers to select and implement relevant water schemes for full water cost recovery. The project aims at developing an integrated water resources management that takes into account economic, technical, social, institutional and environmental implications, to meet both directly and indirectly the EU requirements concerning preservation and enhancement of the quality of the environment and the availability of natural resources and sustainable development.

The WaterStrategyMan DSS: A Comprehensive Decision Support System for the Development of Sustainable Water Management Strategies: Volume III of the WSM Publishable Reports presents the Decision Support System developed in the framework of the WaterStrategyMan project. The WSM DSS was functional to the analysis of the dominant and shifting paradigm options and of their quantitative, qualitative and economic impacts in the selected regional water resource systems. The primary aim was to develop a tool, able to simulate the behaviour of water resource systems under different scenarios of water availability and demand, and including a module for simulating and evaluating alternative water management strategies. Its implementation was preceded by a comprehensive review of existing suitable methodologies and models for water resources and an analysis of their strong and weak points led to the definition of the present architecture of the DSS.

The volume is structured in two parts: Part I presents the principles, concepts and methodology of the WaterStrategyMan DSS, while Part II is a comprehensive review of existing tools for water management and planning. (http://environ.chemeng.ntua.gr/wsm/Uploads/Deliverables/ThirdYear/Deliverable_21_4.pdf)

Decison support system for managing groundwater level (Naveh, N. and Shamir, U. (2000) This research paper deals Hula Decision Support System HDSS to aid Hula site operators in controlling ground water levels in the Hula region. As to minimize the decomposition and subsidence of the peat soils, ensure year round green cover of the area, and improve agricultural production. This is accomplished by management of the amount of water, which flows into and out of the area and controlling water levels in a grid of drainage canals, and by the timing and quantity of irrigation. Water levels in the canals are controlled by a set of hydraulic structures. The hydraulic conductivity k and porosity n of the soil are important parameters in development of the HDSS. These values are difficult to determine for the highly variable conditions in the field.

The management module for the HDSS performs optimization with the following two objectives

1. Minimum deviation from the specified groundwater target level, and

2. Minimum supply of water from the Jordan River to the Hula drainage canals water quantity is limited.

This second objective is achieved indirectly, the DSS determines the dam settings and irrigation quantity and timing over a period of eight weeks, and is solved again whenever conditions change. The results are checked by simulation, using MODFLOW in the GMS modelling package.

Other European examples

Decision support system for domestic water demand management (Frookh, L ,1999) Decision making on one hand can take a considerable time specifically in multi- dimensional or multi- solution problems. Automating this process with the help of a decision support system aids in making the management process efficient since it allows the user to utilize others experience in the decision process with minimal effort. On the other hand, the demand management of domestic water becomes a widening major task in many water companies or authorities. This is due to the rapid increase in water demand, water scarcity and high investment for development of new resources. In the light of this and due to rapid growth of computer technology, such systems are increasingly becoming very important to water resources planners. This paper introduces a decision support system for domestic water demand management. The developed system forms part of a highly integrated water resources management system for river basin. It comprises expert system, multi- decision component and online help files (hypertext file). The system estimates conservation effectiveness as a result of implementing certain conservation measures in a given area and time period. Several conservation measures are incorporated in the system. These include: water metering, water rationing, pressure reduction, public education, water pricing, conservation devices, plumbing codes and water use restrictions. The system capabilities are demonstrated using the data of Swindon demand zone in Thames basin in the UK.

Design of sustainable on-farm surface irrigation systems with a decision support system, Goncalves, J.M.; Pereira, L.S. (1999). The modernization of surface irrigation is a necessary condition for sustainable agricultural development, allowing a good performance in the use of water, energy and labour, and the conservation of natural resources. The surface irrigation design could be improved, with more precision and effectiveness than the traditionally empirical methods, if based on mathematical simulation models, mainly when these are integrated with optimization models, thus allowing the development of economically and environmentally acceptable designs. For this purpose, a decision support system (DSS) was developed to help decision-makers in the process of design and selection of on-farm surface irrigation systems. This DSS is a tool to improve design and selection procedures for surface irrigation which is composed by an input data base, design models for alternative design and impact analysis, and a multiple criteria decision making model that evaluates and ranks the alternative designs. It was tested with data collected from field experiments, and its usefulness was evaluated through the application to a sector of the Lower Mondego Valley of Coimbra in Portugal.

A policy support system for the Dutch Waddenzee: WadBOS is an information system offering support to policy makers actively involved in the Dutch Waddenzee. It has been developed within the framework of the Land Water Information technology program, by commission of the National Institute for Coastal Zone and Marine Management (RIKZ) and directorates Noord-Holland and Noord-Nederland of the Dutch Ministry of Transport, Public Works and Water Management. (http://www.riks.nl/projects/WadBOS)

The Wadden Sea is part of a coastal system extending from the North of the Netherlands into Northern Germany and Western Denmark. In the Netherlands, the sea is a protected nature reserve because of the important ecological functions that it fulfils. At the same time, the sea has important economic functions. Fishing, recreation, transportation, and mining are among the main economic activities. It generates employment, income, leisure, and food for many a household. The management of the different activities and functions of the sea is distributed over a great number of institutions, ranging from the municipal to the European. When decisions are to be made or policies need to be developed relative to the exploitation or protection of the area, incompatible views tend to slow down the decision-making process.

