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Fuzzy Modeling of Interactions Among Environmental Stressors in the Ecosystem of Lake Koronia, Greece

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ABSTRACT / The development of a model for assessing the impact and interactions of stressors in the ecosystem of Lake Koronia, based on fuzzy inference, is presented in this paper. The proposed fuzzy inference model assesses the synergistic interactions among several significant stressors on fish production. These stressors include industrial pollution, pesticide and nutrient usage due to agricultural activities, and water level decrease due to irrigation works. Apart from the experts' knowledge, expressed in a set of fuzzy rules, a number of parameters such as pH, conductivity, biochemical and chemical oxygen demand, and nitrate concentration were used as stressor indicators. The proposed model is capable of simulating the effect of a large variety of environmental conditions, and it can be used as a dynamic tool for ecosystem risk assessment since it produces both qualitative and quantitative results, allowing for comparisons of predictions with on-going observational research and ecosystem monitoring. Its operation was successfully verified for a number of different conditions, ranging from low stressor impact to high stressor impact (where, in fact, the fish production was diminished). Moreover, the proposed fuzzy inference model can be used as a tool for the investigation of the behavior of the aquatic ecosystem under a large number of hypothetical environmental risk scenarios.

Aquatic ecosystems are highly complex systems that are dynamic in space and time and transition through multiple states and multiple equilibria. The impact of individual environmental stressors, acting singly or in combination, can alter the ecosystem state significantly. Stressors may interact and have a combined effect on ecosystems. Thus, it is important to understand not only the impacts of stressors on the ecosystem itself but also the interactions among stressors. Stressor interactions may have an amplifying or a diminishing effect. Thus, natural control mechanisms are evident in ecosystems and the notions of feedback, self-adaptation, and self-organization have been introduced in ecosystem modeling (Straskraba 2000, Prato 2000).

Since ecosystems and the related stressors acting on them are highly complex and nonlinear, a dynamic and spatially explicit model of the ecosystem under study would provide an appropriate basis in assessing the combined effect of stressor interactions. However, the construction of such models requires sophisticated computational and mathematical approaches, and it is time-consuming and computationally expensive (Straskraba 2000, Chi 2000, Gaff and others 2000, Bain and others 2000). In many cases, the complexity of the system prevents construction of such models. Classical analytical approaches sometimes ignore many important factors in order to reduce the complexity of ecosystem models (Karul and others 2000). Graph-theoretic and matrix algebra approaches have been employed in order to identify relationships among ecosystem stressors (Wenger and others 1999, 2000). These approaches are excellent for providing a qualitative description of the linkages and synergisms between stressors. Artificial neural networks have been employed in aquatic ecosystem modeling in a vast variety of applications (e.g., Karul and others 2000, Olden and Jackson 2002, Gitzakis and Tzortzios 2002). Artificial neural networks have excellent generalization capabilities; however, models require the availability of long sequences of measurements and are difficult to interpret. Because of the imprecision of the ecological im-

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pacts and the frequent lack of quantitative information, fuzzy set theory has been used in environmental modeling. However, the main focus of the application of fuzzy sets is the qualitative identification of significant stressors and environmental indices and the fuzzy determination of their magnitude (Silvert 2000, Chang and others 2001, Enea and Salemi 2001, Baros and others 2000). Similarly, fuzzy cognitive maps have been used for the characterization of the stressors behavior (Özesmi 1999). Fuzzy cognitive maps are based on digraphs and are mainly used as a graphical tool for the identification of the types of interactions between stressors. In conclusion, classical analytical modeling approaches were not used in the context of this paper, since they are extremely complex to construct. Graph-theoretic approaches and fuzzy set theory do not provide the means to construct executable simulation models that are required in our approach, whereas a neural network model for the proposed ecosystem cannot be constructed due to the lack of long series of available measurements. Finally, fuzzy cognitive maps are mainly used to identify the behavior and types of interactions between stressors.

This paper develops an alternative methodology for assessing the impact and interactions of stressors in the ecosystem of a lake, based on fuzzy inference. The main advantage of the fuzzy inference technique used in our approach is that it takes into consideration both the knowledge provided by the experts, in the form of fuzzy rules, as well as the available measurements, and it is capable of constructing executable simulation models of the ecosystem behavior.

The ecosystem of Lake Koronia, located northeast of the town of Thessaloniki, Greece, was chosen as an application example for the generated fuzzy model since it is highly affected by industrial, domestic, and agricultural activities.

The proposed fuzzy inference model assesses the combined effect of the interactions among stressors such as industrial sewage, pesticide and nutrient usage, and water level decrease due to irrigation works on the fish production of the lake. Fish production, as measured by fisheries catches (total biomass) was used as a biomarker for ecosystem health, as it was the only metric relating to fish populations for which measurements were available. It is directly related to fish population although there exist differential tolerances of fish species to different types of stress, and they affect the composition of fish community. Moreover, some species may thrive under stress, and this fact may sometimes alter the trajectory and magnitude of change in the population. Thus, populations may persist even if production in a given year is zero. However, such population measurements were not available for the lake.

