Towards Environmental Decision Support Systems

Ulises Cortés[1], Miquel Sànchez-Marrè[1], Ignasi R-Roda[2] and Manel Poch[2]

[1]Secció d'Intel·ligència Artificial. Dept. de Llenguatges i Sistemes Informàtics. Universitat Politècnica de Catalunya.
Campus Nord-Edifici C5. Jordi Girona 1-3. E-08034 Barcelona. Catalonia, Spain.
{ia,miquel)@lsi.upc.es

[2]Laboratori d'Enginyeria Química i Ambiental. Universitat de Girona
Campus de Montilivi. E-17071 Girona. Catalonia, Spain.
ignasi@lequia1.udg.es

Abstract

This is a position paper willing to fix concepts in the interface between Environmental Issues and Artificial Intelligence. In particular we will focus our attention in a class of systems called Environmental Decision Support Systems (EDSS) that have been under develop in the last 10 years. Hopefully this effort will led to a better interaction between Environmental and Artificial Intelligence scientists.

Artificial Intelligence and Environmental Issues

Artificial Intelligence techniques have been applied to environmental management problems for a long period of time with good results as for example in using expert systems advising emergency response teams about how to deal with industrial accidents (Avouris, 1995c), in using expert systems to assist in granting hazardous waste site permits (Wilson, Mikroudis and Fang, 1986), in modelling water quality (Wright et al, 1993), fish stock prediction (Sazonova and Osipov, 1998), and many other environmental engineering applications (Branting et al, 1997), (Yang and Kao, 1996), (Shepherd and Ortolano, 1996). The first reliable applications of Expert Systems to environmental issues appeared in the 80's. See for example the systems developed by (Guariso and Page, 1989), (Page, 1989), (Hushon87) and (Maeda, 1985).

More recently, Artificial Intelligence research has been oriented towards the development of Knowledge-Based Systems (KBS) applied to Environmental issues as for example (Gabaldón et al, 1998), (Guariso and Werthner, 1994), (Okubo et al, 1994), (Serra et al, 1993).

KBS when applied to Environmental Issues receive different denominations such as *Decision Support Systems* (DSS) (Haagsma and Johanns, 1994), (Bender and Simonovic, 1994) *Environmental Decision Support Systems* (EDSS) (Rizzoli and Young, 1997) or *Multiple Objective Decision Support Systems* (MODSS) (El-Swaify and Yakowitz, 1998) or intelligent assistants (see figure 1). Among those names, we chose to use Environmental Decision Support System as this name clearly represents the common intention of many researchers and the users needs. We define an EDSS as an intelligent information system that ameliorates the time in which decisions can be made as well as the consistency and the quality of the decisions, expressed in characteristic quantities of the field of application (Haagsma and Johanns, 1994).

We see EDSS as ideal decision tools for valid recommendations on land, water, and environmental management must include quantitative and analytical components; must span and integrate the physical, biological, socio-economic, and policy elements of decision making. They must also be user-friendly and directly relevant to client needs (El-Swaify and Yakowitz, 1998).

It is clear that the field of application is central to this point of view. An important feature of EDSS is that they allow the use, manage and capture of specialised knowledge, from a wide spectrum of natural sciences, and that they can be effectively applied to a variety of environmental management and design tasks (Michalski and Rademacher, 1993). This specialised knowledge may include among others: a) empirical knowledge about organisms and their environment; b) situational knowledge about local environmental conditions and its possible relationship with the global environment; c) judgmental knowledge about human beliefs, intentions, desires and priorities; and d) theoretical knowledge about biological, physical and chemical phenomena, etc.

There exists a clear understanding among researchers of both fields -- Artificial Intelligence and Environmental Sciences -- that an EDSS that is able to deal with all these kinds of knowledge can be useful in the environmental management process, which typically consists of four activities in the following order:

- *Hazard identification* involves filtering and screening criteria and reasoning about the activity being considered. This phase may be characterised as a continuous activity of the system looking for possible adverse outcomes and includes the search for further data to enhance its own performance.

