A GIS-BASED ENVIRONMENTAL DECISION SUPPORT SYSTEM FOR THE ERHAI LAKE WATERSHED MANAGEMENT

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ABSTRACT

In this paper the integration of environmental models and GIS is exploited. The focus is placed on the development of a GIS-based decision support system for the lake watershed management. The system consists of a GIS database, optimization models, and a user-friendly interface. ArcView GIS is used to enter and compare data from different sources and formats, assess data availability and quality, and identity potential data errors. A centralized database with a structure that allows efficient storage and retrieval of georeferenced time-series data is developed before the water quality simulation and system optimization processes. The database management focuses on the database design and structure to maximize the efficiency of information retrieval and storage. A combination of spatial and non-spatial data is used to develop an optimal system. The system is designed to be flexible, allowing for future expansion and modifications. The decision support system is proposed for use in the management of the lake watershed, providing a comprehensive framework for decision-making. The system is expected to improve the efficiency and effectiveness of water management in the watershed.

INTRODUCTION

Human activities continuously have serious impacts on watershed systems due to economic development and population growth, leading to a series of environmental problems, such as deterioration of water quality, extinction of aquatic species, alternations of river flows, shortage of water resources, and so on (QAO, 1986; Master, 1990). The impact of human activities is especially serious, as it is "cumulatively changing the dynamics of natural system for periods of years but entire watersheds and landscapes over many decades or centuries" (Dopperl et al., 1993).

Watershed management is related to a number of social, economical and environmental factors. Many of these factors have complicated interrelationships between each other, and may vary temporally and spatially with dynamic features (Dowlatbadi et al., 1993). For example, variations of environmental and socio-economic conditions may lead to conflicts between agricultural and industrial activities, and may need compromises among different stakeholders in order to obtain an overall optimal use of land and water for the entire basin; pollution from different human activities in water or on land may affect water quantity and quality, resulting in impacts on diversity/vitality of aquatic biota and ecological processes; prices of agricultural products may affect the planning of crop production levels; and expansion of agricultural production may have impacts on forest cover (and thus timbering production) due to land use conflicts. Consequently, integrated modeling approach that incorporates individual system components within a general framework instead of examining or presenting them in isolation may be useful for providing holistic and comprehensive analysis of a variety of system activities, as well as relevant policy responses for the sustainability of a water resources system (Huang 1995a and b).

Since watershed management is related to a number of land use concerns, effective reflection and presentation of the spatial variations are critical for not only implementation of the modeling results but also interpretation of the related computational processes. Therefore, a systematic approach to incorporate watershed modeling and geographic information system (GIS) technology within a general framework is desired for effectively reflecting the interactive and dynamic features of watershed systems.

Previously, many studies of watershed modeling for individual system components have been reported (Haines et al., 1980; Haines, 1984; Halti 1987; Trex et al., 1987; Gorelick, 1990; Kindler, 1992; Huang, 1996). There are also some reports on the use of GIS for obtaining data and presenting modeling outputs (Braun, 1990; Grayman et al., 1993; Liao et al., 1994). This study is an extension of the previous efforts, emphasizing on the use of GIS for obtaining data and presenting modeling outputs throughout the modeling processes, and incorporating uncertainties in human decision-making processes regarding environmental and planning. In detail, an integrated watershed decision support system - GISWMS (Hybrid GIS-Supported Watershed Modeling System) will be proposed. It will then be
applied to the planning of water pollution control in the Lake Erhai Basin, China. This project was supported by the United Nations Environment Programme (UNEP) (Huang et al., 1995).

OVERVIEW OF THE STUDY AREA

The study area, Lake Erhai Basin, which covers an area of about 2,565 km², is located in the southwest of China (Figure 1). The lake is known as a ‘bright pearl’ with unique sightseeing resources. It is a freshwater lake with a surface area of 250-257 km², an average depth of 10.2 m. There are 117 rivers flowing into the lake, and only Xier River out of the lake. The lake plays a crucial role in local economic development, with its resources available for water supply, agricultural irrigation, fishery, tourism, and navigation. Economic activities in the basin include agricultural and industrial production, net-cage fish culture, forestry, tourism, and lime/brick production. Currently, the major environmental problems in the lake basin are: (i) deterioration of lake water quality and increased soil erosion due to decline of lake water level; (ii) nonpoint source pollution from crop farming, livestock husbandry, and fish culture; (iii) water contamination in Xier River due to industrial wastewater discharge; and (iv) deforestation in the lake basin coupled with increased soil erosion, leading to accelerated sedimentation process in the lake.

