DOI: 10.1007/s00267-004-0307-3

A Hierarchical Fuzzy Decision Support System for the Environmental Rehabilitation of Lake Koronia, Greece

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ABSTRACT / This article presents the design of a fuzzy decision support system (DSS) for the assessment of alternative strategies proposed for the restoration of Lake Koronia, Greece. Fuzzy estimates for the critical characteristics of the possible strategies, such as feasibility, environmental impact, implementation time, and costs are evaluated and supplied to the fuzzy DSS. Different weighting factors are assigned to the critical characteristics and the proposed strategies are ordered with respect to the system responses. The best strategies are selected and their expected impact on the ecosystem is evaluated with the aid of a fuzzy model of the lake. Sensitivity analysis and simulation results have shown that the proposed fuzzy DSS can serve as a valuable tool for the selection and evaluation of appropriate management actions.

Decision theory is an axiomatic theory used for making choices in uncertain conditions (Fischhoff and others 1981). Davis (1988) defined a decision support system (DSS) as a mechanism that facilitates complex decision-making under uncertainty. However, many complex decision-making problems have multiple objectives, and preference trade-offs between differing degrees of achievement for each objective must be taken into account (Jimenez and others, 2003).

Environmental decisions tend to have considerable uncertainty associated with them. The full range of possible outcomes might not be known and it might not be possible to assess probabilities for the outcomes. Additionally, some decisions might lead to irreversible outcomes, and in many cases, there exist multiple decision-makers and multiple objectives. For these reasons there has been considerable application of the DSS approach to environmental problems, particularly in the water resource management area. Simonovic (1996a, Simonovic (1996b), for example, discussed the issue of DSS for sustainable management of water resources. A set of system evaluation criteria was identified, namely environmental integrity, economic efficiency, and equity. Gough and Ward (1996) developed a DSS based on a "soft" system learning approach and applied it to a case study of environmental decision-making under uncertainty. Soncini-Sessa and others (1999) presented a DSS for reservoir management. Recio and others (1999) developed a DSS for the determination of long-term political management of water resources. Prato (1999) developed a Land and Water Resource Management System (LWRMS) for decision-making in the distribution of territorial and aqueous resources between various competitive users. More recently, Quinn and Hanna (2003) developed a DSS for wetland management. The Global Information System (GIS) technology has also been widely used in water-quality management (e.g., Huang and Xia 2001; He 2003).

Many researchers tried to deal with the uncertainties that are inherent in environmental decision-making through fuzzy, stochastic, and other inexact programming approaches. Lee and Wen (1997), for example, applied the technique of fuzzy goal programming to water- quality management in river basins. Sasikumar and others (1999) employed fuzzy optimization methods for planning the water-quality-management system in a river basin. Zeleznikow and Nolan (2001) proposed the use of soft computing for the design of a DSS in uncertain domains. More recently, Chiou and Tzeng,

KEY WORDS: Environmental decision support systems; Fuzzy logic

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(2002) presented a fuzzy integral technique in multicriteria decision-making problems.

The work presented in this article lies in the field of environmental DSS. More specifically, this article presents the development and design of a fuzzy decision support system for the assessment of alternative strategies proposed for the restoration of a lake that is highly affected by industrial and agricultural activities. Fuzzy inference is used to represent the concepts of vagueness and uncertainty associated with the ecosystem. However, the proposed DSS differs from other fuzzy approaches in the sense that results from the fuzzy inference are used to run a lake simulation model (Ioannidou and others 2003) that is based both on experts' knowledge and available measurements.

Moreover, the proposed fuzzy inference system is decomposed in a number of hierarchically interconnected subsystems, thus avoiding the explosion in the number or fuzzy rules [the "curse" of dimensionality (Kosko 1997)]. A dynamic feedback path exists between the fuzzy subsystems, and the proposed model captures the dynamic interactions between the environmental stressors of the lake ecosystem.

The proposed fuzzy DSS allows the evaluation of alternative strategies, as they are proposed in the specific management plans for the lake. The selection of the best strategies is achieved based on a number of specific criteria, and their performance is evaluated with the aid of the fuzzy model of the lake. The results obtained allow the effective redesign and adaptation of the proposed strategies. Sensitivity analysis and simulation results obtained for more than 20 proposed strategies and their variations show that the proposed fuzzy DSS can serve as a valuable tool for the selection and evaluation of appropriate management actions.

Physicochemical Parameters for Lake Koronia

Lake Koronia is located 15 km northeast of the town of Thessaloniki in the region of Macedonia in northern Greece, at a latitude of 40°59' N and a longitude of 23°15' E, and with a mean altitude of 75 m above sea level. In the last 20 years, the lake has suffered from the consequences of increased water diversion for irrigation that led to a dramatic water-level decline and increased pollutant loads, combined with reduced surface runoff, that led to deterioration in water quality. During the 1970s, the lake had an area of 47 km^2 and a mean depth of 5 m; currently, it has an area of less than 30 km^2 and a mean depth of less than 1 m. These factors gave rise to the current hypertrophic conditions, which cannot support fish and other living organisms. As a matter of fact, the water-level decline and the deterioration in water quality led to the death of a large number of fish, and fish production was minimized in the summer of 1995. Fish production was kept to minimum ever since (Piesold and others 1999).

Recent reports on the environmental rehabilitation of the lake have shown that there is an accumulation of inorganic salts in the lake, caused by the continuing decrease in lake volume and by the continuing discharge of high-salinity wastes from the textile industry (Piesold and others 1999; Grammatikopoulou and others 1996; Hellenic Ministry of Agriculture 2001). Similarly, there is an accumulation of nonbiodegradable organic substances originating from external sources (i.e., the continuing discharge of chemical substances from the textile and food industries, pesticides, and fertilizers) and internal sources (i.e., the biological degradation of organic matter in the lake) (Piesold and others 1999; Hellenic Ministry of Agriculture 2001; Tsiouris and others 2002). Due to the increased agricultural activities, the concentration of nutrients and organic matter exceeds the lake capacity for self-purification and, therefore, anoxic conditions prevail in the water column, particularly close to the bottom (Piesold and others 1999, Tsiouris and others 2002). Regarding the ability of the water to support fish life, several parameters, such as the pH, free ammonia, and dissolved oxygen exceed by far the limits that will permit fish and other aquatic organisms to survive (Piesold and others 1999; Hellenic Ministry of Agriculture 2001; Bobori and Economidis 1996).

The variation of these parameters for Lake Koronia is shown in Figures 1a–1c. Measurements were taken from the Greek Ministry of Agriculture, the Ministry of the Environment, and other surveys (Piesold and others 1999; Grammatikopoulou and others 1996; Hellenic Ministry of Agriculture 2001; Tsiouris and others 2002; Bobori and Economidis 1996). Parameter values were normalized in order to be displayed on a common chart (e.g., pH values were multiplied by a factor of 1000). Further analysis on the physicochemical parameters for Lake Koronia and on the feedback interactions among dominant environmental stressors can be found in Ioannidou and others (2003).