- *Risk assessment* involves developing quantitative and qualitative measurements of the target hazard. Environmental Decision Support Systems may include the use of numerical and/or qualitative models, which can produce estimations of the degree of potential hazard. Usually, this phase could be accomplished by a Model-Based System --using a model-based reasoning-- and/or a Knowledge-Based System --using rule-based reasoning-- and/or by a Case-based System --using case-based reasoning—to overcome the heterogeneity of data coming from various sources and with many different levels of precision.
- *Risk evaluation*. Once potential risks have been assessed, it is possible to introduce value judgements regarding the degree of concern about a certain hypothesis. This is possible if the system has accumulated experience solving similar situations using for example a Case-based Reasoning approach, whereby past experience of risk evaluation is used to assist with future judgements.
- *Intervention decision-making* the system needs appropriate methods for controlling or reducing risks. The system also requires knowledge about the context where the activity takes place and must be able to interpret its results and knowledge about the risk/benefits balancing methods.

In this view Hazard Identification is related mostly to data interpretation and data mining. Risk Assessment and Risk Evaluation are related to the problems in the diagnosis phase. Intervention decision-making is related to the decision support techniques.

EDSS play an increasing and important role in helping to reduce the risks resulting from the interaction of human societies and its natural environment. Some of the reasons are as follows:

- The multidisciplinary nature of environmental problems. It implies the co-operation among various elements (modules) of the EDSS, each one specialised in a given topic or a certain kind of model.
- The complexity of environmental problems. In this context, it is often necessary to understand, in limited time, physical and biological processes in relation to socio-economic conditions and applicable legislative frameworks. EDSS may provide fast solutions integrating all those issues.

This interdisciplinary field has attracted the interest of researchers and an increasing of specialised publications and research projects that pay great attention to this blooming area.

Environmental Decision Support Systems

Following the classification proposed by Rizzoli & Young (Rizzoli and Young, 1997), Environmental Decision Support Systems can be divided into two clearly separate categories: problem specific EDSS, and situation and problem specific EDSS. *Problem specific EDSS* are tailored to relatively narrow environmental problems (or domains), but they are applicable to a wide range of different locations (or situations) in the best tradition of KBS.

Situation and problem specific EDSS are tailored both to a specific environmental problem, and to a specific location. These EDSS cannot easily be applied in a new location as many KBS.

In addition, in the same paper, Rizzoli & Young identify a set of desirable features for an ideal EDSS, that are common to any Knowledge-Based System (KBS), and are the following ones:

- The ability to acquire, represent and structure the knowledge in the domain under study.
- The knowledge base (or domain base) must allow the separation of data from models (for model re-usability and prototyping).
- The ability to deal with spatial data (the GIS component).
- The ability to provide expert knowledge specific to the domain of interest.
- The ability to be used effectively for diagnosis, planning, management and optimisation.
- The ability to assist the user during problem formulation and selecting the solution methods.

We also like to add to this list issues related with Security and Distribution. As EDSS grow in importance and acquire more presence in Internet this imposes serious demands on security. This also implies that a bigger group of users may like to have access to the data files and available knowledge, the EDSS has to ensure data concurrency, data consistency, etc.

Our Approach to EDSS

From our point of view actual EDSS can be described as a multi-layered system connecting the user, probably an environmental scientist, with an environmental system or process. See the figure 1 where a chart of an EDSS is depicted.

The first layer is formed of the knowledge acquisition and learning module from various kinds of sensors, spatial (GIS) and/or temporal data base. Several AI, statistical and numerical models constitute the next layer this layer takes care of the data pre-processing. EDSS must be able to cope with data of very broad range of quality as for example: Large Data Volumes, Variable levels of data detail, analytical detail, and data volumes, Unanticipated types of Data, and Data Redundancy.

Let us recall that Information is only of use if it organised and is relevant to the issues at hand. Again, AI techniques prove to be well suited.

Next levels are the reasoning and integration modules that use several kind of models and knowledge to implement a predictive, planning or supervisory task over the environmental system. The expected result of this layer is the choice of a general solution strategy such as: analogy or case-based reasoning to find similar, already solved situations; or the redefinition of the problem (if necessary) using different but known terms. This another of the central contributions of AI to EDSS development.