SYSTEM DESCRIPTION

Interactive Relationships

Based on the consideration of many socio-economic, environmental concerns and the requirement of system modeling, system activities in watershed were divided into several components, including agriculture, industry, in-lake net-cage fish culture, tourism, forest, stone excavation, in-lake navigation, in-lake fishing, lime/brick production, and water supply. They are related to each other and have direct or indirect impacts on the system’s environmental and economic objectives. For example, agricultural production needs water for irrigation and generates nonpoint source pollutants due to manure/fertilizer applications. Water pollution results from nonpoint source losses of sediment, nitrogen and phosphorus from farm lands due to land erosion and washing away of unused nutrients from fertilizers and manure, and irrigation water allocation is related to farming activities, pipe flows, and economic returns. High nitrogen and phosphorus concentrations can lead to eutrophication of water. This should be controlled under allowable levels corresponding to the objective of lake water quality (Hath, 1984).

Figure 2 shows interactive relationships among various system activities and pollution concerns. It is indicated that most of the activities are not only related to each other but also responsible to a number of pollution problems. Any change in one activity may lead to a series of consequences to the others, as well as the related environmental problems. The problems are also interrelated to each other. For example, point/source point source pollution may affect biodiversity, and solid/hazardous waste generation may contribute to point/source pollution. Between the activities and the problems, there exist potential abatement measures such as pollution control projects, and environmental management initiatives. For decisions related to these actions, careful systems analysis would be needed.

![Interactive relationships between human activities and resulting pollution problems](image)

Dynamic Feature

For the planning horizon, social, economic, legislative, and resources conditions will vary with time. Reflection of these temporal variations would be important for generating effective and realistic planning alternatives. Thus, employment of dynamic optimization and systems dynamics methods for the study problem is desired. Due to possibility of continuous changes in system components along with time, it was suggested this study should lead to a “real-time” decision support system. This means...
that the research results should be composed of not only a set of decision alternatives (presented as research reports) but also a computer management system (presented as computer software packages). Decision-makers can then keep inputting varied information (for the future periods) to the software and obtaining updated solutions. Thus, new alternatives can be obtained through interpretation of the solutions.

**Multi-objective Feature**

In the study system under consideration, there exist many environmental, socio-economic, and resources objectives, which are of concern to a number of stakeholders bearing different interests. These objectives also interact to each other, with potentials of limiting or promoting each other. Thus, the problem under consideration is how to make tradeoff or compromise between interests from different stakeholders, in order to maximize overall benefits of the entire system.

**Uncertain Feature**

Many system components and their interrelationships are uncertain in the study system. Normally, people get used of using mean value or middle value to represent uncertain information. However, for a system with many uncertain factors, this approximation may lead to loss of information. For example, it is hard to obtain deterministic value of loading capacity for tourists at a sightseeing spot. Instead, only some uncertain information is available. If we simply present it by a mean or middle value, reliability of the resulting planning may be affected. The above descriptions demonstrate complexity of the study system. Thus, simple decision or expert consultation would not be enough for generating an effective decision support. Employment of systems analysis methods that can incorporate a variety of system components within a general modeling framework is desired.

**Watershed Modeling**

A watershed is a complex system with human activities in water and land. It is impossible to use a simple model to reflect a variety of activities in a watershed. This study developed a modeling system containing three major components: (i) simulation models which are useful for bridging source/impact factors and the related water quality, as well as predicting system behaviors under different conditions, (ii) optimization models which will be used for negotiating a variety of system objectives and generating desired decision alternatives; and (iii) post-simulation/optimization models for further trade-off analysis and risk assessment in order to facilitate practical implementation of the generated alternatives applied to analyze.

**Simulation Modeling**

The mechanisms of pollutant transport in a watershed are very complex, involving many factors such as hydrological, topographical, chemical and biological processes, as well as soil, type and land use conditions. These factors are related to both point and non-point source pollution problems. For effective watershed management and planning, an important issue is the ability to simulate and predict impacts of human activities and related environmental conditions on both water quantity and quality. In this study, hydrological/water quality (HQW) models have been developed to link a number of human activities to their pollution impacts. Four major processes, including hydrological cycle, soil erosion, and water quality, are simulated.

QUAL2E is widely used for modeling water quality of well mixed and dendritic streams (Brown et al., 1987). It simulates the major reactions of nutrient cycles, algal production, benthic and carbonaceous demand, and suspended sediments, and their effects on the dissolved oxygen balance. It can be used for predicting concentrations of up to 15 water quality constituents.

For the hydrological cycle, HSFP (Bockel et al., 1997) simulates for extended periods of time the hydrologic processes, and associated water quality, on pervious and impervious land surfaces and in streams and wet-mixed impoundments. HSFP is generally used for assessing the effects of land-use change, reservoir operations, point or non-point source pollution control, and flow diversions, etc.

