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Perspectives of Environmental Informatics and Systems Analysis

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ABSTRACT. Information technologies are under extraordinarily rapid progress, and a number of them have not been applied to environmental management. In many cases, however, the roles of these technologies have been limited in the provision of improved convenience for system implementation and the generation of nicer presentation of system inputs and outputs. Although these roles are meaningful for extensive transfer of new methodologies and convenient access of research outcomes, they do not directly contribute to methodology development. Therefore, further development of the high performance computing and knowledge management potentials associated with artificial intelligence techniques is desired to promote long-term viability of the environmental informatics. In this paper, recent developments, advancements, challenges, and barriers associated with practices of environmental informatics research were analyzed. A number of related methodologies, applications, and policy considerations were examined. Issues of the needs for environmental systems analysis, the challenges of environmental systems modeling, and the impacts of environmental informatics were discussed. Perspectives of the environmental decision-making in 21st century were investigated, demonstrating many demanding areas for enhanced research efforts.

Keywords: Environmental informatics, decision making, modeling, perspective, systems analysis

1. Introduction

In the past century, the natural environment has provided for various types of resources in support of rapid industrialization and urbanization. As the world's population grows over time, human beings have progressively made greater demands on the environmental resources through an unprecedented increase in technology capacity, energy consumption, international trade, and social complexity. Information technologies are becoming more and more important for environmental management, due to the increasing needs for large-scale computational capability in order to meet the goals of sophisticated environmental decision-making. To explore the ultimate limitation of nature, an analysis of the environment in terms of the physical, chemical, and biological processes and the relationship of these processes and their interactions are becoming critical. Significant efforts are required to analyze the relevant information, simulate the related processes, evaluate the resulting impacts, and generate sound decision alternatives. The system-based approach developed within the last two decades enables us to investigate the complex interactions fundamental to the co-evolution of engineered and natural systems. Recent advances in information technology lean toward making effective search for the sustainable development strategy via integrative efforts between multi–dimensional, multi-scale data analysis and environmental system modeling. This could facilitate decision-maker to intimately link the domain knowledge with the envisioned social, economic, ecological, and environmental objectives leading to foster a new interdisciplinary field, environmental informatics. This new field brings together a variety of information-technology-based measures, in connection with versatile environmental monitoring networks and in association with multidisciplinary mathematical modeling skills to provide risk-informed, consensus-oriented, and cost-effective solution (Chang et al., 2001, 2002).

Traditional mathematical simulation models are useful tools for the forecasting of environmental processes. For example, Li and Chen (1994) proposed a model for simulating organics removal and oxygen consumption by biofilms in an open-channel. Masliev and Somlyody (1994) advanced a probabilistic method for uncertainty analysis and parameter estimation for dissolved oxygen models. Kazmi and Hansen (1997) developed a numerical model for water quality simulation and applied it to a case study in the Yamuna River, India. More studies in this area can be found in Xia (1990), Settesoldi et al. (1994), Nirmalakhandan et al. (1998), Rauch et al. (1998), Shanahan et al. (1998), Somlyody et al. (1998), and Lung et al. (1999). While state-of-the-science models characterizing the fate and transport of contaminants in different environmental compartments or medias are indeed necessary to rigorously understand the short-term and long-term dynamics of pollutant behavior, they may

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be of limited value in finding out the casual effect and cost-benefit relationship for immediate policy planning and regulatory studies. System dynamics model exhibits promising potential to assess feedback mechanisms for identifying system response from a broad sense. Relevant environmental applications can be found in the literature (Guo et al., 2001).