Finally, in the upper level raises the interaction of the user(s) with the EDSS. The user(s) may query the EDSS for justifications and explanations about suggested decisions, and possibly validating plausible alternatives to make a better decision.

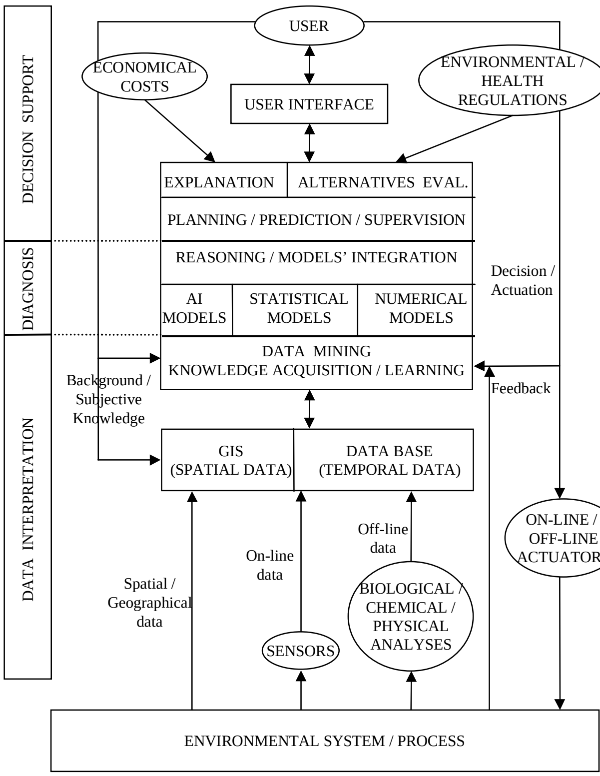

Figure 1: Environmental Decision Support Systems

Development of an EDSS

The development of an EDSS as a complex integrated KBS relies on the idea of model refinement (Steels, 1990). Every stage in the development process involves a relatively straightforward step of transformation from one model to the next. That is from requirements to conceptual model, from conceptual model to design model, and from design model to code. In figure 2, a scheme of the ideal cycle of development of an EDSS is shown.

Of course, during all the cycle of an EDSS development, the co-operation among environmental experts, computer scientists and AI scientists should be needed. In the first step, the environmental problem must be analysed to get a more accurate problem description. From that description, from the environmental process itself and from environmental experts' criteria, an environmental data base should be built to perform a systematic analysis. This broad analysis should include cognitive understanding, statistical and data mining techniques to obtain the relevant data, the correlation among the variables involved, and a list of possible suggested models. The next step is to select a set of methods and models that cover all kind of knowledge and functionalities needed for the decision making process. Once the models are selected, they must be fully implemented by means of some machine learning, data mining, statistical or numerical techniques. After that, those models must be integrated to build the final whole EDSS. The EDSS must be tested to check its performance, accuracy, usefulness and reliability, both from the user's and AI/computer scientist point of view. If there is any wrong feature in any development stage, such as models' integration, models' implementation, selection of models, data base, problem analysis, etc., the developers must come back in the flow and update the required components. When the evaluation phase is all right, the EDSS is ready to be applied to the environment.