Fuzzy Inference Principles

Applicability of the optimization techniques to water-quality management is affected by many factors. First, the water-quality-management systems are complex, and the number of factors and interrelationships are hard to express as mathematical formulas. Also, nonlinearities that exist in the system can hardly be effectively reflected. Second, information for a number

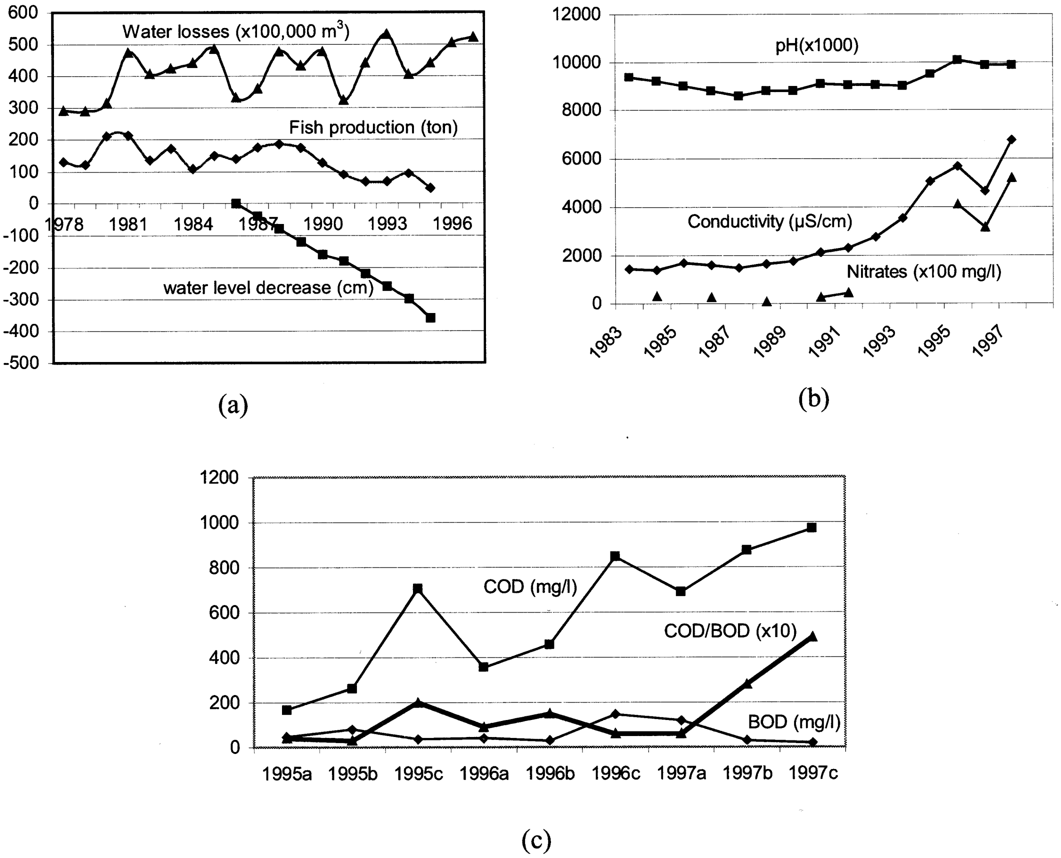

Figure 1. Variation of physicochemical parameters for Lake Koronia.

of system parameters is often unavailable so rough estimations have to be made. Several alternative strategies have to be considered and evaluated in terms of many different criteria, resulting in a vast body of data that are often inaccurate or uncertain. Furthermore, human judgment of events might be significantly different based on individuals' subjective perceptions or personality, even using the same words. Therefore, fuzziness is considered to be applicable. Fuzzy inference can generate models that encapsulate both the knowledge provided by the experts as well as the available measurements for a system. Fuzzy logic provides the means to transform quantitative measurements of environmental variables into fuzzy membership functions. If x represents the value of an environmental variable, then $\mu(x)$ is the corresponding membership in a set of acceptable conditions and takes a value between 0 and 1. Thus, the membership value denotes the degree that an object belongs to a fuzzy set (Zadeh, 1965).

The relationship between an environmental variable x and its membership value $\mu(x)$ can have different forms. In this article, both asymmetric and symmetric membership functions were used for the implementation of the fuzzy sets. A parametric form of the sigmoid function was used, defined as

$$f_s(x, a, c) = \frac{1}{1 + e^{-a(x-c)}} \qquad (1)$$

where the parameters a and c determine its shape and position. This function was used especially at the low and high regions of the input/output variables, reflecting the fact that some certainty exists when assessing very low and very high values. Parameter modification of the proposed sigmoid function allows for sharp thresholds between the fuzzy sets. Additionally, a parametric form of the Normal distribution was also used for the membership functions, defined as

$$f_n(x, \sigma, c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \qquad (2)$$

with σ being the standard deviation and c a parameter specifying the shape of the distribution (Mathworks 1999; Kosko 1997). Standard triangular and trapezoidal membership functions were also used and their forms can be defined using sets of straight-line equations.

Fuzzy variables are combined and formulated as fuzzy relations or "rules." The process of combining the effects of several fuzzy rules is called fuzzy inference. The Mamdani type of fuzzy inference (Mamdani 1974) was used in the proposed DSS system and the related subsystems. The Mamdani inference for N rules R^1, R^2,..., ^{RN} of two fuzzy variables A and B is defined as

$$R^N = \bigvee_k R^k \qquad \text{for } k = 1 - N \tag{3}$$

$$\mu_R^N(x, y) = \bigvee_k(\mu_k^A(x) \wedge \mu_k^B(y)) \qquad \text{for } k = 1 - N \tag{4}$$

where R^k denotes the kth rule (k is the rule index), x takes values in fuzzy variable A, y takes values in fuzzy variable in B, $\mu_A{}^k(x)$ and $\mu_B{}^k(y)$ are the membership functions for the fuzzy sets of variables A and B, respectively, for the kth rule, the symbol $\bigvee$ denotes the max operator, and the symbol $\wedge$ denotes the min operator. More simply, the different antecedents of a rule are connected with logical AND (corresponds to the min operator), and the implication method used when implying from the antecedents is based on the min operator, truncating the output set. Finally, the max operator (corresponding to logical OR) is used when the different rules are aggregated (Mathworks 1999; Kosko 1997).

Because the combined effect of the rules is represented by a combined membership function, it is essential to devise a means of providing a single output value from the fuzzy set. This process is called "defuzzification" and, essentially, it is a way of producing quantitative results from qualitative laws. The center of area method (Kosko 1997; Altrock 1995) was chosen for the output defuzzification. This method calculates the center of the area (COA) of the combined output membership function $\mu_y(y)$ of a variable y, as follows:

$$y_{\text{COA}} = \frac{\displaystyle\int_s y\mu_y(y)\ dy}{\displaystyle\int_S \mu_y(y)\ dy} \tag{5}$$

where S denotes the range of y values covered by the combined output surface [it is called the support of $\mu_y(y)$]. The idea behind this method is that because the output of the fuzzy inference is a geometrical aggregation of fuzzy sets, the geometrical center of the combination of these fuzzy sets takes into consideration even the slightest contribution of each set. Thus, the COA method, when combined with the Mamdani inference, takes into consideration even the smallest influence of a rule because this is accounted for in the combined output area.

Development of the Hierarchical Fuzzy DSS

Design Objectives

The development of the proposed DSS was based on the following principles: (1) restoration of the water balance in the lake, (2) improvement of the water quality, and (3) development of a sustainable environment around the lake. Any viable strategy selected by the DSS must satisfy the following conditions: (1) The water supply to the lake should be of a high quality, as the lake has very limited self-purification capabilities, (2) the water supplied to the lake through diversions of water from other sources (rivers, springs, etc.) must not have a negative effect on the environmental state of these sources and must not affect the native population counting on them, and (3) it must be environmentally and financially self-sustained, allowing reusability of the water resources. Strategies that are impractical or inflict irreversible environmental damage must be excluded. Moreover, some strategies should be excluded based on expected benefit over cost criteria.