Besides, optimization techniques have been widely used in the field of environmental management and pollution control. The results provide bases for decisions related to allocation of waste loadings, deployment of monitoring network, and implementation of pollution abatement activities (Chen and Chang, 1998; Huang et al., 1999; Chang and Tseng, 2001; Ning et al. 2002). Multi-objective evaluation has received wide attention in environmental applications, such as solid waste management (Minor and Jacobs, 1994). Hybrid approaches existed in the literature for handling multidisciplinary issues. For example, Chang et al. (1997a) and Chang and Wei (1999) developed a multi-objective mixed-integer programming, which incorporated with geographical information system (GIS) for routing and scheduling collection vehicles in solid waste management systems. Alidi (1998) utilized a goal-programming model to aid in the integrated MSW management, using the analytic hierarchy process (AHP) technique for determining the weights and priorities for a given set of goals. Such extension work does enrich the application spectrum in the context of systems analysis.

The integrated modeling systems with the aid of simulation, regression, and optimization analyses have utilized existing disciplines common in operations research and management science applications to design various environmental management systems for different study regimes (Yen et al., 2003; Yen and Chang, 2003). They may significantly help address the forcings of human-induced impacts, identify the responses in the environmental systems, and assess consequence due to such disturbance in our society. Overall, it enables scientists, engineers, and managers to project consequences of management alternatives, provide insightful planning, and formulate environmental policy such that effective decision-making schemes can be identified (Somlyody et al., 1998; Lung et al., 1999). The key challenge is how to make complementary use of models with different features, scales, and complexity as well as data collected from multiple types of sensors to pursuing a full understanding of the air-sea-land-biosphere interaction mechanisms under the impacts of infrastructure operation, resources consumption, and global change. These modeling frameworks themselves have to be highly modularized and are adaptable to multiple computation platforms in dealing with various types of issues in environmental systems. In an attempt to find a balance between competing social, economic, ecological, and environmental factors in the context of sustainable development to meet the goals in governmental policy formulation and decision-making in different countries, seamless integration of soft information and quantitative results obtained from integrative modeling studies may exhibit the beauty of environmental systems analysis.

2. Challenges of Environmental Systems Modeling

However, this goal involves several challenges. The first challenge is the characterization of uncertainties that exist in many intertwined system parameters that could make the environmental systems extremely complicated. Applicability of modeling techniques to environmental management is affected by many factors. Firstly, environmental systems are complicated, where a number of factors and interrelationships are hard to be expressed as mathematical formulas; also, nonlinearity that exists in system can hardly be effectively reflected. Secondly, information for a number of system parameters is often unavailable, such that rough estimations have to be made. Also, a large portion of information that is available may not be quantifiable; instead, this type of information could be simply the implicit knowledge from decision makers. Thus, inputs for a modeling system may only be a small part of the entire information in a study system; consequently, the modeling outputs may only be useful for providing part of decision support, while another part should be from solid investigations of the ambiguous and unquantifiable information through innovative information technologies. Thirdly, for information that is quantifiable, a significant part of it may not exist as deterministic data. This creates difficulties in expression of the uncertainties, as well as solution for models that contain uncertain parameters and/or relationships (Kindler, 1992; Huang, 1996; Huang et al., 1996; Lee and Wen, 1997; Sasikumar et al., 1999). Many researchers tried to deal with the uncertainties through the inclusion of fuzzy, stochastic and other inexact modeling approaches in the context of optimization analysis (Trezos and Yeh, 1987; Cardwell and Ellis, 1993; Chang et al., 1996a, b; Lee and Wen, 1997; Sasikumar et al., 1999). In particular, Huang et al. (1996) and Huang (1996) proposed inexact optimization models for watershed environmental planning, and applied them to two real-world case studies. A second challenge is the quantitative description of how is the risk involved in decision-making related to the uncetainty in modeling process. While risk involved in environmental assessment might become another source of uncertainty, uncertainties in environmental systems may cause a certain level of risk that might affect the final decision in environmental management. Consequently, risks and uncertainties associated with a variety of system behaviors, objectives identification, and their interrelationships have received significant attention from both environmental management and information science (Beck, 1987). An associated challenge is to develop the capability to minimize the uncertainties and risks using advanced information and communication technologies. To ease the challenges and to enhance model feasibility and applicability, there is need for scientists to incorporate these advanced information and communication technologies along with up-to-date monitoring and measurement devices to aid in environmental systems modeling.