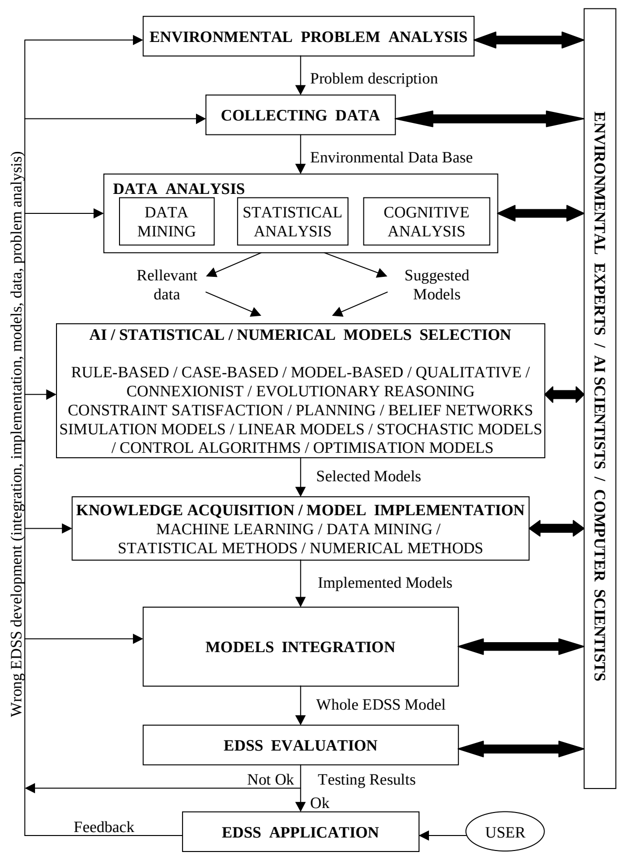

Figure 2: Development of an EDSS

A great contribution of Artificial Intelligence to the development of EDSS is the integration of several methods (Avesani, Perini and Ricci, 1999), (Sànchez-Marrè et al, 1997) and the seminal work by Krovvidy (1991) complementing the classical statistical models (simulation, statistical analysis, linear models, etc) and numerical models (control algorithms, optimisation techniques, etc). This co-operation makes the resulting systems more reliable and powerful, and able to cope with real world environmental systems.

Among the AI techniques and methods more often used in the development of EDSS in past years, the following ones can be signalled:

- Rule-based reasoning (Serra et al, 1994), (Chapman and Patry, 1989), and (Hushon, 1987).
- Planning (Avesani, 1999) and (Krovidy et al, 1994).
- Case-based reasoning (Branting, Hastings and Lookwood, 1997), (Sànchez-Marrè et al, 1997), (Jones and Roydhouse, 1995) and (Krovidy and Wee, 1993).
- Qualitative reasoning (Mora-López and Conejo, 1998), (Heller et al, 1995) and (Kompare, 1994).
- Constraint satisfaction (Avesani, Perini and Ricci, 1999) and (Paggio et al, 1998).
- Model-based reasoning (Sangüesa and Burrell, 1999), (Englehart, 1997), (Varis, 1997) and (Chong and Walley, 1996).
- Connexionist reasoning (Zhu et al, 1998), (Wen and Vassiliadis, 1998), and (Tan and Smeins, 1996).
- Evolutionary computing (Mulligan and Brown, 1998), (Savi and Walters, 1997) and (Zhan et al, 1995) .
- Fuzzy logic techniques (Genovesi, Hermand and Steyer, 1999), (Manesis, Sapidis and King, 1998), and (Chang, Chen and Chen, 1997).

New generation of Decision Support Systems

Let us recall the first definition we gave of an EDSS as an intelligent information system that ameliorates the time in which decisions can be made as well as the consistency and the quality of the decisions. These systems directly support decision-makers by offering criteria for the evaluation of alternatives or for justifying decisions. The inter-operation with different partners must be interactive, user-friendly, fast and performant. See the upper layer in figure 2.

With the increasing maturity of Artificial Intelligence techniques, in special those related with Knowledge Engineering, new dimensions in assisting users in environmental decision making are available. For example, many environmental systems are characterised both by incomplete models and by limited empirical data. Accurate prediction of the behaviour of such systems requires exploitation of multiple, individually incomplete, knowledge sources. The application of multiple complementary problem solving techniques (i.e. Case-Based Reasoning and Constraint Satisfaction) (Krovvidy and Wee, 1993), (Hastings, Branting and Lockwood, 1996), can often help to reduce this uncertainty.

In Artificial Intelligence, this situation is often referred to as having an ill-structured domain (Robertson et al, 1991). The relationships among the concepts or attributes of the domain are not enough known and there is not much agreement among the experts. The relationships among the various phenomena that characterise the system are insufficiently understood. The multifaceted nature of the environmental problems invariably emerges when it is necessary to make a choice among different plausible solutions.