The development of WadBOS started in 1996 when CUBWAD, the association of government organizations responsible for the management of the Wadden Sea, concluded that policy-making could be enhanced if the abundant existing knowledge about the Wadden Sea, which is generally spread among the many policy making, management, and research bodies active in the region, would be gathered, ordered, linked and made available in an operational form to those responsible for policy-making. It was expected that an information system representing the Wadden Sea in an holistic manner, integrating ecological functions and human activities at the appropriate temporal and spatial scales would be a very useful instrument for this purpose. Such system was expected to enable the exploration of the autonomous dynamics of the Wadden system as well as the analysis of effects of policy measures thereon.

Today, 5 years later, WadBOS exists in its second version. It is a Decision Support System featuring an integrated model representing the ecological and the economic functions of the sea. The constituting sub-models represent processes operating at different time scales, ranging from daily to yearly. They also represent spatial processes operating at three different spatial scales: the whole sea, 12 relatively homogeneous compartments within the sea, and small cellular units of 25 ha each. The WadBOS system relies heavily on GIS information for its inputs, but its models need economic, demographic and ecological data from other sources equally well. WadBOS has been developed to be useful for and usable by the decision makers in the region working in isolation or in a group setting. A lot of effort has gone into its user-friendly character, its interactive capabilities, the (geo)graphical representation of its dynamic output, and its transparency. The system has been instrumental in analytical exercises, but its communication and learning capabilities have proven to be at the least as important.

Geography-referenced Regional Exposure Assessment Tool for European Rivers GREAT-ER (Berlekamp et al., 2000) (http://www.usf.uni-osnabrueck.de/projects/GREAT-

ER/GREAT-ER.html) The European project GREAT-ER (Geo-referenced Regional xposure 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.

A global perspective

A large number of water related DSS literature, projects, and application examples can be found, primarily in the US and Canada.

IWR-PLAN: The US Army Corps of Engineers Institute for Water Resources (IWR) has developed IWR-PLAN Decision Support Software to assist with the formulation and comparison of alternative plans. While IWR-PLAN was initially developed to assist with environmental restoration and watershed planning studies, the program can be useful in planning studies addressing a wide variety of problems. IWR-PLAN can assist with plan formulation by combining solutions to planning problems and calculating the additive effects of each combination, or "plan." IWR-PLAN can assist with plan comparison by conducting cost effectiveness and incremental cost analyses, identifying the plans which are the best financial investments and displaying the effects of each on a range of decision variables. The software is available via the IWR-PLAN Internet Download Site: http://www.pmcl.com/iwrplan/General_Info/overview.htm

Integrated Decision Making for Watershed Management - Monograph #21 (2002)
The Journal of the American Water Resources Association (JAWRA)
While the concept of land use change is not new, the rate, scale, and kind of changes that have been taking place over the last 100 years or so have been unprecedented. As a result, at this point nearly half of the land surface of the earth has been transformed by human action. In the U.S. this number exceeds 60 percent, with urban expansion alone claiming more than an additional 440,000 acres of land each year. The consequences on the environment can be far-reaching and long lasting.

With this in mind, the papers included in this Monograph can be grouped into two categories: (1) decision support tools and (2) institutional issues or stakeholders (with a few having elements of both). The majority of these papers represent some of the latest developments in multidisciplinary/integrated research on watershed management. Some of these papers develop new tools while others describe the use of existing tools in a watershed environment and evaluate their effectiveness. Several papers employ case studies to demonstrate the use of various models, concepts, and methodologies. As is often the case, the objective in many of them is to maintain, or at times improve, the integrity of the ecosystem under scarce water conditions and multiple demands.

This monograph documents this new knowledge and experience and makes it available to new scientists as well as to seasoned researchers from diverse disciplines, such as ecology, physical, and social sciences. It will facilitate various agencies and decision makers in their planning efforts.

The GLOOWA-Volta Project: The interdisciplinary GLOWA Volta Project (GVP) aims firstly at providing an analysis of the physical and socio-economic determinants of the hydrological cycle in the Volta Basin in the face of global change. Based on this, its envisioned major output is secondly the development of a scientifically sound and adequately tested Decision Support System (DSS) for the assessment, sustainable use and development of the Basin's water resources. The DSS will provide a comprehensive monitoring and simulation framework, enabling decision makers to evaluate the impacts of climatic and land use trends with particular regard to the consequences of deliberate policies, investments and other interventions on the social, economic and biological productivity of water resources. A vital precondition for the success of this effort is the development of scientific capacity and infrastructure within the Basin to ensure the self-sustainability of the DSS. The project's first phase (GVP I), which ended in April 2003, focused on the development of conceptual frameworks, feasibility studies and initial model runs, as well as on capacity building and the field work of the first set of Ph.D. students (13) and the permanent staff.

For the project's second phase (GVP II), four strategic goals were defined:

- Successful completion of Phase I activities
  Inclusion / Project coverage of Burkina Faso
- Technical integration of disciplinary models and knowledge generation frameworks
- Development of a prototype DSS

http://www.glowa.org/eng/volta/volta_overview.htm

Economic and environmental impact assessment using a watershed management decision support tool (Fulcher, C.; Prato, T.; Zhou, Y. (1997)) A Watershed Management Decision Support System (WAMADSS) is used to evaluate the economic and environmental consequences of alternative land use/management practices (LUMPs). WAMADSS consists of three components: (1) a GIS, (2) an economic model, and (3) two environmental simulation models. Specifically, ArcInfo serves as the engine for integrating the Cost and Return Estimator (CARE) program, the AGricultural

NonPoint source (AGNPS) pollution model and the Soil and Water Assessment Tool (SWAT) in a seamless interactive decision support system. The three components are accessed through a graphical user interface which enables decision makers to generate scenarios. Specifically, the user changes LUMPs and WAMADSS generates model input files, executes the programs and imports the output into the GIS. Tabular and spatial results are then viewed side-by-side for different scenarios.