The USLE (Universal Soil Loss Equation) (Renard et al., 1991) estimates annual sheet and rill erosion as affected by six factors: rainfall erosivity, soil erodibility, slope length, slope steepness, cover and management, and conservation practices. Concepts of USLE have been customized to the detailed study basin, which provides prediction of soil loss under different hydrological, climatological and landscape conditions (Huang, 1995a). Since the majority of parameters related to soil loss are uncertain in their nature, probabilistic and inexact analyses for the uncertainties will be undertaken throughout the modeling process.

**Optimization Modeling**

An inexact-fuzzy multijob linear programming (IFMOP) model is developed to form an environmental decision support system, in association with a number of simulation/evaluation tools. The IFMOP is proposed by extending the inexact fuzzy linear programming (IFLP) method (Huang et al., 1993) to a multijob decision-making problem. An interactive approach is proposed for conveniently obtaining indispensable information from decision-makers among the IFMOP modeling process. The IFLP was developed as a branch of inexact mathematical programming (Huang, 1994) which is effective for optimization under incomplete uncertainty (e.g., information with known fluctuation intervals but unknown probabilistic or possibilistic distributions). The method has been successfully applied to a variety of management and planning problems (Huang, 1994, Huang, 1996, Huang et al., 1996, Yeh, 1996). The IFMOP is a hybrid of the IFLP and fuzzy multijob-problem. Membership functions for both objectives and constraints are formulated to reflect uncertainties in different system components and their interrelationships. A solution algorithm for inexact linear programming (Huang, 1996) is employed to handle uncertainties in the left-hand side coefficients. Thus, the IFMOP allows uncertainties to be directly communicated into the programming processes and resulting solutions. Its inexact solutions can be interpreted for generating decision alternatives and conducting further risk analyses. Also, the IFMOP solution approaches do not lead to complicated intermediate submodels, and thus have reasonable computational requirements. A general multijob linear programming problem with inexact parameters can be formulated as follows:

\[
\text{min } f_i = C_i^1 x_1 + C_i^2 x_2 + \ldots + C_i^n x_n \quad (1a)
\]

\[
\text{max } f_i = C_i^1 x_1 + C_i^2 x_2 + \ldots + C_i^n x_n \quad (1b)
\]

Subject to:

\[
A^1 x_1 + A^2 x_2 + \ldots + A^n x_n = b^1 + b^2 + \ldots + b^n \quad (1c)
\]

\[
x_i \geq 0 \quad (1d)
\]

where \(x_i \in [x_i^1,x_i^2] \), \(C_i = c_i^1 x_1 + c_i^2 x_2 + \ldots + c_i^n x_n \), \(c_i^1 \in [c_i^1], c_i^2 \in [c_i^2], \ldots, c_i^n \in [c_i^n] \), and \([x_i^1,x_i^2]\) denotes a set of interval numbers.

When all parameters in model (1) are known as intervals without distribution information, this is an inexact multijob programming (IMOP) problem. When some of the parameters are assigned with membership functions, the model becomes a hybrid inexact-fuzzy MOP (IFMOP) problem. In this study, the
IFP algorithm is used for converting uncertain multiobjective problems into their deterministic forms. Thus, coefficients in the objective functions and the constraints' left-hand sides are handled as inexact intervals, while linear membership functions are assigned to fuzzy goals of the system objectives and the right-hand side constraint values.

The study area was divided into seven subareas with different environmental, economic, and resource characteristics. The planning horizon was 15 years which were further divided into two periods (1995 to 2000 and 2001 to 2010). Based on detailed investigation of the study system and extensive interaction with local authorities and stakeholders, three groups of objectives were considered to have top priority, including (1) economic return, (2) forest coverage, and (3) water quality (minimization of nitrogen, phosphorous, and COD losses) and soil conservation.

The conceptual expression of the IFMOP model is as follows:

\[
\text{maximize} \quad \text{economic return}, \quad \text{forest cover},
\]

\[
\text{minimize} \quad \text{soil loss}, \quad \text{water quality objectives:}
\]

- nitrogen loss,
- phosphorous loss,
- COD discharge,

\[
\text{subject to:}
\]

- land availability constraints,
- agricultural production constraints,
- forest-related activity constraints,
- industrial activity constraints,
- tourism-related activity constraints,
- net-cage fish culture constraints,
- lime/brick production constraints,
- water demand/supply constraints,
- soil loss constraints,
- water quality constraints,
- technical constraints.