EDSS may contribute to reduce this effect by building different scenarios, called *what-if* scenarios, so the decision maker could make-up his mind having as much as information as possible.

Conflict is inherent in environmental problem solving. The complexity of the fields and the multiplicity of views and interests involved call for mechanisms of reconciliation of disparate, often conflicting goals and contradictory information as pointed out by El-Swaify and Yakowitz, (1998). Sociologists, when modelling the process of environmental decision making, identify the existence of conflict and advocate the importance of negotiation and consensus making in this process (Avouris, 1995b).

Nevertheless, EDSS have an important role in these processes by deriving in a comprehensive, systematic, economic, and fast way the possible consequences of decisions for the environment.

Expert systems have played an important role in supporting environmental decision-makers (Wright et al, 1993). Although many applications still rely on them, the current tendency is to create autonomous agents that take profit of the implicit distributed nature of environmental problems and of the compiled past experience in specific areas that they can content deal with, facilitating the users their tasks. Nevertheless, Expert Systems provide some kind of objectivity and confidence in this highly subjective problem-solving context (Sànchez-Marrè et al, 1996).

Another approach is that of Co-operating Knowledge-Based Systems (CKBS) (Ohtsuki, Kawazoe and Masui, 1998), (Avouris, 1995). Given the interdisciplinary nature and decentralised management of environmental problems, the co-operation among several experts is necessary to cope with all the variables and issues both to a local and global levels. Distributed Artificial Intelligence offers a wide range of possibilities.

The typical results of this approach is the choice of the level and of a formal method of description that can only interpreted by a human or an EDSS using a general solution strategy such as: analogy or case-based reasoning to find similar, already solved problems; redefinition of the problem (if necessary) using different but known terms; deduction of a particular strategy from an existing one.

Conclusions

One of the essential points of the application of AI techniques to EDSS relies on the knowledge-based knowledge management facilities that they provide to accelerate the problem identification. EDSS are in fact, from this point of view, a relevant class of KBS.

Another important point is the integration of several AI techniques with numerical and/or statistical models in a single system providing higher accuracy, reliability and usefulness.

Integration, may vary from simple file transfer between different methods and programs to fully integrated systems. It can be expected that this kind of systems may be designed as distributed systems.

Today, EDSS are already used as a basis for a better support to decision taking for action in many real applications

The number of applications of EDSS is increasing very rapidly and this is not only restricted to traditional hardware devices. Although this positive impression AI applications to Environmental issues still lower in comparison with AI systems in other fields as medicine or manufacturing. Since the arrival of the Internet, the possibilities of connecting machines and sensors are enabling the distribution of the computation, opening new and cheap ways to effectively solve problems (Baeza et al, 1998). Using Internet and/or Intranets, the accesses to stored information becomes easier allowing controlling the effects of actions and solutions in a more efficient way; also the time to reach and to authorise decisions will decrease (Balstad, 1996), (El-Swaify, 1998). Moreover, the collective memory of an organisation could be better maintained and be more useful as a Case Base or a Knowledge Base (Sànchez-Marrè, 1999).

The automatic construction of specialised Ontologies for environmental issues is one of the key lines of future development in the research of EDSS (Clark and Porter, 1997). Associated with this task remains the maintenance of Knowledge Bases problem.

The key to useful computer based decision support systems is, as said before, *integration*. The concept of integration recognises that in any given software system for real-world applications, several sources of information, more than one problem representation or model, different problem-solving techniques, and finally a multi-faceted and problem-oriented interface ought to be combined in a common framework to provide a realistic and useful information base.

The integrated EDSS of the next generation will be built around one or more coupled models, numerical simulation models, rule or case-driven, geographically distributed and integrated with a GIS. The use of Internet will allow to think in this new generation as multi-agents architecture where modules (or Agents) communicate via an inter-agent facility -- supported by a common Ontology-- to co-operate in the problem solving task.