Information technology and decision-support systems in AGL (Antoine, J.,1998)
This paper presents the information and decision-support systems currently applied in the Land and Water Development Division (AGL) of FAO. It briefly describes the tools used to store and analyse information and generate and disseminate information products for land and water decisions and presents some future perspectives for development of land and water information systems in AGL.

Integrated Flood Plain and Disaster management using the MIKE 11 decision support system (Kjelds, J.T., Müller, H. G, 1996)
Flooding is a natural and variable phenomena, it can occur on any land surface, ranging from a street intersection, a home lot to the extensive rural flood plain areas inundated by large rivers. Flooding results in damage to property, crops and negative impacts on human welfare. Flood Plain Management aims to minimize damages and reduce the threat to human life and welfare when major flood events occur. Along with these more traditional river engineering and flood defence tasks come also the requirements of applying new solutions. These should not only meet the stringent design requirements but also preserve and enhance the environment. Application of the hydraulic numerical modelling tool MIKE 11 for flood analysis and flood plain management is a strategic and essential tool for an integrated Flood Plain Management approach, using "Decision Support System" (DSS) technology. The MIKE 11 modelling system is developed by the Danish Hydraulic Institute.

Multi-model integration in decision support system: a technical user interface approach for watershed and lake management scenarios (Lam, D.; Leon, L.; Hamilton, S.; Crookshank, N.; Bonin, D.; Swayne, D., 2002) Computer simulations using mathematical models provide useful tools to investigate different scenarios based on watershed management strategies and environmental conditions. To study the impact of these strategies and conditions, different models must be linked or coupled following hydrological pathways in air, soil and water. To connect one model to another successfully, we need to resolve a number of computational issues such as the compatibility of software tools and the consistency of the temporal and spatial scales and model assumptions used. To keep track of these issues and to provide efficient algorithms to resolve them, we propose to use a technical user interface approach based on expert system technologies that provide intelligent access to databases, models, scenarios and decision support output. We use the watershed management study on Lake Seymour, B.C., Canada, as an example to illustrate this approach.

OntoWEDSS: an ontology-underpinned decision-system for wastewater management (Ceccaroni, L.; Cortes, U.; Sanchez-Marre, M., 2002) This paper characterizes part of an interdisciplinary research on artificial intelligence techniques applied to environmental decision-support systems. The architecture's design of OntoWEDSS, a decision support system for wastewater management, is presented. This system augments classic rule-based reasoning and case-based reasoning with a domain ontology. The integration of the newly created WaWO ontology provides a more flexible management capability to OntoWEDSS. The construction of the decision support system is based on a specific case study but the system is also of general interest, given that its ontology-underpinned architecture can be applied to any wastewater treatment plant and, at an appropriate level of abstraction, to other environmental domains. The OntoWEDSS system helps improve the diagnosis of faulty states of a treatment plant, it provides support for wastewater-related complex problem-solving, and it facilitates knowledge modelling and reuse by means of the WaWO ontology. In particular, the following issues are dealt with: (1) the improvement of the modelling of information about wastewater treatment processes and the clarification of a part of the existing terminological confusion in the domain, (2) the incorporation of ontology-modelled microbiologic knowledge related to the treatment process into the reasoning process and (3) the creation of a decision support system with three layers (perception, diagnosis and decision support) which combines knowledge through a novel integration between KBSs and ontologies, thus providing better results.

PlanIT: A multiuser 4D decision support tool for land and water resource planning Holyland, P. W. (2002) PlanIT is a PC based decision support system (DSS) designed for end users from farmers to government agencies. It is designed to be a generic multi-user platform to integrate biophysical, economic, and social data and models in a user friendly format. The user interface is a 4D world, showing photos of the farm or catchment draped over terrain, that can vary through time. The software allows for mapping, and editing both natural and man-made objects within the landscape. The user can visualise, analyse, simulate, and cost land management options including building dams, digging drains, fencing, choosing crops, re-vegetating, and applying pesticide etc. Market and climate forecasts can be input to allow managers of natural resources (farmers, agencies, developers, financiers) to explore what-if scenarios and arrive at decisions that optimise both the profitability of the enterprise and sustainability of the resource. The DSS matrix can be edited to allow for weighting of preferred outcomes. The background software “engines” include a standard games engine linked to biophysical simulation models, cost-benefit analysis software, a multi-objective decision support tool, and market and climate historical and forecast data. Outputs include standard environmental, financial statement, and social decision outcomes.