The operation of the proposed fuzzy inference model is successfully verified for a number of different conditions, ranging from low to high stress (where, in fact, the fish production was diminished). It will be shown that the fuzzy inference system is capable of encapsulating stressor dynamics and interactions, as these are expressed in experts' knowledge and available measurements. It may prove particularly useful for analysis of water pollution, a pressing issue that needs attention of the world population, water experts, and policy-makers (Simonovic 2002).

In the remainder of this paper we present an analysis of the physicochemical and morphological characteristics of Lake Koronia, and the main stressors and their interactions are identified. Next, an introduction to fuzzy inference is presented and the design and development of the proposed fuzzy inference system is shown. This is followed by the presentation of simulation results for model validation against real-world data as well as for the investigation of the behavior of the ecosystem. Finally, the last section presents the overall assessment of the fuzzy inference system and the final conclusions.

Physicochemical and Morphological Characteristics of Lake Koronia

Lake Koronia, also known as Lake Lagadas, is located 15 km northeast of the town of Thessaloniki in the region of Macedonia in northern Greece (Figure 1) 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. The lake forms the upstream part of the Mygdonian basin. It is surrounded on the north and south by mountains ranging in height from 600 to 1200 m and on the west by lower hills. The lake has a surface area of approximately 30 km^2, and the main tributary to the lake is Bogdanas, with a catchment area of 300 km^2 to the north. In the past, the lake was connected to Lake Volvi, which lies about 15 km downstream (Figure 1) by the river Derveni. Lake Volvi discharges into the Strymon Gulf of the Aegean Sea. The lake is part of a freshwater ecosystem protected by the RAMSAR convention (Piesold and others 1999, Grammatikopoulou and others 1996).

In the last 20 years, the lake has suffered from the consequences of reduced surface runoff, increased water diversion for irrigation, and increased pollutant loads. As a result, the area of the lake decreased dramatically (during the 1970s the lake had an area of 47 km^2, whereas currently it has an area of less than 30 km^2) and water quality deteriorated. These factors gave

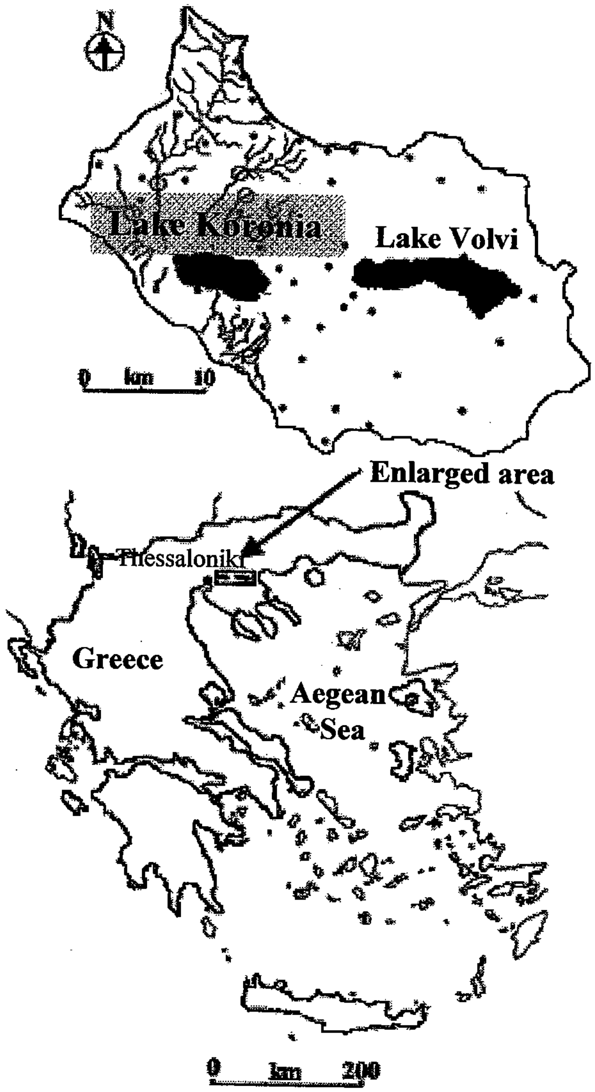

Figure 1. Geographical location of Lake Koronia.

rise to the current hypertrophic conditions, which cannot support fish and other living organisms. As a matter of fact, the water level decline resulted in the disruption of water flow between Lake Koronia and Lake Volvi, thus disrupting the natural migrating path for fish and eels. When this was combined with the deterioration in water quality, it led to the death of a large number of fish, and fish production was minimal in the summer of 1995. Fish production has remained low 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 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, Liberopoulou 1994).