As Guariso and Werthner (1989) already pointed out, EDSS will not and cannot do the work that remains to be done by humans. A better computer support does not automatically imply a better decision. It is still the humans responsibility to be aware of the environmental situation of our planet and to cope with all the problems connected with it..

Acknowledgements

We acknowledge the support of the Spanish Research Agency CICyT projects TIC96-0878 and AMB97-0889.

References

Avesani, P., Perini, A. & Ricci, F. Combining CBR and constraint reasoning in planning forest fire fighting. In Proc. of the First European workshop on Case-Based reasoning, pp. 235-239. 1993.

Avesani, P., Perini, A. & Ricci, F. Interactive case-based planning for forest fire management. *Applied Intelligence*. 1999 (to appear)

Avouris, N.M. Cooperating expert systems for environmental applications. In Environmental Informatics: Methodology and applications of environmental Information Processing. Avouris, N.M. & Page, B. (Eds.) pp. 111-125. 1995

Avouris, N.M. & Page, B. (Eds.) Environmental Informatics: Methodology and applications of environmental Information Processing. Kluwer. 1995.

Avouris, N.M. Co-operating Knowledge-Based Systems for Environmental Decision-Support. *Knowledge-Based Systems* 8(1):39-53. 1995.

Baeza, J., Gabriel, D. & Lafuente, J. An Expert Supervisory System for a Pilot WWTP. In Workshop Binding Environmental Sciences and Artificial Intelligence (BESAI´98), Cortés, U. & Sànchez-Marrè, M. (Eds.) pp 25-35. 1998.

Bender, M. & Simonovic, S.P. Decision Support System for long-range stream-flow forecasting. *Journal of Computing in Civil Engineering* 8(1):20-34. 1994.

Branting, K., Hastings, J.D. & Lockwood, J.A. Integrating cases and models for prediction in Biological systems. *AI Applications* 11(1):29-48. 1997.

Chapman, D. & Patry, G.G. (Eds.). Dynamic Modelling and Expert Systems in Wastewater Engineering. Lewis Publishers. Chelsea, 1989.

Chang, N.B., Chen, Y.L. & Chen, H.W. A fuzzy regression analysis for the construction cost estimation of wastewater treatment plants. *Journal of Environmental Science and Health*. Part A-Environmental Science and Engineering & Toxic and Hazardous Substance Control

32(4):885-899, 1997

Chong, H.G. & Walley, W. Rule-base versus probabilistic approaches to the diagnosis of faults in wastewater treatment processes. *Artificial Intelligence in Engineering* 10(3):265-273. 1996.

Clark, P. And Porter, B. Building Concept Representation from Reusable Components. 14th National Conference on Artificial Intelligence (AAAI'97). pp 369:376.1997

Cortés, U. & Sànchez-Marrè, M. (Eds.) Workshop Binding Environmental Sciences and Artificial Intelligence

(BESAI'98). European Conference on Artificial Intelligence (ECAI'98). Workshop Notes. 1998.

El-Swaify, S.A. & Yakowitz, D.S. (Eds.) Multiple objective Decision Making for Land, Water, and Environmental Management. Lewis Publishers. 1998.

Englehart, J.D. Bayesian-Risk Analysis for Sustainable Process Design. *Journal of Environmental Engineering* 123(1):71-79. 1997.

Gabaldón, C., Ferrer, J., Seco, A. & Marzal, P. A software for the integrated design of wastewater treatment plants. *Environmental Modelling & Software* 13(1):31-44. 1998.

Genovesi, A., Harmand, J. & Steyer, J.-P. Integrated Fault detection and isolation: Application to a Winery's Wastewater Treatment Plant. *Applied Intelligence*. 1999

Guariso, G. & Page, B.(Eds.) Computers support for environmental impact assessment. IFIP. North-Holland. ISBN 0-444-81838-3. 1994

Guariso, G. & Werthner, H.(Eds.) Environmental Decision Support Systems. Ellis Horwood-Wiley. 1989.

Haagsma, I.G. & Johanns, R.D. Decision support systems: An integrated approach. In Environmental Systems Vol. II. Zannetti, P. (Ed.) pp. 205-212. 1994.