3. Impacts of Environmental Informatics

In the past decades, a number of computer-based modeling techniques were developed for studying environmental management systems and providing related decision supports (Chang and Wang, 1996; Chang et al., 1997a, b). Especially, many comprehensive decision support systems (DSS) were advanced and applied to real-world problems. Such computer-based systems have interactive, graphical, and dynamic characteristics and can be directly used for addressing specific management issues and assisting individuals in their problem-solving processes (Loucks and da Costa, 1991; Simonovic, 1996a,b; Soncini-Sessa et al., 1999). The strategic effort in this regard is to provide scientific answers to overarching questions in cases when early warning, special operation, and emergency response need to be particularly taken into account.

Nowadays, information technologies are seen to play a major role in the sustainability-based decision- making process. A typical computer-based technology that has been widely used in assisting environmental systems analysis is GIS. GIS is effective in handling complicated spatial information that is essential for many environmental studies, as well as providing platforms for integrating various models, systems, and interfaces (Lovejoy et al., 1997; Huang et al., 1999). In the past decade, many GIS-aided environmental modeling and decision-support systems have been developed (Mailhot et al., 1997; Huang et al., 1999). The geo-coding exercises carried out by many agencies over the last few years, coupled with advances in geo-information processing tools have made available large volumes of datasets that can be used during environmental decision making process. Remote sensing (RS) is another important computer-based technology for supporting environmental systems modeling to perform systems analysis (Blaakman et al., 1995; Goksel, 1998). Space-borne, air-borne, and ground-borne remote sensing technologies vastly supplements the ground-based sampling scheme in the context of environmental monitoring and measurement. Most of RS projects produce large volumes of spatial information, while GIS is an effective tool for storing, manipulating and analyzing them. Consequently, a number of integrated environmental modeling and RS-GIS studies have been reported. Recent advances in the technical integration of GIS and RS in connection with global position system (GPS) and database management systems (DBMS) successfully streamline the information flows among stakeholders.

Despite, the recently renewed interest in utilization of information technologies in environmental studies, several fundamental and applied aspects related to the utilization of some new technologies still draw much attention from the scientific community. Firstly, there has been a unanimous recognition of the importance of OpenGIS® defined by open interfaces and protocols among heterogeneous computer platforms. Specifications support interoperable solutions that "geo-enable" the wireless and location-based applications throughout the Internet environment. This advance could allow remote users to share enormous amount of spatial data across various computer platforms. Secondly, recent advances in high performance computing have shown great potential to improve the prediction accuracy in the practice of environmental systems modeling. High performance computing is needed when we have to assess large-scale environmental changes and impacts in both prognostic and retrospective sense. Grid computing associated with computer clustering is the most promising system nowadays. Grids are based on large scale resource sharing. The notion of a grid system assumes a virtual pool of resources. A grid is a collection of distributed computing resources available over a local or wide area network that appear to an end user or application as one large virtual computing system with unlimited capacity. Grid computing is an approach to distribute computing that spans not only locations but also organizations, machine architectures and software boundaries to provide unlimited power, collaboration and information access to everyone connected to a grid (Zhang, 2003). The vision for building such a system is to create virtual dynamic organizations through secure, coordinated resource-sharing among individuals, institutions, and resources (Le Vine et al., 2003). Apart from computational resources grids are expected to operate on a wider range of resources like storage, network, data, software, graphical and audio input/output devices, manipulators, sensors, and so on. Yet the virtual pool of resources is dynamic and diverse in actual operation. Resources can be added and withdrawn at any time and location and their performance or load can change frequently in response to the required computational load. The users do not need to have a priori knowledge about the actual type, state and features of the resources constituting the pool (Kacsuk et al., 2002). Thirdly, large-scale database search in conjunction with artificial intelligence techniques, such as artificial neural networks, fuzzy reasoning, knowledge-based expert systems and other data mining tools, also have the significant potential to be of much use in environmental decision-making schemes. Developing a valuable decision support system is an inherently collaborative endeavor involving a diverse group of people with different backgrounds, values and experiences. A number of information technologies, such as knowledge acquisition, data mining, uncertainty analysis, and expert system technologies, could be helpful to increase data integrity and reliability of decision-making.