Environmental reports on the rehabilitation of the ecosystem of Lake Koronia have shown that a water level of 73 m above sea level (equivalent to a water supply of 200 Mm^3 to the lake) is desired, whereas the water quality should be suitable for cyprinoids (Piesold and others 1999).

Thus, the proposed DSS assesses the restoration strategies in terms of the following criteria:

1. *Feasibility* of a strategy, a measure related to the practicality of its implementation
2. *Environmental impact* of a strategy to the nearby resources, related to the competition among local basins for sharing the available resources
3. *Overall implementation time,* a critical issue especially when the lake is in a degraded environmental state
4. *Overall cost,* including initial cost and maintenance costs.

Strategies proposed for the restoration of the lake fall into two broad categories: (1) water- level-restoration strategies and (2) water-quality-improvement strategies. The water supply from external natural sources is planned to take place only during winter months, when agricultural needs are limited. The water supplied to the lake should be of premium quality on a continuing basis and the danger of polluting the water during transportation should be kept to a minimum. Finally, it

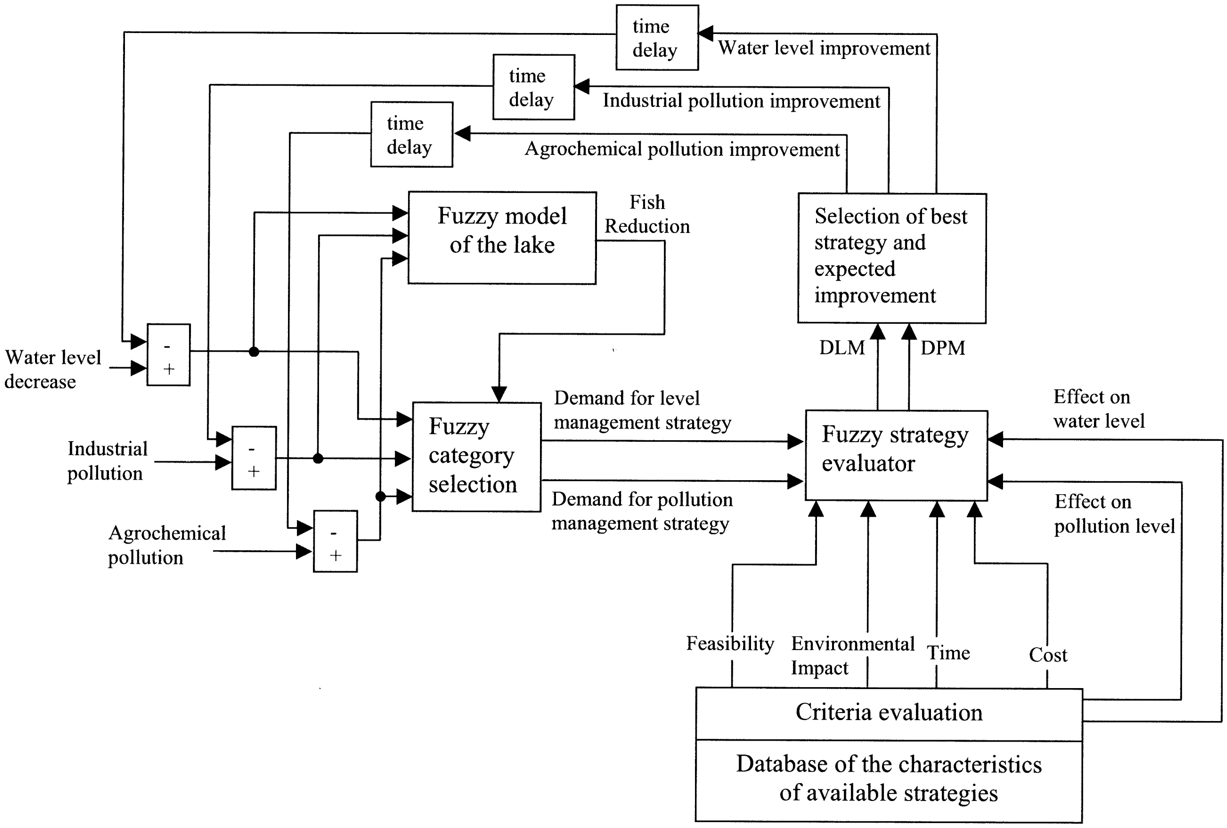

Figure 2. Block diagram of the fuzzy DSS architecture.

must be mentioned that the improvement in water quality is directly related to the increase of water volume in the lake.

The effect of environmental decisions on the ecosystem manifests itself through the use indicators. For an indicator to provide valuable information, it must be related in a predictable way to both management actions and to some parts of the system that can influence the sustainability of the system. Indicators should provide remedial responses (Cornforth 1999). Thus, the criteria for selecting indicators were the following: (1) Indicators must be sensitive and respond predictably to variations in management, (2) indicators must correlate well with the ecosystem processes, and (3) indicators must be simple in concept. It has been shown by Ioannidou and others (2003) that fish reduction can serve as an indicator of the ecosystem state and it also satisfies the above-mentioned criteria. Additionally, water-level decrease and industrial and agrochemical pollution as related to the conductivity, pH, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), and nitrates variation (shown in Figure 1) were used in the fuzzy model of Lake Koronia presented by Ioannidou and others (2003). Because the same model is used in the proposed DSS in order to assess the environmental state, the same indicators were also adopted.

DSS Overview

A block diagram of the proposed DSS is shown in Figure 2. The fuzzy model of the lake receives at its inputs the external values for the indicators water-level decrease, industrial pollution, and agrochemical pollution, based on the available measurements. More specifically, apart from the water-level decrease that is used directly as a state variable, a fuzzy combination of the variations in conductivity, pH, COD, and BOD was used to determine the fuzzy sets for the state variable "industrial pollution." Additionally, a fuzzy combination of the variations in nitrates, conductivity, pH, and water losses was used to determine the fuzzy sets for the state variable "agricultural activities" (Ioannidou and others 2003). The conductivity and pH are used as measures of both industrial pollution and agricultural activities, as they are very important factors. The lake model takes into consideration both the available measurements as well as the experts' knowledge, formulated in a set of fuzzy rules, and produces at its output an estimate of the fish production capabilities of the lake. The *fish reduction index* is combined with the external inputs in the *fuzzy category selection* block. The status of the index combined with the external indicators provides two outputs: the demand for a level management strategy or a pollution management strategy. Thus, depending on the status of the ecosystem, one category of strategies might be more desirable than the other for immediate application.

The *database storing the characteristics* of all available strategies is used to evaluate each strategy with respect to the criteria described in the previous section (i.e., feasibility, environmental impact, implementation time, and cost). Additionally, the expected effect of a strategy on the restoration of the water level or the pollution level is reported. In this way, strategies aiming at restoring the water level are discriminated from strategies aiming at improving pollution. It must be noted that some of these criteria might be inexact or of a fuzzy nature.

Based on these criteria and the demand for the appropriate category of strategies, the *fuzzy strategy evaluator* block assesses all possible strategies and assigns to each one of them a degree of applicability under the present ecosystem status. This information is fed to the *selection of best strategy and expected improvement* block through two signals: (1) degree of applicability for level management strategies (DLM) and (2) degree of applicability for pollution management strategies (DPM). This block orders all available strategies with respect to their degree of applicability and selects the strategy that provided the maximum response (both from level management and pollution management strategies). Each strategy in the database is associated with three normalised parameters that are estimates of the improvement that is expected to be achieved, after the application of the specific strategy (1) in the water level, (2) in industrial pollution, and (3) in agrochemical pollution. The improvement parameters refer to a specific time period of application or to a repeated application of a specific strategy for a succession of time steps. Thus, a time delay appropriate for the chosen strategy is imposed on the improvement parameters, whose values are subtracted from the external values, in the appropriate subtractor blocks (initially their values are set to zero). The outputs of the subtractor blocks serve as the new estimates of the ecosystem status and they are fed to the *fuzzy lake model* block, as shown in Figure 2. This block evaluates the new value for the fish reduction index. The improvement achieved on the fish reduction index serves as a measure of the overall improvement achieved after the application of the chosen strategy.

