DECISION SUPPORT SYSTEMS FOR ENVIRONMENTAL PROBLEMS AT DIFFERENT SCALES

Marek Makowski
International Institute for Applied Systems Analysis, Laxenburg, A-2361 Austria

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Summary

The article presents three Decision Support Systems (DSS) applied to complex problems of natural environment management of different scale, namely regional water quality management, land use planning, and European air quality management. These

problems are not only of different scale but the way the described DSSs are used are also very different.

Nevertheless, these three applications have a number a common characteristics as regards the applied methodological background of multi-objective decision support and its application to environmental decision-making problems described in article Multi-objective Decision Support Including Sensitivity Analysis. This chapter provides insights into these problems which might be interesting to specialists working in the respective fields. It also illustrates various problems related to the development and use of DSSs, which are interesting for both users and developers of DSSs.

1. Introduction

There is a vast diversity of natural environment problems that need to be analyzed for providing sensible help in better understanding these problems and in identification and/or examination of various actions that can result in desired effects. These problems have different characteristics in several dimensions:

- The type of the problem (its nature, scale, required accuracy, time horizon)
- The nature of the decision process
- The needs for the decision support

Every DSS, even for the same type of problem, needs to be different, in order to correspond well to the needs of the corresponding decision making process. For example, DSSs for a very specific problem of controlling a system of water reservoirs are using very different models, each of them being relevant to a particular water system and the requirement analysis for the corresponding DSS.

Given such a diversity of problems and the corresponding DSSs, it is not possible to even summarize a representative sample of decision support systems for environmental problems in an article. Moreover, short summaries of DSSs would neither be useful for users nor for developers of DSSs. Therefore, this article instead of an oversimplified summary of DSSs presents three DSSs that have been developed for complex environmental problems of different scale. Enough detail of each DSS is provided to illustrate several key issues that are relevant to decision support of any complex problem.

The truth is that there are no simple ways of rationally solving any complex problem (article 4.20.4.1 provides arguments for this statement). Unfortunately, there are many books and software tools that advertise simple approaches applicable to almost any decision problem. The role of this article is to illustrate the complexity of the development and use of DSSs, which is needed for understanding the possibilities and limitations of model-based decision support by both users and developers of DSSs.

A real understanding of these issues requires a more detailed presentation of each problem and the corresponding DSS, and a discussion of several key issues that are of a more general interest for users and developers of DSSs, and are relevant to various (also very different) decision problems.

The three problems and corresponding DSS presented in this article are:

- RWQM, Regional Water Quality Management, applied to the Nitra River basin in Slovakia
- AEZWIN, Land Use Planning DSS, being applied in several countries in Africa and Asia
- RAINS, system of models used for analysis of cost-effective policies aimed at improving European air quality that is used for supporting intergovernmental negotiations in Europe

RWQM uses a rather small and simple MIP type model, but it shows how the classical water quality modeling approaches had to be modified in order to provide the needed support for regional water quality management. AEZWIN uses large-scale LP type models that are composed by users based on a sophisticated system of programs developed for various elements of land use planning. An interesting common feature of RWQM and AEZWIN is that both of them have the same DSS structure, and use common modular software tools.

The third DSS, RAINS, uses a complex NLP model, and its implementation and use demonstrate several methodological and technical issues that are relevant to any DSS aimed at rationally supporting decision analysis and support for complex environmental problems.

2. Regional Water Quality Management

2.1. The Problem

The scope of the problem considered here is a river basin, or a region composed of several basins, in which untreated or inadequately treated municipal and industrial wastewater emissions should be reduced in order to improve ambient water quality. At each discharge point, one technology out of a set of possible technologies can be implemented in order to meet the desired water quality goals in the region. In this selection of technologies, or strategy development, decision makers must evaluate the trade-offs among a large number of alternatives based on, among other things, effluent and/or ambient water quality standards and goals; capital investment and annual operating costs; and the principles of equity, uniformity, and efficiency.

The traditional approach, as used in developed countries, is based on the selection of generally uniform effluent standards which, in turn, are often based on given technologies. This is the well-known policy of ``best available technology''. Under such an approach, both ambient water quality standards and budget requirements are considered only indirectly. The following two conditions must be met:

- If effluent standards are defined stringently enough, then ambient water quality will be ``good enough''.
- Enough money (or willingness to pay) is available to achieve ``safe'' environmental conditions (without raising the issues of how safe they are and how much should be paid for them).

Unfortunately, such a robust and uniform policy may not be an affordable option for countries and or regions with tight financial resources, for which there is a competition of various social needs (like health-care, restructuring of economy, securing pension-system). In such cases various trade-offs between investment and operating costs on one side and the resulting water quality have to be examined.