Use of Historical Data as a Decision Support Tool in Watershed Management: A Case Study of the Upper Nilwala Basin in Sri Lanka (Elkaduwa, W.K.B; Sakthivadivel, R.,1999) Watershed analysis provides a framework for ecosystem management, which is currently the best option for conservation and management of natural resources. The water cycle regulates and reflects the natural variability of the physical processes which impact on ecosystems. Considering the constraints associated with presently available techniques for evaluating land use impacts on the water cycle, such as paired catchment method and modelling, this study provides an alternative approach to ascertain the actual changes in hydrologic response of a particular watershed to land use transformations made in the past. In this alternative rapid approach, long-term historical time series data on stream-flow, rainfall, and land use are analyzed to discern changes in hydrologic effects. Landscape-level history, conditions, and response potential are also used as a guide to identify appropriate land use management options depending on the degree of variation in hydrologic response of the watershed compared to that of the stable conditions, which existed with a substantial forest cover in the past. The model was developed using the data for Nilwala watershed in the southern Sri Lanka. Using the model, suitable land use management practices for agricultural land uses were identified mainly based on their ability to mimic the forest ecosystems.

Reservoir management decision support (Palomo, J.; Rios Insua, D.; Salewicz, K. A., 2002) We describe our work in developing decision support tools to manage large international rivers. This is a complex environmental decision making problem due to the presence of multiple objectives stemming from multiple uses of the reservoirs (energy production, irrigation, flood protection, ...), several sources of uncertainty (inflows, water demand, evaporation, ...), long-term effects of decisions, ...In comparison with other methodologies applied to solve operational problems, decision analysis has provided effective means to model preferences and beliefs of managers, leading to complex stochastic dynamic programming problems. To solve them, we have introduced novel computational strategies. The practical success of our approach stimulated us to develop BayRes, an interactive and integrated Decision Support System for solving operational control problems for reservoir management. Recent improvements in BayRes will be also discussed.

MSU Crop irrigation decision support system, CIDSS
(Ritchie, J; Baer, B.; Dunham, D.) The MSU Crop Irrigation Decision Support System (CIDSS) was developed at Michigan State University. CIDSS predicts soil water based on both observed and predicted soil and weather data. CIDSS was designed to be simple and fast for real-world use.

MODSIM-DSS is a generalized river basin Decision Support System and network flow model developed at Colorado State University designed specifically to meet the growing demands and pressures on river basin managers today (http://modsim.engr.colostate.edu/)

Rapid growth in population centres and mounting needs for irrigation have dramatically increased the need to expand sources of reliable water supply and increase hydropower energy production, while attending to environmental and ecological issues. To further complicate the issue, publicly owned water systems must often deal with severe restrictions from complex legal agreements, contracts, federal regulations, interstate compacts, and pressures from various special interest groups. Optimal coordination of these many facets of river basin systems requires the assistance of computer modelling tools to provide information upon which to base rational management decisions.
MODSIM-DSS was designed for this highly complex and constantly evolving river basin management environment.

MODSIM-DSS has been linked with stream-aquifer models for analysis of the conjunctive use of groundwater and surface water resources, as well as water quality simulation models for assessing the effectiveness of pollution control strategies. MODSIM-DSS can also be used with geographic information systems for managing the intensive spatial data base requirements of river basin management. MODSIM-DSS is structured as a decision support system, with a graphical user interface (GUI) allowing users to create any river basin system topology by simply clicking on various icons and placing system objects in any desired configuration on the display. Data structures embodied in each model object are controlled by a data base management system, which is also queried by simple mouse activation. Formatted data files are prepared interactively and a highly efficient network flow optimization model is automatically executed from the interface without requiring any direct intervention by the user. Results of the network optimization are presented in useful graphical plots.

Red River Basin Decision Support System (RRBDSS) (Simonovic 1998) The International Joint Commission Red River Task Force has recommended the development of a Red River Basin Decision Support System (RRBDSS). The purpose of the RRBDSS is to provide tools for supporting the decision making process of selected flood management activities. Workshops by the IJC and GDIN have investigated the needs and potential applications for users throughout the Red River Basin (SAIC 1999). As a result, a number of target uses have been identified (IJC 1998, Deutschman and Bender 1999a 1999b):

- Flood forecasting and early warning
- Monitoring and managing a flood event
- Post-flood restoration
- Flood damage mitigation
- Emergency response
- Coordination and communication
- Basin management planning

- Flood risk assessment
- Flood proofing
- Conceptual planning and remediation of flood control measures
- Hydrology of small watersheds
- Real-time reservoir operation
- Real-time status of ice and debris jams

The Project Design Team (PDT) and Project Review Team (PRT) recently re-prioritized the development of tools in a table for the RRBDIN. A requirements document describing how the table will be implemented is under preparation. These tools are primarily focused on providing engineers and scientists data and information necessary for common applications and analysis.

Syr Darya River Basin: Since the break-up of the Soviet Union, deterioration of water regulating structures, migration of trained personnel, and reduced capacity for information management has damaged the effectiveness of the water control and allocation systems for the Aral Sea basin. Central Asias Syr Darya River Basin in particular faces a multitude of water policy, management, and technical challenges. The upper basin of the Syr Darya River lies mostly in Kyrgyzstan, from where the river flows through Tajikistan and Uzbekistan into the lower basin in Kazakhstan, and then into the Aral Sea. Distribution of water between the countries in the Syr Darya River Basin is determined by international agreement where, in practice, the basin demands are largely carried over from year to year based on historic water requirements computed during the Soviet era.

USAID is funding project to design a Decision Support System (DSS) to improve the capacity for planning, controlling, and allocating water resources in the Syr Darya River Basin. Due to a lack of reliable and verifiable water data, there is considerable disagreement among the republics along the river basin regarding water distribution efficiencies and on-farm water requirements. The DSS will improve flow measurement and control, and will contain information for the riparian countries along the basin that will reduce the potential for water allocation conflicts.