For strategies requiring repeated application for a succession of time steps, the procedure is repeated along the feedback loop, until the final index is produced. The actual value for the time step is specified by the time period required for the improvement parameters to take effect. As it will be shown in the last section of the article, the simulation time steps for the proposed case study are set to years. Moreover, depending on the status of the ecosystem after the application of the best strategy, the next best strategy can be applied (e.g., a level management strategy followed by a pollution management strategy as the next best strategy). In this case, the effects on the ecosystem are cumulative.

DSS Implementation

The fuzzy inference blocks shown in Figure 2 were designed according to the fuzzy design principles described by Equations 1–5. The fuzzy systems were implemented in the well- established computational environment of MatLab (Mathworks 1999) with the aid of the Fuzzy Logic Toolbox. The fuzzy systems were interconnected together with the time delays, the database of characteristics, the subtractors, and the selection of best strategy block in MatLab’s Simulink Environment (Mathworks 1999), which allows simulations and performance comparisons to be made for the overall system. The number of fuzzy membership functions for each input and output variable of each fuzzy block, as well as their shape, size, and degree of overlap were investigated in several design attempts in order to satisfy both the qualitative knowledge expressed by sets of fuzzy rules, and the quantitative parameter variations. It must be noted that zero threshold values (alpha values) for determining the membership of a value to a fuzzy set were used. Strategies are ranked relative to each other, and by setting threshold values to zero, even the slightest contribution of a proposed strategy is taken into account. The most significant subsystems are presented in detail in the following subsections. The design for the rest of the blocks follows the same lines; it is simpler and hence not shown.

Fuzzy Model of the Lake

The fuzzy model of the lake assesses the combined effect of the positive feedback interactions among the most significant stressors (i.e., industrial pollution, pesticide, and nutrient usage due to agricultural activities, and water-level decrease due to irrigation works) on the reduction of fish production in the lake. Stressor interactions might be of an augmenting or a diminishing type and the existence of positive feedback loops among them is a critical issue, as it might lead the ecosystem to a nonreversible state (Ioannidou and others 2003).

The proposed model was based on a set of fuzzy rules that express the experts' knowledge and on available measurements for the physicochemical parameters of the lake, which are shown in Figure 1. Its operation was successfully verified for a variety of environmental conditions, including critical states for the lake. This model is used in the proposed fuzzy DSS, within the bounds of the data it has been trained for and its generalization capabilities (Ioannidou and others 2003), in order to provide an estimate for the fish reduction index and to assess the improvement resulting after the application of a strategy, as shown in Figure 2. A more detailed analysis on the fuzzy model of the lake and its operation can be found in Ioannidou and others (2003).

Fuzzy Strategy Evaluator

The fuzzy strategy evaluator takes at its inputs the values for the criteria feasibility, environmental impact, implementation time, and cost, as they are evaluated at the output of the *database of the characteristics of available strategies* block and combines them with the demand that exists for a level or pollution management strategy (as these demands are produced at the output of the *fuzzy category selection* block). For each of the available strategies, its expected effects on water and pollution level are also fed to the fuzzy strategy evaluator, serving as rough estimates of the suitability of the strategy for water-level restoration and pollution-level restoration, respectively, as shown in Figure 2. Thus, the proposed block receives eight inputs and produces two outputs (DLM, DPM). In this sense, its design can be considered quite complex. Assuming that only a moderate number of fuzzy sets is used for each input (e.g., five), this would result in a combinatorial explosion in the number of fuzzy rules, that is a total of $5^8 = 390{,}625$ possible rules would be required [the "curse" of dimensionality in fuzzy design (Kosko 1997)]. The design of such a huge fuzzy inference system would be extremely tedious and the extreme partition of the knowledge space into hundreds of thousands of rules (most of them being of insignificant value or even impossible to occur in reality) would no longer directly reflect the experts' knowledge about the system. Moreover, such a system would be slow in execution speed and requiring a very large storage space.

In order to overcome these difficulties, the proposed fuzzy block was hierarchically decomposed into the five interconnected fuzzy subblocks FS1–FS5 shown in Figure 3. The FS1 system receives at its inputs the *demand for level management strategy,* as calculated by the fuzzy category selection block, and the *effect on the water level* that a proposed strategy is expected to have. The fuzzy sets and rules for this block were derived according to the following considerations: If there exists a high demand for a level management strategy and, at the same time, a specific strategy chosen from the database is expected to have a large positive effect on water level, then this block produces a very high output. If, on the other hand, the current demand for a level management strategy is low or the expected effect of a specific strategy on water level is low, then the output of this block is also low (needless to point out that if both demand and expected effect are low, the output is very low). The FS3 system is almost identical to FS1, but applied to a *demand for pollution management strategy* and to an expected effect of a specific strategy on pollution levels. Thus, the *effect on water level* and the *effect on pollution level* signals are used to discriminate between level management and pollution management strategies, respectively.

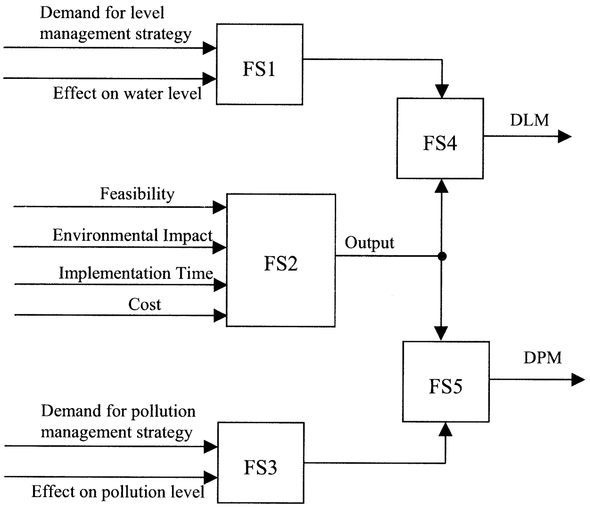

Figure 3. Hierarchical decomposition of the fuzzy strategy evaluator block.