The detailed model and solution method was provided in Huang et al. (1996).

Generally, this hybrid inexact-fuzzy optimization approach will have effective identification, quantification, communication, and assessment of uncertainties in different forms and the associated interactive solution process. The ORSYS is capable of dealing with large-scale (mix-integer) linear programming problems. It can retrieve the information from the EXCEL worksheet and export the solutions back to the EXCEL. Figure 3 shows EXCEL and ORSYS modules used in the optimization process.

GIS-SUPPORTED WATER QUALITY MANAGEMENT SYSTEM

Geographical information system (GIS) is used for graphically analyzing managing knowledge of the study watershed by capturing, manipulating, processing, and displaying spatial and geo-referenced data. The GIS technology is chosen as a basic tool throughout the modeling processes due to its ability to clearly expose complex environmental conditions within the watershed. GIS is used in three areas throughout the system development and implementation process: (i) managing spatial and non-spatial database; (ii) linking models; and (iii) providing interface between the models and their users.

Database Management

The GIS database management subsystem focuses on the attributes and data necessary to run the simulation models. The major elements include soil properties, climate, topography, hydrography, land use, water quality, pollution sources, and environmental management practices. GIS is used for data entry, comparing data from different sources and formats, assessing data availability and quality (e.g., accuracy and scale), and identifying errors in data (Grossmann et al., 1993). All encoded digital data, coverages, and model variables in the GIS were spatially organized with a consistent resolution and coordinate system. Spatial graphic data from different sources with different formats are entered into and analyzed by ArcInfo, and presented by ArcView. Nonspatial data are stored as attribute files. Figure 4 graphically shows an ArcView display for data and map. The developed GIS system assures the integrity of data and makes it possible for them to be used in the modeling processes, and result analysis and presentation.

![Figure 3 EXCEL and ORSYS modules used in model-base management subsystem](image)

**Figure 3** EXCEL and ORSYS modules used in model-base management subsystem

**Model-base Management**

The GIS system, with its spatial analysis functions, is used to connect each individual model to form an integrated modeling framework. Especially, the simulation and optimization models can be connected to allow the simulated results be input into the optimization models and the optimized results be reflected in the simulation. These connections are achieved through ArcView.
GIS Interface

This component provides a two-way communication between the system and its users. A system user may interactively delineate an area of concern, identify contamination sources to be considered, add additional data, or specify a particular planning objective. On the other hand, the system can explain to the user about each step in the modeling process, and display results from running simulation and optimization models. The system also provides its users an evaluation of quality of the data, accuracy of the results, and level of the uncertainties. If the users are not satisfied with the results from the available inputs, the system can recommend what data are needed to improve the modeling performance.

This interface links watershed database, various models, and system users together. Thus, the developed system can not only access and manipulate a great variety of basinwide data and provide a wide range of analytical functions and processes to prepare data for modeling, but also provide basin planner with direct graphic information. For example, users may easily modify the tradeoffs between different objectives based on a graphical menu, and then obtain solutions under the new scenario. This function is useful for decision-makers to review the flexible decision space provided by the modeling outputs and make their judgement and/or adjustment for the generated alternatives.

Data display is the final stage in the modeling process, which is concerned with the communication of geographic information to the user. ArcView is used for displaying the modeling results. The software allows users to create their own views of geographic data. The users may use basic ArcView statistical and spatial query functions to selectively output information. The Avenue scripting language, as well as VISUAL BASIC and VISUAL C++, are used to create user interfaces (Figure 5).

RESULTS AND DISCUSSION

According to the local authority, protection of water quality in Lake Erhai is of the highest priority. Economic development in the study basin should not be based on the cost of lake water contamination. This leads to four modeling scenarios corresponding to different environmental-economic tradeoffs.

Among them, scenarios 1 provides a balance between environmental and economic objectives. It is suitable for the existing system and its potential development in the future, and is thus recommended for practical implementation. Table 1 shows solutions to the six objective functions under this scenario.

<table>
<thead>
<tr>
<th>Objective Function</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic benefit, $10,000</td>
<td>414,378</td>
<td>583,830</td>
</tr>
<tr>
<td>Forest coverage, km²</td>
<td>1,712</td>
<td>1,875</td>
</tr>
<tr>
<td>Soil loss, ton</td>
<td>12,311,270</td>
<td>13,377,854</td>
</tr>
<tr>
<td>Nitrogen discharge, kg</td>
<td>7,838,750</td>
<td>10,067,193</td>
</tr>
<tr>
<td>Phosphorous discharge, kg</td>
<td>1,291,996</td>
<td>1,857,567</td>
</tr>
<tr>
<td>COD discharge, kg</td>
<td>251,129,094</td>
<td>348,814,867</td>
</tr>
</tbody>
</table>