Hence, reaching successful consensus-based efforts that might be collected or retrieved by artificial intelligence techniques will require a significant sharing of domain knowledge amongst the stakeholders, scientists, engineers, and decision makers throughout wireless and/or wired network.

As an interdisciplinary field, research on environmental informatics is in fact an integration effort. Figure 1 describes the integrative structure between environmental systems modeling, environmental monitoring and measurement, and environmental informatics. Advances of sensor synergy skills and telecommunication technology make large-scale ground-based sampling scheme feasible. The main difficulties associated with such an effort rest upon model synthesis when dealing with various features, scales, and complexities. They include handling connection among various simulation, optimization, and assessment models as well as the related information technologies and platforms, linkage between inputs and outputs of various technologies, quantification of a number of socio-economic factors, and solution procedure for the resulting large-scale integrated models. These difficulties have affected practical applicability of the integrated approach (Fenz et al., 1998; Scharf, 1998; Vijayan et al., 1999). Facing these difficulties, it is essential to gain insight into integrative efforts in order to identify effective approaches for overcoming or mitigating these challenges.

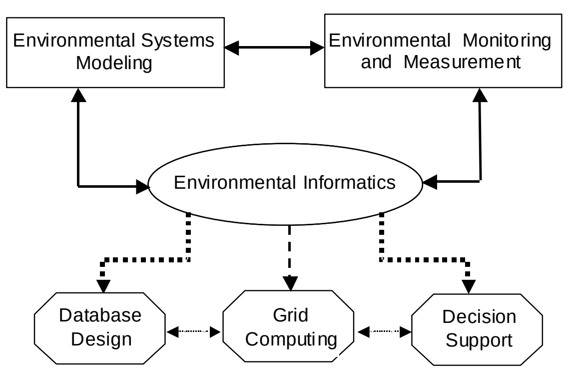

Figure 1. Components of environmental informatics and their relevant interactions.

4. Perspectives of the Environmental Decision Making in the 21st Century

Environmental management systems generally have multi-objective, interactive, dynamic and uncertain features. Complexities exist in determination of system parameters, reflection of interactive relationships, formulation of modeling approaches, interpretation of research outputs, and implementation of recommended policies. Often, to quantify such systems, a number of simplifications have to be made, such as linear, continuous, static, single-objective, and/or deterministic assumptions. These simplifications, however, would be responsible for the final errors once failures of systems analysis do occur. How to effectively reflect these complexities when bearing with these risks involved has been a challenging question facing environmental researchers.

Many challenges exist in the application of modeling techniques to environmental management. Most of environmental models can only deal with limited spatial and temporal units in a system due to difficulties in computational requirement and data availability. However, what decision makers desire to know might be either detailed plans based on much finer units or just a broad justification. This could lead to incompatibility between the researchers' outputs and the users' demands, and raises the question about usefulness of the modeling solutions. Moreover, the collection of environmental statistics is fraught with difficulties, due to the wide range of environmental phenomena, data sources, and agencies involved, as well as the complexities of their temporal and spatial characteristics (Briggs, 1995). Consequently, many environmental data are subject to significant problems of uncertainties, inconsistencies, and errors. To obtain improved reliability and certainty, solid works on validation of input-data before they are used for further analysis are desired, where a number of information technologies could make crucial roles. The insufficiency of data about pollution sources, mitigation measures, natural conditions, and environmental quality records, as well as the lack of information related to cultural, social, economic and political factors often hinder the development of effective management strategies. Inevitable on-site investigation could ease such problems. Thus, when models are used for providing decision support, the researchers have to conduct solid on-site works to gain as much insight of the study system as the local managers and stakeholders before claiming that they are wiser and can do better jobs. Involvement of information technologies would be desired for facilitating research to gain profound knowledge and understanding of the study system without heavily involving in on-site investigation. This motivates many agencies to build up on-line environmental database management system and decision support system to aid in various environmental impact assessment and policy decision-making based on a fast and friendly environment.