The FS2 block receives at its inputs the rest of the strategy evaluation criteria (i.e., feasibility, environmental impact, implementation time, and cost). Each strategy is evaluated with respect to these criteria, and strategies that are more feasible than others pose smaller environmental risk and can be implemented quickly and with a small cost produce a higher value at the system output. The number and form of the fuzzy sets for each input and the output of the FS2 block were varied in a number of alternative design attempts, in order to produce the desired performance. The input/output fuzzy sets are shown in Figure 4. Additionally, a

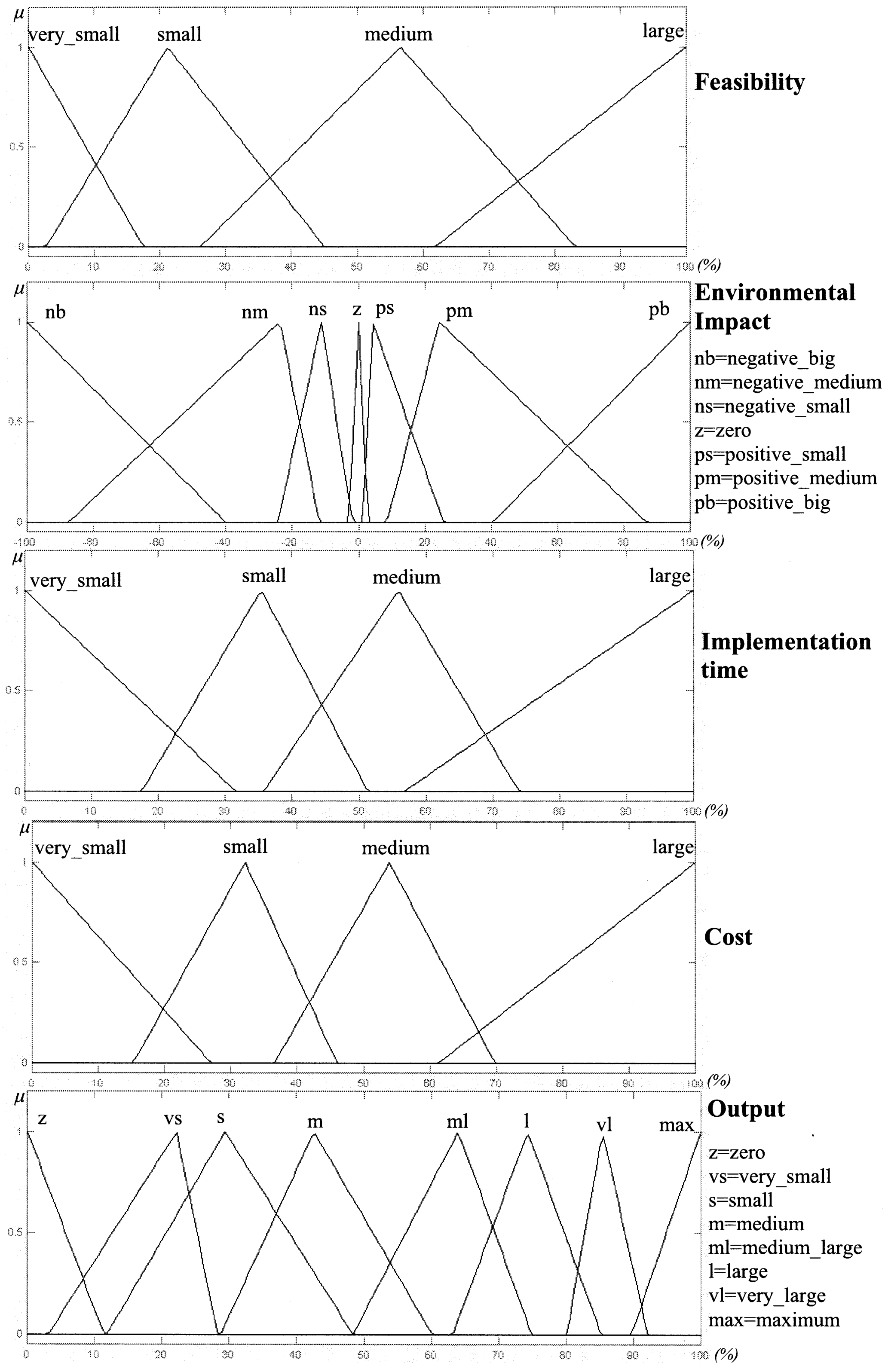

Figure 4. Fuzzy set design for the input and output variables of the FS2 block.

Table 1. Characteristic fuzzy rule examples for the FS2 block

Rule no.		Feasibility		Environmental impact		Implementation time		Cost		Output
1.	*IF*	very_small	*AND*	negative_big	*AND*	very_small	*AND*	very_small	*THEN*	very_small
17.	*IF*	very_small	*AND*	negative_medium	*AND*	very_small	*AND*	very_small	*THEN*	small
33.	*IF*	very_small	*AND*	negative_small	*AND*	very_small	*AND*	very_small	*THEN*	small
65.	*IF*	very_small	*AND*	positive_small	*AND*	very_small	*AND*	very_small	*THEN*	medium
97.	*IF*	very_small	*AND*	positive_big	*AND*	very_small	*AND*	very_small	*THEN*	medium_large
130.	*IF*	small	*AND*	negative_medium	*AND*	very_small	*AND*	small	*THEN*	medium
150.	*IF*	small	*AND*	negative_small	*AND*	small	*AND*	small	*THEN*	medium
166.	*IF*	small	*AND*	zero	*AND*	small	*AND*	small	*THEN*	medium_large
263.	*IF*	medium	*AND*	negative_small	*AND*	small	*AND*	medium	*THEN*	medium_large
386.	*IF*	large	*AND*	zero	*AND*	very_small	*AND*	small	*THEN*	very_large
402.	*IF*	large	*AND*	positive_small	*AND*	very_small	*AND*	small	*THEN*	very_large
433.	*IF*	large	*AND*	positive_big	*AND*	very_small	*AND*	very_small	*THEN*	max
434.	*IF*	large	*AND*	positive_big	*AND*	very_small	*AND*	small	*THEN*	max
443.	*IF*	large	*AND*	positive_big	*AND*	medium	*AND*	medium	*THEN*	very_large
448.	*IF*	large	*AND*	positive_big	*AND*	large	*AND*	large	*THEN*	large

priority scheme was implemented with the fuzzy rules so that the criteria are weighted from a higher to a lower significance, in the order feasibility, environmental impact, implementation time, and cost. In this sense, strategies that are more practical and feasible or pose a smaller environmental risk produce higher output values than strategies that are fast to implement or they cost less even though they are not as feasible or they are associated with greater environmental risks. This approach is in absolute accordance to the experts' suggestions presented in the management plans (Piesold and others 1999). An overall number of 448 rules were implemented by the authors for the fuzzy inference system, by combining the input fuzzy sets for the respective criteria and after adopting the experts' suggestions and priority scheme, as proposed in the management plans and research reports. Some characteristic rules are shown in Table 1.

The FS4 fuzzy subsystem combines the outputs of the FS1 and FS2 subsystems in order to produce the degree of applicability for level management strategies (DLM). Its design requirements are much simpler than those for the FS2, and the fuzzy rules were formed by taking into consideration the fact that a high FS1 output (high demand and high effect on water level) when combined with a high FS2 output (a strategy that scores high values with respect to the criteria) should produce a high DLM signal (and the converse).

The design of the FS5 fuzzy subsystem is almost identical to the FS4, combining the outputs of the FS2 and FS3 subsystems and producing the degree of applicability for pollution management strategies (DLM).

Results and Discussion

Computer Simulations

In order to investigate the performance of the proposed DSS a series of computer-generated strategies were used, each one associated with different criteria values. A code number is assigned to each strategy and the variation in the respective criteria values produces the corresponding variation in the DLM and DPM values, as shown in Figure 5.