The DSS is being developed by RTis hydrologists and DSS specialists with a team of local specialists. The fundamental design for the DSS includes an attribute database encompassing the entire Syr Darya River Basin that interfaces with a water resource allocation model. There is also an interface to a Geographical Information System component for presentation of model results.

From theory to practice: Implementation considerations

To quote from the NOSTRUM-DSS project description:

> *In theory, Decision Support System (DSS) should have an enormous potential as tools for the identification of optimal water resource management regimes in the Mediterranean basin, where water resource scarcity could prove a contributing factor to conflict and instability. DSS tools can help to design management strategies which are flexible enough to accommodate changing political and socio-economic situations as well as technological innovations, but, at the same time, strict enough to ensure the ecological sustainability of water uses. Yet, DSS' potentiality is too often not exploited because of various reasons, first of all a lack of interaction between policy makers and researchers: on the one hand, researchers are often not responsive to the needs of stakeholders and policy makers; on the other hand, policy makers have a tendency not to use scientific information for the formulation of water resources management policies. In addition, water planning is traditionally understood within a centralised framework, which focuses on engineering solutions: the current attempt to move towards participatory planning for water resources can significantly be improved by the adoption of suitably designed DSS tools, which take into consideration the interests, needs and objectives of all relevant stakeholders.*

However, the analysis of existing initiatives and operational systems clearly indicates that the potential of DSS notwithstanding, its practical application falls well below expectation, at least by scientists and developers. More succinctly, there are no well known examples of operational DSS use for integrated water resources management. Most descriptions refer to development rather than application, and even development is usually described in future terms.

This section discusses a few implementation considerations that seek answers to this apparent discrepancy. These revolve around

- The intended application framework, integrated water resources management and the implied target audience and users and their need for DSS in practical policy and decision making processes;
- The relationship between the scientific and somewhat theoretical aspiration of decision theory versus the practice of governance, planning, and management of natural resources and its unavoidable shortcuts;
- The institutional framework and requirements for the practical use of participatory decision support system.

IWRM and DSS revisited

Integrated water resources management is an attractive but largely academic idea: there are hardly any real world cases yet. One of the earliest examples maybe the TVA (Tennessee Valley Authority, see www.tva.gov) initiated as part of Roosevelt's New Deal in the 1930s, which aimed at integrating regional planning, cultural and socio-economic development and the environment and water resources management in a common framework. This was later in the 1970s and 80s a fabled case study of applied systems analysis growing out of attempts to apply the logistics lessons learned in WWII to civilian projects. More typically, this was attempted in the then USSR by GOSPLAN, the almighty state planning bureau, in large river development and diversion projects, e.g., in Siberia.

The main problem is the lack of institutional structures like TVA that match the broad scope and aspirations of integrated management. The appropriate institutions simply do not yet exist. And where they are being created (or renamed) within the framework of the EU Water Framework Directive (60/2000/EC), as basin commissions or authorities, they often suffer the same fate as environmental ministries did in the 70s and 80s as latecomers to a system that had all important power structures already well defined and allocated, i.e., they ended up without real political power, clout, and influence.

Reliance on market mechanism also largely fails, as there simply are not enough and effective mechanisms to include all aspects of a truly integrated management, starting with a real market for water itself. Different users like agriculture, industry, and cities still are consuming water under very different price structures, despite the fact that the water comes from shared sources. User pay for the provision of water, not the water itself, i.e., the opportunity costs. Another problem is to reconcile short term gains and long-term costs in additional to other externalities

So the main requirement to make integrated water resources management a reality is to build and empower the necessary **institutional structures** within our overall system of governance.

Information requirements: who needs a DSS

The idea of decision support systems is no doubt attractive from a rationalist point of view. And in domains that do operate predominantly on rational principles, they work. Scheduling, routing, even the autopilot are example of vastly successful but very narrow control or decision support systems. An example in the water domain would be simple reservoir management for a singular purpose like power generation or irrigation scheduling.

As soon however as we enter to domain of politics, rational argument gets a backseat. We have to deal with multiple and conflicting criteria and perceptions, expectations and objectives, in fact plural rationalities and hidden agenda, which hardly needs elaboration. The role of a politician or the mythical decision maker is to make decisions that can not be made on (naïve) rational grounds. Else, we would use computers to much better effects and at lower costs.

A good decision makers doe not need a system that helps him make decisions: he or she needs a system that **justifies the decisions**. Of course, as soon as technical and physically based systems are involved, some basic constraints have to be met: dams should not break immediately, but if they silt up beyond a legislative period, it is less of a problem (*exempla sunt*). The current thinking is that while a DSS should be relevant for policy making, we do not aim at politicians as decision makers but decision making processes that involve as many actors or stakeholders, empowered by shared reliable information and driven by noble motives. Nice idea. However, it only compounds the problem by multiplying it, thus further muddying the water, sometimes literally.

So for any DSS, the primary consideration is: **cui bono**. Openness will help to salve the designer consciences, but I believe it is important to realize that there is simply no such thing as a non-partisan objective DSS.

The subjective element

The goal of any DSS development is or should be to truly integrate it into institutional processes for routine use**.** Being used may be the one and only measure of success. But such a process of institutional integration and thus change and learning takes many years, and is very rare.