Hastings, J., Branting, K. & Lockwood, J. A Multi-Paradigm reasoning System for Rangeland Management. Computers and Electronics in Agriculture 16(1). 1996.

Heller, U., Struss, P., Guerrin, F. & Roque, W. A qualitative modelling approach to algal bloom prediction. In IJCAI-95 Workshop on Artificial Intelligence and the Environment. Mason, C. (Ed), pp. 21-26. 1995.

Hushon, J.M. Expert systems for environmental problems. *Environmental Science and Technology* 21(9):838-841. 1987.

Jones, E.K. & Roydhouse, A. Retrieving structured spatial information from large databases: a progress report. In IJCAI-95 Workshop on Artificial Intelligence and the Environment, pp. 49-57. 1995.

Kompare, B. Qualitative modelling of environmental processes. In Zannetti, P. (Ed) Environmental Systems Vol. II. Computer Techniques in Environmental Studies V. Computational Mechanics Publications. 1994.

Krovviddy, S., Wee, W.G., Suidan, M., Summers, R.S., Coleman, J.J. & Rossman, L. Intelligent sequence planning for wastewater treatment systems. *IEEE Expert*, Dec., pp 15-20. 1994.

Krovvidy, S. & Wee, W.G. Wastewater treatment system from case-based reasoning. *Machine Learning* 10(3):341-363. 1993.

Krovviddy, S., Wee, W.G., Summers, R.S. & Coleman, J.J. An AI approach for wastewater treatment systems. *Applied Intelligence* 1(1):247-261. 1991.

Maeda, K. An Intelligent Decision Support System for activated Sludge Wastewater treatment Systems. *Instrumentation and Control of Water and Wastewater Treatment Systems*. 1985.

Manesis, S.A., Sapidis, D.J. & King, R.E. Intelligent Control of wastewater treatment plants. *Artificial Intelligence in Engineering* 12(1998):275-281. 1998.

Mason, C. (Ed.) Workshop on Artificial Intelligence and the Environment. IJCAI-95 Workshop Program Working Notes. 1995.

Michalski, R. & Radermacher, F.J. Challenges for Information Systems: Representation, Modelling, and Meta-knowledge. In Recent Developments in Decision Support Systems. Holsapple, C.W. & Whinston (Eds.), pp. 3-22. 1993

Mora-López, Ll. & Conejo, R. Qualitative Reasoning Model for the Prediction of Climatic Data. In Workshop Binding Environmental Sciences and Artificial Intelligence (BESAI'98), Cortés, U. & Sànchez-Marrè, M. (Eds.) pp. 55-67. 1998.

Ohtsuki, T., Kawazoe, T. & Masui, T. Intelligent control system based on blackboard concept for wastewater treatment processes. *Water Science and Technology* 37(12):77-85. 1998.

Okubo, T., Kubo, K., Hosomi, M. & Murakami, A. A Knowledge-based decision support system for selecting small-scale wastewater treatment processes. *Water Science Technology* 30(2):175-184. 1994.

Page, B. An analysis of Environmental Expert System Applications with Special Emphasis on Canada and the Federal Republic of Germany. Fachbereich Informatik. Bericht 144/89. Hamburg. 1989.

Paggio, R., Agre, G., Dichev, C., Dochev, D., Umann, G. & Rozman, T. TRACE- A development platform for Environmental Decision Support Systems. In Workshop Binding Environmental Sciences and Artificial Intelligence (BESAI'98), Cortés, U. & Sànchez-Marrè, M. (Eds.), pp. 145-160. 1998.

Robertson, D., Bundy, A., Muetzelfeldt, R. Haggith, M. & Uschold, M. Eco-Logic. Logic-based Approaches to Ecological Models. MIT Press. 1991.

Rizzoli, A. E. & Young, W.Y. Delivering environmental decision support systems: software tools and techniques. *Environmental Modelling & Software* 12(2-3):237-249. 1997.

Sànchez-Marrè, M., Cortés, U. R.-Roda, I. & Poch, M. Sustainable Case Learning for Continuous Domains. Environmental Modelling and Software. Accepted. To be appear *in Environmental Modelling & Software*. 1999.