2.2. Model Formulation

The model outlined here has been developed for the Nitra River Basin in Slovakia. The river water quality model applied to this case study is quite simple but it was adequate for this application. It is based on the concept of linear transfer coefficients, which are derived from first-order rate equations and the (linear) extended Streeter-Phelps model incorporating dissolved oxygen (DO), carbonaceous oxygen demand, and nitrogenous oxygen demand. Steady-state hydraulics are considered, based on a ``critical design flow''. Complete mixing downstream of each emission and tributary confluence and uniform flow along the river between these points are assumed.

For the Nitra River basin a set of locations or points is defined, each of which is characterized by at least one of the following:

- An emission point, at which wastewater is discharged; the amount of discharged pollutants depends on the treatment technology chosen in the decision process
- An abstraction point, at which water is withdrawn from the river; at these points one can consider a ``negative'' emission, whereby the constituent loads are reduced proportionally to the reduction in river flow.
- A monitoring point, at which concentrations of water quality constituents are compared to given standards
- A confluence point, which represents the junction of two rivers; constituent loads are the sum of loads from both rivers.
- A weir point, where DO is added to the river due to the increase in turbulence downstream of a weir or small dam.
- Other points where hydraulic and hydrologic data exist and therefore new travel times and transfer coefficients can be calculated; the loads of constituents do not change at these points.

Each of these points is called a node, denoted by the subscript j. At every node the equations that define water quality (i.e., mass balances of constituents) are given. Overall, four water quality constituents (of which three are real state variables) are considered. In the equations the subscript l is used to denote the respective constituents:

1. DO (dissolved oxygen)
2. CBOD (carbonaceous biochemical oxygen demand)
3. NBOD (nitrogenous biochemical oxygen demand), which is calculated directly from NH_4, assuming that all of the nitrogen consumes oxygen
4. NH_4 (ammonia).

The decision variables are the treatment technologies to be implemented at the nodes where wastewater emissions occur. These are denoted by x_{jn}, where n is the technology choice at emission node *j*. These technology options include the option of no treatment (with raw waste concentrations and no cost), as well as the option of maintaining the existing technology (with the operating cost, but no investment cost). Only one technology can be implemented at each node, and this logical condition is represented by the following constraint:

$$\sum_{n \in N(j)} x_{jn} = 1 \qquad x_{jn} \in (0,1) \;\; i \in E \tag{1}$$

where $N(j)$ is the set of technologies considered for emission node *j*, and *E* is the set of nodes where emissions occur.

Auxiliary variables (defined for easier handling of the model and interpreting results from its analysis) in the model include variables related to water quality and variables related to cost.

Focusing on the first set, we consider the water quality constituent concentrations resulting from the implementation of the *n*-th technology at the *j*-th emission node, em_{jnl} (mg/l).

The emission load of the *l*-th constituent at the *j*-th node
is denoted by e_{jl} (g/s) and is defined by:

$$e_{jl} = q_j \sum_{n \in N(j)} x_{jn} em_{jnl} \quad l \in (1,3) \tag{2}$$

where q_j (m^3/s) is the waste flow rate. Note that due to equation (2), for each *j* exactly one out of $N(j)$ binary variables, x_{jn}, will be equal to one while the others will be equal to zero.

Next, the ambient constituent concentrations must be defined. The ambient concentration of DO (mg/l), typically the most important water quality indicator, is affected by several constituents, as well as by its saturation level. The DO concentration (denoted for the *j*-th node by aq_{j0}) is given by the extended Streeter-Phelps model, analytically integrated step by step as follows:

$$\begin{aligned} aq_{j0} = \quad & [1/(Q_j + W_j)] * \left(\sum_{i \in I(j)} \Big(b_{i0} + Q_i * \Big(DOsat_j - \right. \\ & \left. - TC_{i0} \left(DOsat_i - aq_{i0} \right) - \sum_{l \in \{1,2,4\}} TCp_{il}\, aq_{il} \Big) \Big) + ioxy_j \right) \end{aligned} \tag{3}$$

In this, the set $I(j)$ is composed of indices of nodes located immediately upstream of the *j*-th node (this set contains two elements for confluence nodes and one element otherwise), aq_{il} (mg/l) are the upstream concentrations of oxygen-demanding constituents (CBOD, NBOD, SOD), and the remaining right-hand side quantities are given (or computed from given data):

$DOsat_j$ (mg/l) is DO saturation level at the j-th node, TC_{i0} is a dimensionless transfer coefficient for the DO deficit (defined as $DOsat_j$ - aq_{i0}), TCp_{il} are dimensionless transfer coefficients for CBOD, NBOD, and SOD, respectively; Q_j (m^3/s) is the river flow just below node j, W_j (m^3/s) is the withdrawal occurring at the j-th node, b_{i0} (g/s) is the background level of DO entering the river upstream of node j, and $ioxy_j$ (g/s) is the DO emission at node j. Thus, the summation term represents the DO coming from upstream, which consists of oxygen transfer from the upstream node(s) as well as ``background'' oxygen from groundwater infiltration flow (for simplicity, we assume that background loads of other constituents do not affect DO until the next reach downstream). This upstream mass is then mixed with the DO load from the wastewater emission, $ioxy_j$, hence the division by the total flow Q_j+W_j. Calculation of the transfer coefficients has been done on the basis of the Streeter-Phelps equations (exponential terms expressing transformations due to decay and re-aeration over the travel time).