Most operational systems depend on an individual, a **champion**. As soon as he or she retires, the system slowly (or sometime very swiftly) dies. A champion is a person that has something to gain from introducing a DSS, which is usually rather remote from its apparent and primary function. To be effective, a champion must be high enough in the institutional hierarchy to have the power and portfolio to decide on the investment of implementing a DSS; and she must be low enough (usually young enough) to understand the underlying technology sufficiently to not be scared by it and see the potential for gaining power.

DSS changes the power structures in institutions, as it purports to dissociate decision making authority from individuals, or threaten to shift it within the institution, and if only by providing a mechanism to question and double check any decisions and make open justification a standard requirement. This, however, runs contrary to a main feature of institutional logic, which is to exert and maintain control. So only an individual powerful and eager enough can implement and nurture a DSS against laws of institutional inertia and thermodynamics.

At the same time, it is important to understand and accept that a DSS does not and can not represent some objective reality. It is the product of people and used by people, and thus at least in part, subjective. The reality it reflects is, in some sense also a social construct. One can assure compliance with basic laws of nature such as the conservation laws underlying any water resources model and first order logic as a basic principle of structured discourse. But the semantics of its interpretation are subject to interpersonal agreement rather than any law of nature or objective reality.

Uncertainty and precision

Like any other formal, simplifying and thus model based method, DS suffer from uncertainty and error in data, procedures, and interpretation. On the other hand, numerical representation require or at least suggest a certain (and often staggering if not amusing) level of precision where common sense will do, necessarily. This is not only true for DSS, but for models in general, but then models can be viewed as one subclass and essential component of any DSS. While the statement must be anathema to any neo-positivist, it is easily argued: Any DSS is a model of sorts, and thus due to the necessary simplifications, as well data errors and sheer ignorance, subject to considerable uncertainties. The ranges of uncertainty can be astounding, just take a minute to think HOW we measure something as basic as rainfall or runoff, where we can very easily reach errors up to 20 or 30% around a mean estimate. Water quality is even more complex, uncertainties much larger, and usually ignored for simple reasons of practicality and cost. What it usually leads to is that apparent precision of the empirical basis by far outstrips the robustness of many decisions, which could also be understood as an argument for deductive rather than inductive reasoning in a DSS. Unfortunately, this is also a nice theory only.

What is important in a DSS is to make the participants in the decision process at any level start to **think in a structured way** about the problem. What is important is the formulation of good questions (that, we assume naively, if answered correctly would make the decision to take immediately obvious).

A good DSS provides a **common language,** by making basic elements of the decision making process more explicit: **criteria, objectives, constraints**. Once they are defined and agreed upon, the **mechanisms of trade-off and compromise** should become more obvious, even if any “optimal” solution may be as elusive as ever. It is important to realize (assuming we operate in a democratic society under the rule of law which is not necessarily self evident) that the mechanism to arrive at a decision may be more important than the actual outcome: we will never know whether what has been chosen was indeed the best possible solution, as we can not run parallel blind test like in

medical research (or any good laboratory science). Therefore, we must ensure that we collectively (or at least as a majority) take the responsibility for any decision taken, whatever the outcome. This shared responsibility and consensus is a very basic requirement of our social fabric:
A good DSS contributes to **shared responsibility**.

Choice between alternatives

Eventually, any decision boils down to a choice between alternatives. A DSS is designed to make the choice process more open, rational, free of contradictions, eliminate or at least indicate dominated alternatives, make trade-off obvious and thus negotiable, etc. This most critical role however, must be to offer a sufficiently rich set of alternatives to chose from: only if the set is large enough, we can expect it to include some sufficiently good and desirable alternatives. A too small set leads to Hobson's choice, even by setting up some straw-men to artificially increase the repertoire.

A good DSS makes it easy to **design and generate** alternatives. The bigger the set of alternatives to choose from is, the larger is the probability that a generally acceptable solution will be included in the set.

Participatory approaches

To quote from the Dublin Statement: „Water Development and Management should be based on a Participatory Approach..."

1. Legislation relating to this principle was analysed under the assumption that water related activities are not confined to the interests of limited groups of users, geographical boundaries, sectoral institutions, or national jurisdictions. Participation, (and venues and opportunities thereof), was the criterion informing the analysis.
2. Generally, meaningful participation is associated to well defined national policies for which water is either a main component or a relevant input. Policy implementation is usually associated with socially acknowledged, relatively well informed, government organisations with adequate capabilities and appropriate legal mandates. These institutions have evolved from sector oriented to resource oriented, with strong indications that the concept of the river basin is steadily, albeit laboriously, coming into the institutional scene.
3. The review of experiences strongly suggest that the institutional dimension of water management is a system, where relatively successful water management experiences (success in this context is contingent to what a system knew and sought at specific times) have included a balance of government institutions and policies and stakeholders participation.