Strategies 1–11, for example, display the DPM variation for a gradual increase in feasibility (ranging from 0 to 100, in steps of 10) and for very small and fixed values in the environmental impact, implementation time, and cost criteria. Clearly, DPM increases as the feasibility of a strategy increases. Similarly, strategies 12–21 display the DPM variation for a gradual increase in environmental impact (ranging from −100 to +100 in steps of 20) and the rest of the criteria are set to fixed and small values. Strategies 22–24 correspond to an increase in implementation time (in steps of 30), whereas strategies 25–27 correspond to an increase in cost (again in steps of 30), the rest of the criteria are fixed to low values. Because the increase in implementation time and cost has a negative impact on the suitability of a strategy, these variations account for the drop in the DPM output. Strategies 28–37 correspond to a simultaneous increase in feasibility and environmental impact while keeping implementation time and cost to a minimum, thus producing high DPM outputs. The same situation is repeated in strategies 38–47, strategies 48–57, and strategies 58–67, but for increasingly higher implementation time and cost values. The

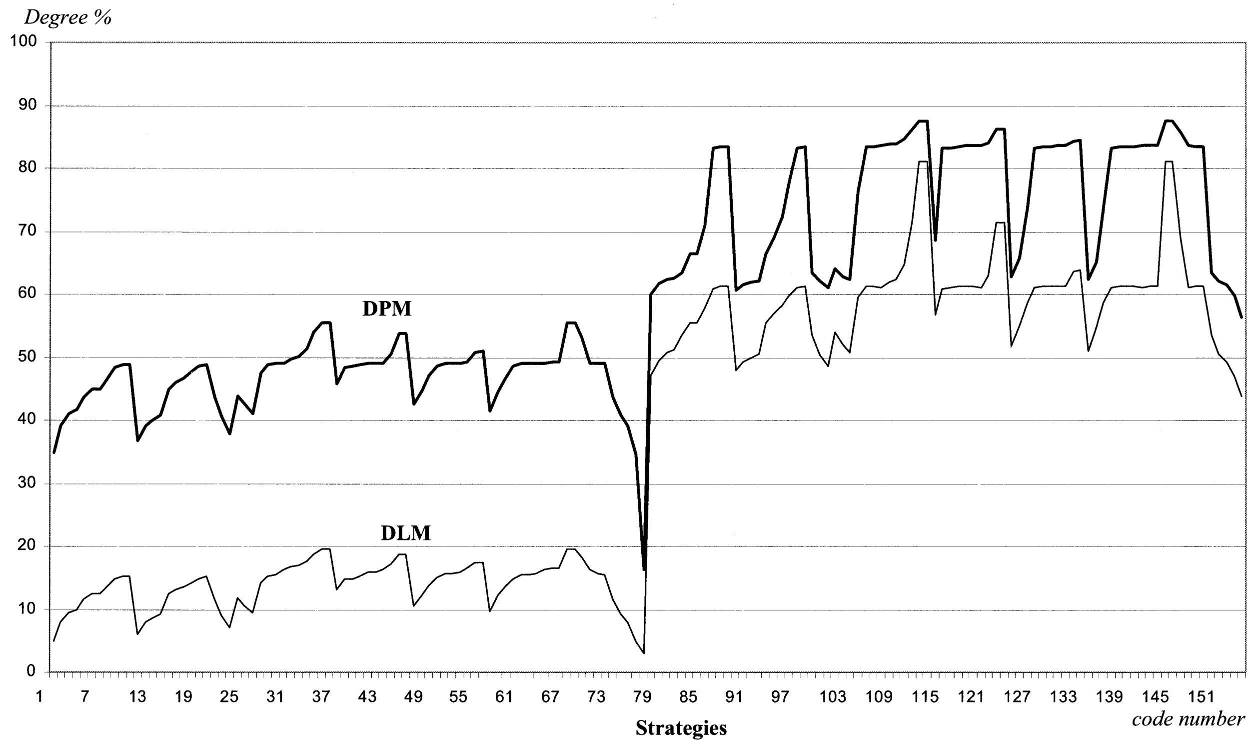

Figure 5. Fuzzy DSS results for a series of computer-generated strategies.

gradual increase in implementation time and cost accounts for the lower maximum values achieved for the corresponding sets of strategies.

Although for strategies 1–78 the variation in the DLM values shown in Figure 5 is qualitatively similar to that of the DPM values, the maximum DLM levels attained are quite lower. This is due to the fact that the signals *demand for level management strategy* (at the output of the fuzzy category selection block) and *effect on water level* (at the output of the criteria evaluation block) are set to minimum values whereas, signals *demand for pollution management strategy* and *effect on pollution level* are both set to one-third of the theoretical maximum value (signals vary from 0 to 100). Moreover, the variation of the criteria values for strategies 79–156 follows the same patterns as in strategies 1–78, but signals *demand for pollution management strategy* and *effect on pollution level* are both set to the value 90. Signals *demand for level management strategy* and *effect on water level* are both set to the value 60. This fact accounts for the higher DPM and DLM values and the steeper slopes obtained for this set of strategies. Thus, a maximum output response is obtained when there exists a high demand for a category of strategies, the expected effect of a particular strategy in that category is high, and, at the same time, feasibility and environmental impact values are high while implementation time and cost are kept low.

Sensitivity Analysis

Proper uncertainty assessment is essential to allow decision-makers to judge whether the model results are sufficiently accurate to support decision-making (Saloranta and others, 2003). A series of sensitivity analyses were performed in order to assess uncertainties relating to the proposed DSS parameter values and to the quality of input data. The system's response to variations of the input parameters was examined for a set of randomly generated strategies, evenly covering the range of input criteria and output values. The sensitivity degree S_Y is defined as follows:

$$S_Y = \frac{\Delta Y / Y}{\Delta X / X} \tag{6}$$

where Y denotes an output state (the response to a particular strategy) and X represents one of the criteria that affect the system; ΔY and ΔX denote increments of output state Y and criterion X, respectively, and S_Y is the sensitivity degree of state Y to criterion X. For n output states (Y_1, Y_2,..., Y_n, corresponding to different strategies), the general sensitivity degree to criterion X can be defined as follows (Guo and others, 2001):

$$S = \frac{1}{n}\sum_{i=1}^{n} S_{Yi} \tag{7}$$

Table 2. Sensitivity analysis results

Criterion	Sensitivity degree
Feasibility	0.22
Environmental impact	0.15
Implementation time	0.1
Overall cost	0.04

The sensitivity degrees for the criteria feasibility, environmental impact, implementation time, and cost were calculated according to Equation 7 by inducing a variation of ±5% in the values of a specific criterion, for all of the computer-generated strategies, while keeping the values of the rest of the criteria constant. The procedure was repeated for each criterion in turn. Table 2 displays the result of the sensitivity analysis for the above-mentioned criteria. It is indicated that the proposed DSS responds to all criteria with a low degree of sensitivity. Moreover, the sensitivity-degree values to all criteria reflect the relative importance of the criteria in the order feasibility, environmental impact, implementation time, and cost, as it was adopted in the construction of the fuzzy rules.

Furthermore, the impact of the simultaneous variation of input criteria on the ranking of strategies has to be investigated (Jimenez and others, 2003). Strategies were ranked according to the DPM and DLM values, and random variations were simultaneously added to the input criteria values. The magnitude of the random variations (normalized, uniform noise added around central values) was increased up to the 10% of the criteria values, in multiple simulation runs. The number of strategies that are ordered in a different rank, as a result of the addition of noise, serves as an indication of the impact of the criteria variations on the ranking of alternative strategies. Figure 6 displays the percentage of strategies ordered in a different rank, for various amounts of noise, ranging from 0 to ± 10% around the criteria values. Thus, if the criteria values for a strategy were varied simultaneously within an interval of ±3%, no differences in ranking were observed and the proposed DSS is quite robust. As the noise interval increases to ±5%, some strategies are ordered in a different rank, whereas for a larger noise interval, the number of these strategies increases significantly, as a result of the combined variation of all criteria.