Ambient concentrations of the other constituents such as CBOD and NBOD (denoted by aq_{jl}) are defined by:

$$aq_{jl} = \left(\sum_{i \in I(j)} \left(b_{il} + TC_{il} aq_{il} Q_i \right) + e_{jl} \right) / \left(Q_j + W_j \right) \quad l \in \{1,3\} \tag{4}$$

where, as in equation (3), the first term in this equation represents the background load of constituent l which accounts for nonpoint or noncontrollable source pollution, the second term represents the load of the constituent l arriving from the upstream reach(es), and the third term represents the emission load of constituent l at node j. Cross-impact transfer coefficients, TCp_{il}, are not included here since these constituents are not affected by the DO level unless anoxic conditions exist.

Based on these ambient constituent concentrations, the following three indices of water quality are defined:

$$DO = \min_{j \in M} \left(aq_{j0} \right) \tag{5}$$

$$BOD = \max_{j \in M} \left(aq_{j1} \right) \tag{6}$$

$$NH_4 = \max_{j \in M} \left(aq_{j3} \right) \tag{7}$$

where aq_{jl} (defined by (3) or (4)) is the ambient concentration of the l-th constituent at node j, and set M contains indices of monitoring nodes.

Finally, several cost variables are defined in the model. Corresponding to the n-th treatment technology implemented at the j-th node are an investment cost IC_{jn} and an operation and maintenance cost OMC_{jn}. The investment costs Inv_j for the j-th emission point are defined by:

$$Inv_j = \sum_{n \in N(j)} x_{jn} IC_{jn} \qquad j \in E. \tag{8}$$

The operation and maintenance costs OM_j are given by:

$$OM_j = \sum_{n \in N(j)} x_{jn} OMC_{jn} \qquad j \in E. \tag{9}$$

The total annual cost (TAC) of each technology is determined from the two previous cost components as:

$$TAC_j = \left[r\left(r+1\right)^m / \left(\left(r+1\right)^m - 1\right) \right] Inv_j + OM_j \qquad j \in E, \tag{10}$$

where r is a given discount rate, m is a given capital recovery period, and the multiplier of the first term is called the uniform series capital recovery factor. One may also want to consider the sums of respective costs for the whole region:

$$Tot\_Inv = \sum_{j \in E} Inv_j, \tag{11}$$

$$Tot\_OM = \sum_{j \in E} OM_j, \tag{12}$$

$$Tot\_TAC = \sum_{j \in E} TAC_j, \tag{13}$$

The treatment alternatives at various MWWTPs, along with the corresponding effluent concentrations and costs, have been designed in separate field studies for each MWWTP. Each alternative was developed on the basis of technological calculations using physical, biological, and chemical processes, as well as their combination. These lead to well-known methods such as mechanical—biological treatment with or without denitrification, mechanical--biological treatment with chemical addition to remove phosphorus and/or to increase the capacity of the plant, biological--chemical treatment with denitrification, and so forth. The alternatives identified also depend on whether upgrading an existing facility or constructing a new plant is considered a viable option.

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in which model-based decision support can help the modern decision making process; it presents the methodology and software tools for building mathematical models and for their multicriteria analysis; the presented methods and tools are illustrated by detailed presentation of four complex environmental applications, including the three models outlined in this article.]

Biographical Sketch

Marek Makowski graduated in 1970 from the Faculty of Electronics of the Warsaw University of Technology in the field of automatic control and computer sciences. He had also studied mathematics at the Warsaw University. In 1970 he joined SRI (the Systems Research Institute of the Polish Academy of Sciences). He received Ph.D. in 1976 from the Polish Academy of Sciences for the thesis on the optimization of environmental models. Before joining IIASA in 1987 he had been a leader of the project on the development of decision support systems for various applications in Poland, and since 1976 he has been actively participating in joint projects with IIASA. During his affiliation with IIASA he was on leave from the Systems Research Institute of the Polish Academy of Sciences. He joined the Computer Services Department of IIASA in August 1987 to work on the development and application of mathematical programming software. He was Acting Project Leader of the Methodology of Decision Analysis (MDA) Project from September 1989 until August 1991, and since then has been a member of this project. As of January 1997 he continues the activities he has been engaged in within the MDA Project (which terminated at the end of 1996) within the new Risk, Modeling and Policy Project. Dr. Makowski specializes in Control Engineering, Computer Science and Applied Mathematics. His current research interests include applications of mathematical programming methods and of relevant user interfaces in decision support systems, the development of methodology, algorithms, and software for decision support using multicriteria optimization.