4. Such experiences, drawing from places as far apart as California and South Africa, indicate that meaningful stakeholder participation requires, at the least, a certain degree of government overseeing, and, occasionally, support. Such support may consist of promotion and encouragement of involvement and dissemination of information. Otherwise there is an ever present risk of participation becoming co-opted by well informed, intent-specific, special interests groups.
5. Conciliation of interests, public consultations, and hearings are some of the manners in which interested parties and stakeholders, not necessarily having a conventional (in the typical sense) proprietary interest in water, are able to participate. More formal structures include advisory boards, integration within government bodies and associations and districts with field goals and responsibilities.
6. Interestingly, some legislations acknowledge the global scope of water issues and acknowledge trans-national interests through references to international treaties and obligations.
7. Some laws recognise the intimate connection existing between participation and information at all levels.
8. Some systems, where agricultural and other subsidies have traditionally coexisted with relatively strong participation, seem to indicate that a main, although not necessarily exclusive, prompt to participate is economic self-interest.
9. Finally, on account of Mexican experiences, it seems relevant to notice that technical needs, opportunities for economies of scale and scope, and other factors need to be taken into account when applying the concept of the lowest appropriate level. Also, the lowest appropriate level and the private sector are not synonymous: water corporations purveying water services are private, but many are global.

Irrespective of participatory approaches compounding any of the problems that DSS have even *in camera*, the idea of wide participation is appealing. This, however, requires that a DSS is primarily a vehicle for communication, as the substance related background of many participants, actors, and stakeholders will differ widely.

Therefore, a good DSS is graphical (in a wide sense), easy to understand, and intuitive. It is a tool for education and empowerment by information as much as a tool to structure decision processes. It first and foremost must provide a common language, easy to understand and use, to enable the **dialog** of give and take that is central to any compromise solution.

Professional responsibility

It is easy to cheat with a DSS. Complexity and uncertainties make it very difficult to identify bias, introduced on purpose or unwittingly, starting with the selection of alternatives provided or the rules and mechanisms to generate them.

Therefore, the only recourse when at the same time aiming at broad participation (and thus necessarily an - at least partly - lay audience *vis a vis* at least some of the technical aspects of the decision problem) is to enforce professional responsibility of the developer or moderator that supplies a DSS or facilitates it use. An excellent strategy to keep everybody honest is to ensure the use of simple, generally understandable language and easy to understand, intuitive imagery.

Multi-attribute theory: multiple objectives and criteria

Any non-trivial real-world decision problem involves multiple criteria that describe the alternatives, and are used to express constraints and objectives, and usually also multiple, and often conflicting objectives.

Consider a simple abstraction (based on the introduction to “Conflicting Objectives in Decisions” by Bell, Keeney and Raiffa (1978):
A decision involves the choice between alternatives A_1 … A_n; These are described by a set of attributes X_1,…, X_j ,…, X_n, and each alternative A_i can be described in terms of these attributes or criteria. Thus choice or alternative A_i can be described with the attribute vector $X_i = (x_{i1}, \ldots, x_{ij}, \ldots x_{in})$.

The attribute set X is not given *a priori.* Its selection and definition is one of the most critical steps in the decision making process. It can easily be demonstrated that adding or deleting criteria from consideration is a very powerful way to influence decisions. Once the vector is defined, the task is to measure the distance, in some sense, of each alternative (a point in this criteria hyperspace) to the decision maker’s expectations or aspirations – this involves the problem of scaling incommensurate dimensions.

The primary concern is to make sure the criteria are relevant, that is they describe aspects of the decision problem that are indeed meaningful and relevant to all stakeholders and actors. This invariable will lead to the fact that are incommensurable, i.e. they have very different units that can not be readily converted. The criteria will also include intangibles that are not amenable to direct measurement but may reflect psychological or aesthetic considerations, believes, fears, perceptions which are extremely difficult to measure or elicit and scale. The problem of environmental valuation, but also the cost or the value of human life are typical, and usually controversial examples.

Water resources management decisions may have a considerable life time. Their consequences evolve over time. Beyond introducing uncertainties about future boundary conditions (for example, energy prices) this leads to considerations of intergenerational effects or trade-offs. Requirements for long-term equity and sustainability will an additional dimension.

Goal programming and the satisficing paradigm

Reference point approaches might be seen as a generalization of goal programming. They were developed later than goal programming, starting with research done at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg near Vienna, Austria, specifically as a tool of environmental model analysis, although these approaches have found applications also in engineering design and other fields of decision support since that time. In parallel, similar or equivalent approaches were developed, e.g. the weighted Chebyshev1 procedure by Steuer and Cho (1983) or the satisficing trade-off Method by Nakayama and Sawaragi (1983). Later, Korhonen and Laakso (1985) drawn the attention to the fact that reference point methods can be considered as generalized goal programming. This generalization tries to preserve main advantages of goal programming and to overcome its basic disadvantage.

The main advantages of goal programming are related to the psychologically appealing idea that we should set a goal in objective space and try to come close to it. Coming close to a goal suggests minimizing a distance measure between an attainable objective vector (decision outcome) and the goal vector. The basic disadvantage relates to the fact that this idea is mathematically inconsistent with the concept of vector-optimality or efficiency. One of basic requirements { a general sufficient condition for efficiency { for a function to produce a vector-optimal outcome (when minimized or maximized) is an appropriate monotonicity of this function. But any norm, representing the concept of a distance measure, is obviously not monotone when its argument crosses zero. Therefore, norm minimization cannot, without additional assumptions, provide vector-optimal or efficient solutions.

According to Simon, real decision makers do not optimize their utility when making decisions, for many reasons. Simon postulated that actual decision makers, through learning, adaptively develop aspiration levels for various important outcomes of their decisions. Then they seek decisions that would result either:

- In outcomes as close as possible to the aspiration levels, if the latter are not attainable (which corresponds to an optimization of decisions, but in the sense of the distance from aspiration levels);
- In outcomes equal to aspiration levels, if the latter are attainable (which corresponds to stopping improvements in this case).