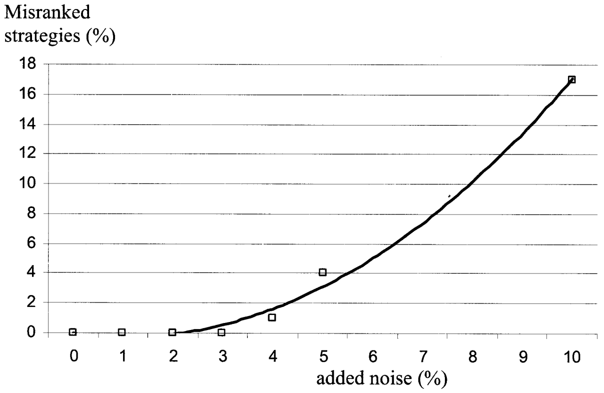

Figure 6. Percentage of strategies ordered in a different rank, for various amounts of noise.

Case Study: Application of the DSS to Lake Koronia

The proposed DSS was applied to a number of strategies that have been suggested for the rehabilitation of Lake Koronia in the management plans (Piesold and others 1999) and research reports (Tsiouris and others 2002; Grammatikopoulou and others 1996). These strategies fall within two main categories: (1) strategies aiming at restoring water levels in the lake and (2) strategies aiming at improving the pollution levels. Each category comprises of 10 strategies and they are briefly described as follows:

Strategies for the restoration of water levels:

1. *Water diversion from the Aksios River:* This strategy would be quite difficult to implement because the flow of the Aksios River is controlled by dams that lie outside the Greek borders. Moreover, waters are of unreliable quality containing heavy loads of nutrients.
2. *Water diversion from the Strymon River:* Irrigation systems based on water from the Strymon River already exist in the Strymon valley. Moreover, there exist plans for water diversion from the Strymon River for the restoration of Lake Doirani (which lies to the north of Lake Koronia). Thus, this strategy would exert additional strain to the valley's resources, resulting in negative environmental impact. Finally, the river flow is also controlled by dams that lie outside the Greek borders and waters are of unreliable quality.
3. *Water diversion from the Aliakmon River:* It has been estimated that water divergence of up to 4% of the mean river flow during winter will not have any negative impact on the ecology of the river (a large portion of the water overflow in Aliakon's reservoir during winter is wasted in the sea). Additionally, there already exist water channels covering part of the distance between the river and Lake Koronia, and the construction of the rest of the channels is quite feasible. Water quality is of high standards because there are no domestic or industrial sewage

discharging in the river (very small amounts of asbestos are present, but they can be removed).

4. *Water supply from the wastewater processing unit of the town of Thessaloniki:* This strategy requires water desalination and thus, costs are raised. Additionally, water quality is unreliable.
5. *Water diversion from the Laggadiki and Scholari torrents:* Torrent Laggadiki is already supplying Lake Koronia with water and the construction of a channel would probably have a negative environmental impact. Torrent Scholari is already feeding the nearby Lake Volvi with water and the full diversion of its waters would have negative environmental impact for that lake. As a compromise, the partial water diversion at a rate of 10–15 Mm^3/year would provide a quite feasible solution, easy to implement and of low cost. Additionally, any negative environmental impacts would be reversible by the partial (or full) diversion of water flow.
6. *Rainfall water diversion from the village of Asvestochori:* This requires the construction of a series of regulating dams. Additionally, the construction of a huge reservoir is required and this would have a negative environmental impact. Even if the dams and reservoir were constructed, operational problems would arise.
7. *Water drained from Lake Volvi:* This strategy would result in the reduction of water storage in Lake Volvi, as it is expected to increase hydraulic and environmental stresses. Moreover, the negative environmental impacts would not be easily reversible.
8. *Water drained from the deep aquifer:* The deep aquifer is already stressed due to heavy water pumping for irrigation purposes. It is expected that this strategy would have a negative environmental impact. Because there do not exist specific data and studies on that matter, the strategy would be very hard to implement. It is also expected to have a negative impact on the quality of water, because the quality of the shallow aquifer is continuously deteriorating.
9. *Maintenance and restoration of irrigation networks:* Existing irrigation networks are unreliable. Water consumption can be reduced by adopting new techniques such as microirrigation techniques (e.g., by water drops). These techniques are also expected to reduce pollution from agrochemicals.
10. *Limitation in the number of water pumps and drills through a state regulatory policy:* Although this strategy has a low cost of implementation, it is associated with high management overheads. It would result in a reduction in the consumption of water for irrigation purposes, but it also requires some policy decisions to be taken at the government level (e.g., support for periodic rests in cultivation).

Strategies for the improvement of pollution levels:

11. *Installation of a water sewage treatment Unit for the town of Lagadas:* This unit would have a direct positive effect on the ecosystem of the lake. It calls for immediate and urgent implementation. Such a treatment unit should be also capable of processing domestic sewage from neighboring villages and from the meat and dairy industries. If installations are extended so that the unit could also process industrial sewage, an improvement of 20– 25% in water quality is expected in the immediate future.
12. *Restoration of the sewerage system of Lagadas:* The complete renewal of the sewerage system is proposed. The new sewerage system should also serve the nearby industries. This strategy can be combined with the construction of a waste-treatment lagoon, as proposed next.
13. *Waste treatment in a waste maturing lagoon:* This is an inexpensive strategy that can be combined with others, such as the construction of a sewage treatment unit and the restoration of the sewerage system.
14. *Collection and treatment of water sewage from communities with population of more than 2000:* This is an inexpensive and feasible strategy. It is in accordance with the European Union regulations for wetlands and, thus, it can be funded.
15. *Extension of the water sewage treatment unit of Lagadas in order to process industrial sewage:* Connecting the industries to the proposed sewage unit would result in an increase in the processed water flow to Lake Koronia. In any case, the industries are under the obligation to treat their sewage, according to European Union regulations. However, it is quite difficult to estimate the required capacity of such a unit. Moreover, water sewages from the industries are of heterogeneous composition. This strategy can be combined with the waste maturing lagoon strategy and it is expected to lead to a 25–30% reduction of pollutant loads.
16. *Installation of industrial sewage-treatment equipment in each industrial unit:* This strategy requires considerable improvement of the installations and internal operation of the industrial units. Installation, maintenance, and operational costs for active carbon filters are considerable. Moreover, extra costs are associated with the installation of specific instrumentation equipment (measuring COD, salin-

Table 3. Criteria values and expected improvement for level and pollution management strategies

Strategy No.	Effect on water level	Effect on pollution level	Feasibility (low-difficult)	Environmental impact (negative to positive)	Implementation time (months)	Overall cost MECU (Million Euro)	Expected improvement in water inflow (Mm^3/year)	Expected improvement in industrial pollution (%/year)	Expected improvement in agrochemical pollution (%/year)
1	90	5	60	−40	52	16	15	3	3
2	90	5	50	−50	37	13.5	15	3	3
3	90	5	60	60	33	17.3	15	3	3
4	90	5	10	−30	36	25	15	3	3
5	70	5	60	0	7	1.8	12	3	3
6	50	2	10	−20	23	6.5	1	1	1
7	90	5	60	−70	26	6.2	15	3	3
8	90	5	10	−80	9	0.2	15	3	3
9	60	3	10	20	36	10	4	1	3
10	60	3	10	10	36	0.3	5	1	2
11	0	90	80	80	24	2	0	25	0
12	0	80	50	50	48	20	0	10	0
13	0	80	50	50	15	2	0	8	0
14	0	60	30	20	48	20	0	5	0
15	0	90	80	80	48	2	0	30	0
16	0	90	50	80	30	10	0	30	0
17	0	80	10	80	60	20	0	10	0
18	0	60	30	30	24	20	0	0	5
19	0	60	10	0	24	20	0	0	5
20	0	60	30	0	24	10	0	0	5

ity, etc.). Thus, this strategy calls for governmental funding. If this strategy is implemented, a 25–30% improvement in pollutant loads discharging to Lake Koronia is expected.