Sànchez-Marrè, M., Cortés, U., R-Roda, I., Poch, M. & Lafuente, J. Learning and adaptation in WWTP through Case-based Reasoning. *Microcomputers in Civil Engineering* 12(4):251-266. Special issue on Machine Learning, 1997.

Sànchez-Marrè, M., Cortés, U., Béjar, J., de Grácia, J., Lafuente, J. & Poch, M. Concept formation in WWTP by means of classification techniques: a compared study. *Applied Intelligence* 7(2):147-166. 1997.

Sànchez-Marrè, M., Cortés, U., Lafuente, J., R.-Roda, J. & Poch, M. DAI-DEPUR: an Integrated and Distributed Architecture for Wastewater Treatment Plants Supervision. Artificial Intelligence in Engineering 10(3):275-285. 1996.

Sangüesa, R. & Burrell, P. Application of Bayesian network learning methods to wastewater treatment plants. *Applied Intelligence*. 1999.

Savic, D.A. & Walters, G.A. Genetic Algorithms for Least-Cost Design of Water Distribution Networks. *Journal of Water Resources Planning and Management*, Vol. 123, No. 2, 1997.

Sazonova, L. & Osipov, G. Intelligent System for Fish Stock Prediction and Allowable Catch Evaluation. In Workshop Binding Environmental Sciences and Artificial Intelligence (BESAI'98), Cortés, U. & Sànchez-Marrè, M. (Eds.) pp 161-176. 1998.

Serra, P., Sànchez-Marrè, M., Lafuente, J., Cortés, U. & Poch, M. (1994) DEPUR: a knowledge based tool for wastewater treatment plants. *Engineering Applications of Artificial Intelligence* 7(1):23-30. 1994

Serra, P., Lafuente, J., Moreno, R., de Prada, C. & Poch, M. Development of a real-time expert system for wastewater treatment plants control. *Control. Eng. Practice* 1(2):329-335. 1993

Shepherd, A. & Ortolano, L. Water-supply system operations: Critiquing expert-system approach. *J. of Water Resources Planning and Management.* 122(5):348-355. 1996.

Steels, L. Components of expertise. *AI Magazine* 11(2):28-49. 1990.

Tan S.S. & Smeins, F.E. Predicting Grassland Community Changes With An Artificial Neural-Network Model. Ecological Modelling 84(1-3):91-97, 1996,

Varis, O. Bayesian decision analysis for environmental and resource management. *Environmental Modelling & Software* 12(2-3):177-185. 1997.

Wen, C-H. & Vassiliadis, C.A. Applying Hybrid artificial Intelligence in wastewater treatment. *Engineering Applications of Artificial Intelligence.* 11:685-705. 1998.

Wilson, J.L., Mikroudis, K. & Fang, H.Y. GEOTOX: A Knowledge-Based System for Hazardous Site Evaluation. In *Applications of Artificial Intelligence in Engineering Problems*. Sriram, D. & Adey, R. (Eds.), pp. 661-671. 1986.

Wright, J., Wiggins, L., Jain, R. & John Kim, T. (Eds.) Expert systems in Environmental Planning. Springer-Verlag. ISBN 3-540-56063-7. 1993.

Yang, C.T. & Kao, J.J. An expert-system for selecting and sequencing wastewater treatment processes. *Water Science & Technology* 34(3-4):347-353. 1996.

Zannetti, P. (Ed) Environmental Systems Vol. II. Computer Techniques in Environmental Studies V. Computational Mechanics Publications. 1994.

Zhang, B-T., Ohm, P. & Mühlenbein, H. Water pollution with evolutionary neural trees. In IJCAI-95 Workshop on Artificial Intelligence and the Environment. Mason, C. (Ed), pp. 32-40, 1995.

Zhu, J., Zurcher, J., Rao, M. & Meng, M. Q-H. A on-line wastewater quality predication system based on a time-delay neural network. *Engineering Applications of Artificial Intelligence* 11:747-758. 1998.