We see that satisficing decision making can be in fact mathematically represented by goal programming. Thus, reference point optimization is a generalization of the goal programming approach to such cases when we can and want to improve (minimize or maximize) certain outcomes beyond their reference points, which is a commonly observed behaviour in negotiation situations.

Discrete multi-criteria methods

Since each scenario is described by more than one performance variable or criterion, the direct comparison does not necessarily result in a clear ranking structure: improvements in some criteria may be offset by deterioration in others. This can only be resolved (and resulting in an eventual ranking and selection) through the introduction of a preference structure that defines the trade-offs between objectives.

The basic optimization problem can be formulates as:

$$\min F(x),\ x \in X_0$$

where

$$x = (x_1, x_2, \ldots\ldots, x_n)\ ;\ x \in R^n$$

is the vector of decision variables (the scenario parameters), and

$$f(x) = (f_1(x), f_2(x), \ldots, f_p(x)) \in R^p$$

defines the objective function. X_0 defines the set of feasible alternatives that satisfy the constraints:

$$X_0 = x \in R^n \ \mathrm{I}\ h_1(x) \leq 0, \ldots, h_k(x) \leq 0$$

In the case of numerous scenarios with multiple criteria, we can define the partial ordering

$$f(x^1) \leq f(x^2) : \leftrightarrow f_i(x^1) \leq f_i(x^2)$$
$$\forall_i = 1,2,\ldots,p f(x^1),\ f(x^2) \in R^p$$

where at least one of the inequalities is strict. A solution for the overall problem is a Pareto-optimal solution:

$$f(\hat{x}) \in R^p \leftrightarrow \exists\ f(\hat{x}) \neq f(\hat{x}) \leq f(\hat{x}) \text{ and } x \in X_0$$

As a generic decision support tool, we can now implement a discrete multi-criteria approach to find an efficient strategy (scenario) that satisfies all the actors and stake holders involved in the water resources management decision processes.

The preferences of decision makers can conveniently be defined in terms of a reference point, that indicates one (arbitrary but preferred) location in the solution space. Normalizing the solution space in terms of achievement or degree of satisfying each of the criteria between nadir and utopia allows us to find the nearest available Pareto solution efficiently by a simple distance calculation.

Since decision and solution space are of relatively high dimensionality, the direct comparison of a larger number of alternatives becomes difficult in cognitive terms. The data sets describing the scenarios can be displayed in simple scattergrams, using a user defined set of criteria for the (normalized) axes. Along these axes, constraints in terms of minimal and maximal acceptable values of the performance variable in question can be set, leading to a screening and reduction of alternatives.

As an implicit reference point, the *utopia point* can be used. Consequently, and unless the user overrides this default by specifying and explicit reference point, the system always has a solution (the feasible alternative nearest to the reference point) that can be indicated and highlighted on the scattergrams and in a listing of named alternatives.

Satisficing revisited

A naïve second look at the satisficing paradigm will yield some suggestions for the implementation of DSS and their use in a participatory decision making process.

We conceptualise the set of alternatives (existing or to be generated) as described by a attribute vector X_i The decision maker now expresses aspirations in terms of these criteria. For each, the requirement expressing aspirations can be to:

1. Minimize or maximize the value of the criterion;
2. Meet a constraint, i.e., a minimal or maximal allowable value.

In the optimization case (1), there are implicit trade-offs between the objectives, expressed in terms of the criteria implied, when we try to improve more than one at a time, conjunctively. Much of the multi-attribute decision theory literature revolves around how to best elicit and implement these relationships, for example as weights on individual criteria expressing relative importance, or as a reference point defining scaling for all of them simultaneously. However, both the procedure and the underlying concepts are somewhat complex, involved, and not easily used other than with a captive audience of students of decision theory..

In the case of expressing aspiration as a set of constraints, the procedure is simple, intuitively understandable, and lends itself well to a participatory approach:

1. An initial set of reasonable constraint values are defined in the natural units of the criteria which makes the procedure easy to understand;
2. A solution or set of solution that meets the criteria is “found” in the set of available alternatives or generated e.g., by simulation modelling;
3. If the set is empty, the constraints are relaxed – the sequence and degree of relaxation are a reflection of the DM’s preferences, but at the same time an

understanding of tradeoffs, possibly the results of a negotiation process between several decision makers with conflicting objectives;

4. If the set includes more than one solution, the constraints can be tightened in the same interactive and iterative procedure as above, but in the opposite direction.
5. The procedure ends whenever the decision makers are satisfied.

From a game theoretical point of view (e.g., Gibbons 1997), step (3) is where the transition from a perceived zero-sum game or a version of the prisoners dilemma with dominant strategies with a possibly suboptimal equilibrium to a cooperative game should be introduced. In terms of water use, while allocation for consumptive use may indeed be understood as a zero sum game, total extractions are not. The possibility for recycling and re-use of water clearly shows the potential for a cooperative game approach.

The idea of a cooperative game approach, however, requires the introduction of the appropriate coordination and in fact, exchange mechanisms: without the possibility to trade water in some sense so that the overall benefits of use can be increased together with individual user benefits, this is difficult if not impossible to implement.

This simply requires the institutional structures or market mechanisms to make this level of cooperation and coordination, i.e., truly integrated water resources management, possible.

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