17. *Relocation of the industries in the industrial park:* This strategy is feasible only for new industries, if appropriate financial incentives are provided. It would be quite expensive to relocate already existing units.
18. *Reduction in the use of fertilizers and pesticides:* This strategy would result in considerable improvement in water quality, because pollutants are carried to the lake through surface-water runoff. Farmers would also benefit by the reduction in the associated costs. This strategy would require the appropriate training of the farmers and, additionally, financial incentives must be provided.
19. *Removal of the sediment from the bottom of the lake:* A partial (or even full) removal of the bottom sediment using mechanical scraping off or chemical methods is suggested. It is expected to result in improvements in water quality because the polluted sediment at the bottom delays the restoration of the ecosystem. Implementation costs are quite high.

Table 4. Relative ranking of strategies for two environmental states: water-level decrease = 90%, industrial pollution = 20%, agrochemical pollution = 20%; water-level decrease = 20%, industrial pollution = 90%, agrochemical pollution = 90%

Level management strategies		Pollution management strategies	
Rank	Strategy No.	Rank	Strategy No.
1	3	1	11
2	5	2	15
3	7	3	13
4	1	4	16
5	2	5	12
6	8	6	18
7	4	7	20
8	9	8	17
9	10	9	14
10	6	10	19

20. *Aquatic vegetation management and reintroduction of fish population:* This strategy calls for harvesting of old vegetation and introduction of new species that can reduce the amounts of phosphorus and heavy metals from the lake sediment (such as reed

Table 5. Fuzzy DSS results for two environmental states

Case	Water-level decrease % (initial/final)	Industrial pollution % (initial/final)	Agrochemical pollution % (initial/final)	Fish reduction % (initial/final)	Strategy selected
a	90/45	20/11	20/11	73.03/43.48	3
b	20/20	90/15	90/90	96.61/58.60	11

beds). The reintroduction of fish population is not a feasible solution at present, due to the deteriorating quality of water and the decline in water levels.

Table 3 presents the criteria values assigned to each strategy, according to fuzzy estimations based on management plans and measured values. For example, a relatively low feasibility value is assigned to strategies that are difficult to implement, according to the above discussion, whereas strategies that can be implemented easily are assigned a relatively high feasibility value. Moreover, the expected improvement in water flow and industrial and agrochemical pollution associated with each strategy, as expressed in the management plans, is used to generate the new fish production index, after its application. The criteria values for each strategy were stored in the database of characteristics. It must be pointed out that the values for criteria implementation time and overall cost shown in Table 3 are mean arithmetic values provided by the experts in the management plans and research reports (Piesold and others 1999) and the fuzzy ranges for the fuzzy sets were normalized in the interval [0–100], as shown in Figure 4. Thus, values for these two criteria are directly converted to single arithmetic values. The corresponding ranges for the fuzzy sets of criteria feasibility and environmental impact are determined after comparing the available strategies relatively to each other. The normalized range for feasibility lies in the interval [0–100] (from hardest to implement to easiest to implement strategy) and the normalized range for environmental impact lies in the interval [−100.0 + 100] (from large negative environmental impact to large positive environmental impact). Because the evaluation of these two criteria is provided by the experts in relative linguistic terms (as recorded in the management plans and research reports and depicted by appropriate fuzzy sets), a defuzzification step is required in order to produce a single arithmetic value from the appropriate fuzzy range.

The proposed fuzzy DSS was applied to a variety of environmental conditions and two characteristic cases are as follows: (1) when water level decrease has reached 90% of the maximum recorded value shown in Figure 1, whereas industrial and agrochemical pollution levels have reached only 20% of their maximum recorded values in Figure 1, and (2) water-level decrease at 20% and industrial and agrochemical pollution levels at 90% of their maximum recorded values. The ranking of strategies, as produced by the fuzzy DSS, is shown in Table 4 In the first case, the water-level management strategies produced considerably higher output values than the pollution management strategies. In the second case, pollution management strategies produced much higher output values, as was expected.

The best water level management strategy chosen in the first case was strategy number 3, (i.e., water diversion from the Aliakmon river). The application of this strategy over a period of three simulation periods (each period corresponds to a year) resulted in a considerable improvement for the fish reduction index, as shown in Table 5 In the second case, the best pollution management strategy chosen was strategy number 11, installation of a water sewage treatment unit in Lagadas, and its application for three simulation periods (3 years) again resulted in considerable improvement for the fish reduction index, as shown in Table 5 In this case, the next best strategy is strategy number 15 (i.e., extension of the water sewage treatment unit of Lagadas in order to process industrial sewage, which basically is an extension of the best strategy chosen).

Thus, in both cases of environmental conditions, the proposed fuzzy DSS selected that strategy from the appropriate category of strategies that is more feasible to implement, is associated with the best environmental impact, is fast to implement, and is relatively inexpensive.

The fuzzy DSS presented in this article is capable of encompassing the concepts of vagueness and uncertainty associated with the ecosystem. One of its basic contributions is that it employs fuzzy inference for the generation of simulation models based both on the expert's knowledge and available measurements. Additionally, the fuzzy inference system is more flexible, compared to other approaches, because it can be decomposed into a number of hierarchically interconnected subsystems. In this sense, first the explosion in the number of rules is avoided and second, the hierarchical modules can be replaced by appropriate modules if, for example, the DSS is to be applied to a different area. Moreover, the fuzzy DSS presented in this article supports continuous looping and iteration of information, it supports both arithmetic and fuzzy data, and it was shown that it is quite robust in the presence of noise. Finally, simulation results allow the effective redesign and adaptation of a proposed strategy. After a strategy is evaluated and ranked with respect to the rest of the available strategies, it can then be redesigned if required (e.g., by increasing its positive environmental impact or by speeding up the expected implementation time, so that it becomes more competitive).

Conclusions

This article presented the development and design of a fuzzy decision support system for the assessment of alternative strategies proposed for the restoration of a lake that is highly affected by industrial and agricultural activities. Modeling, monitoring, and decision-making in the proposed DSS constitute a continuous, interrelated, and recursive system. Fuzzy inference is used to represent uncertainties associated with the model and criteria evaluation. The performance of the system was evaluated both for a large number of computer-generated strategies and for a number of specific strategies proposed for the restoration of Lake Koronia. A series of sensitivity analyses have shown that the proposed DSS is robust in the presence of noise.

Environmental management plans must be continuously revised in order to meet new environmental conditions. The proposed DSS is flexible in the sense that it can be easily redesigned and adapted to cover the requirements of new management plans and to evaluate strategies under changing criteria values, or even using different sets of criteria.

Some of the limitations in the use of the proposed DSS come from the quality of the input data, the level of expertise reflected in the fuzzy rules, and the generalization capabilities of the lake model. Moreover, the evaluation of the criteria values can, in some cases, be associated with low confidence intervals, or criteria values might not be available for certain strategies. Finally, the use of the proposed DSS is based on the model of the lake that maps the specific anthropogenic stressors and their interactions. If it were to be applied to a different ecosystem, then a new lake model would be required in order to model the new stressors and interactions. It could also be possible that, depending on the criticality of the ecosystem state, the inclusion of additional criteria might be required. One of the advantages of the proposed DSS is that its hierarchical structure can easily accommodate such changes.

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