Scenario 2 is suitable for situations where industrial development is emphasized, which may lead to increased economic return as well as increased risks of lake water pollution problems. This scenario corresponds to a relatively optimistic environmental management strategy. However, reliability of achieving water quality objectives may become dependent upon how pollution problems are controlled. Scenario 3 emphasizes on industrial water pollution control with the cost of significantly reduced economic return. This corresponds to a conservative strategy. Potential adjustments of the generated decision plans by decision-makers are possible based on the provided computer software packages and interfaces. Thus, based on the modeling outputs, the post-modeling analyses, and the acquired knowledge of the system’s characteristics, many specific environmental management actions can be identified.

For the planning of human activities, the results show that economic activities are necessary for regional development. Among them, tourism industry would be promoted due to its low pollution potential and high economic efficiency. However, the related tourist flow is not only related to human efforts for improving scenic spots and service sector, but also a number of external factors. This means that there exists an upper limit for potential tourist flow. Figure 6 provides tourism development plan for the seven sub-areas.

Agriculture is a traditional activity in the basin area. The majority of population in the region are farmers. Agricultural activities
produce less than 1/5 of total economic return in the basin area. At the same time, they generate significant nonpoint source pollution problems. Since agriculture has been developed to a matured level, and the related management measures can only partly mitigate the environmental problems, it is suggested that the agricultural activities and the related pollution concerns may not fluctuate with time so significantly as other activities (e.g., tourism and industry). As an example, Figure 7 presents the solution for vegetable farming:

![Figure 7: Planning for vegetable farming](image)

For industrial activities, cigarette industry contributes to the majority of regional economy with relatively low pollution potential. Food processing industry would be promoted since it is needed for supporting tourism development and for corresponding to improved living standard. Figure 8 shows planning for the food processing industry. For the other industries, pulp, chemical fibre and leather production generate large amounts of organic pollutants (with high COD concentrations) under the existing technologies. It is suggested they be significantly reduced or cut. For textile, paper and cement industries, it is recommended that their status would be flexible from short-term management point of view. Since the study system is now with demanding environmental conditions, a relatively conservative strategy may be desired. Therefore, from long-term planning point of view, it is suggested that those industries' further development be limited. At the same time, development of high-tech industries with low or no pollution impacts would be encouraged.

![Figure 8: Planning for food processing industry](image)

Net-cage fish culture should be cut due to its significant contribution to N and P pollution problems in the lake. An alternative for this type of activity is to develop fish ponds out of the lake. Number of vessels for in-lake fishing and navigation should be limited to reduce direct sewage/waste discharge into the lake. Sanitary toilets should be installed within the existing vessels. Also, public lavatories with sanitary facilities should be constructed at docks for the vessels, with the sewage being collected and treated periodically.

**CONCLUSION**

1. In this study, a hybrid GIS-supported watershed modeling system is developed for integrated planning of water pollution control in the Lake Erhai Basin. This system consists of three major components: database, modelbase, and user interface. The modelbase includes three aspects: (i) simulation models for bridging source/impact factors and the related water quantity and quality, (ii) an optimization model for compromising a variety of system objectives and generating desired decision alternatives, and (iii) post-modeling analysis for further trade-off analysis and risk assessment. The GIS technology is chosen as a basic tool throughout the modeling process. It allows smooth communication among the database, the models and the users.

2. An inexact-fuzzy multi-objective programming (IFMOP) model is developed as a planning tool. It can effectively reflect uncertain, interactive, and multiobjective features of the study system. The inexact solutions provide decision-makers with a flexible decision space, and are useful for further risk analysis. Three decision alternatives are generated by adjusting decision variable values within their solution intervals.

3. An important advantage of this study is its real-time feature. When environmental and socio-economic conditions are significantly changed in the future (e.g., when an unexpected large project is developed in the basin area two or three years later), the provided planning alternatives may become not applicable. Consequently, updated alternatives need to be provided. For the previous environmental planning, the provided reports may become useless, and a new planning project may have to be initiated again. In comparison, this study provides not only research reports for planning based on the existing information, but also a set of flexible computer software packages. Thus, when conditions are significantly changed in the future, local engineers/planners can input updated information into the computer-managed database, run the user-friendly modeling software, and obtain a new set of planning alternatives through the provided graphic interfaces.

4. This study is the first integrated environmental planning study in China. Comprehensively and quantitatively, it provides planning schemes based on development/application of a set of effective decision-support methodologies. The provide software and part of the recommended schemes have been used by the local authorities in their management practices.

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