It is suggested that the completion of modeling or design based on the available data means halfway only, and the remaining half is to examine how information that are unavailable but may present as implicit knowledge of decision makers or stakeholders could be collected by various remote sensing instruments and acquired through innovative information technologies such as artificial intelligence and data mining. This would require high performance computation in most cases. Figure 2 demonstrates a typical system configuration using 4S information technology concept (GIS/GPS/RS/DBMS) that enables us to facilitate various spatial analyses, data sharing and distribution, and modeling assessment. This computer node could become one of the OpenGIS®

and/or grid computing smart nodes to share essential data and knowledge distributed in the Internet for meeting a high-end sophisticated knowledge management goal or support vast computational capacity for performing share-vision modeling analysis (Chen et al., 2003). When using this kind of DSS to help solve environmental issues, the final difficulties might include how system can be sustained and how all system components can be comprehensively formulated and maintained in the information world.

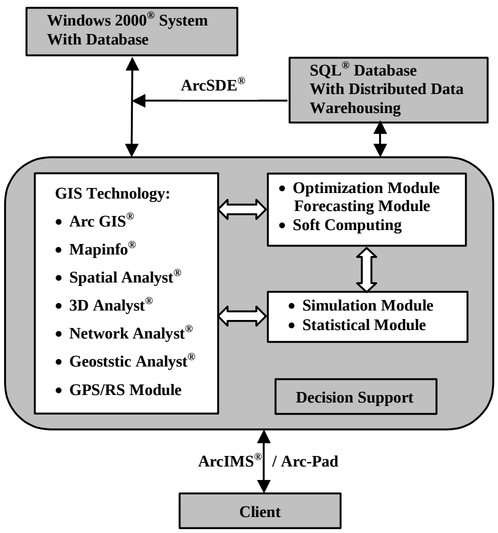

Figure 2. Outlay for the proposed decision support system.

5. Concluding Remarks

Most of quantitative models can only reflect part of impact factors, leaving the remaining that are uncertain or unavailable out of the modeling frameworks. Another concern of the research outputs is its dynamic feature. Conditions in environmental management systems will keep changing with time, demanding periodically up-dated decision support. It is thus desired by users and decision makers that the research outputs be "dynamic". Information technologies are under extraordinarily rapid progress, and a number of them have not been applied to environmental management yet. In many cases, however, the roles of these technologies have been limited in the provision of improved convenience for system implementation and the generation of nicer presentation of system inputs/outputs (i.e., visualization). Although these roles are meaningful for extensive transfer of new methodologies and convenient access of research out-comes, they do not directly contribute to methodology development. Therefore, further development of the high performance computing and knowledge management potential associated with the artificial intelligence tech-niques is desired to promote long-term viability of the environmental informatics.

With the vision we have gained in OpenGIS® and grid computing, on-line real time large-scale model synthesis and data exchange will become feasible in the near future. This means the provision of integrated com-puter software packages that allow users to input updated information into the software system, run the system, and obtain updated results in the Internet environment is anticipated. Obviously, in line with this trend, more information technologies will be taken for addressing the complex environmental concerns that we cannot address them successfully today. This must rely on fostering and nurturing a new field "Environmental Informatics" as a new niche in the area of environmental engineering.

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