Limnological water quality assessment is typically based on physicochemical analyses and their effect on certain biomarkers. These biomarkers can provide information on the response of organisms to organic pollution of surface waters and other environmental contaminants, such as pesticides, fertilizers, PCBs, and heavy metals (Adam and others 2001). In the context of this paper, fish production was used as the basic biomarker indicating ecosystem health.

Generally, it has been shown that surface waters, particularly small lakes receiving sewage treatment plant discharges, are not only influenced by a few isolated contaminants but also by complex pollutant mixtures or "cocktails," which are composed of nitrogenic compounds, phosphate, heavy metals, PCB, pesticides, and detergents. Likely sources for contamination of Lake Koronia in this paper include intense agricultural activities (Piesold and others 1999, Hellenic Ministry of Agriculture 2001) and industrial sewage plant effluents from the textile, food, and dairy industries (Piesold and others 1999, Hellenic Ministry of Agriculture 2001). The following water parameters were examined (Adam and others 2001, Australian and New Zealand Guidelines for Fresh and Marine Water Quality 1999): (1) Conductivity—the high variability in conductivity values is caused by sewage plants or rain water drainages and by runoff from agricultural areas. (2) pH—small pH changes may result in severe alterations of biological or geological processes. (3) Biochemical oxygen demand (BOD) and chemical oxygen demand (COD)—increased values of BOD are mainly due to the influence of wastewater discharges and/or agricultural activities.

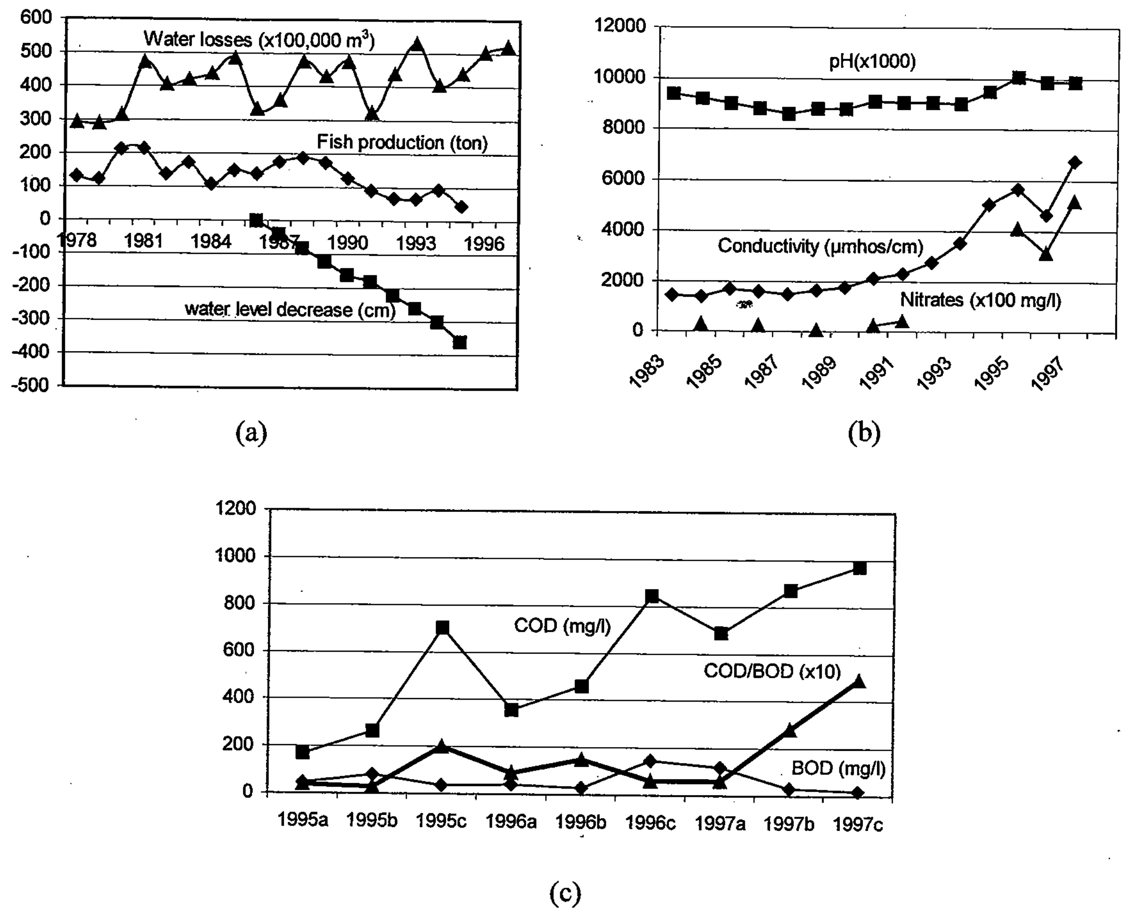

Figure 2. Variation of physicochemical parameters for Lake Koronia (data taken from Piesold and others 1999, Hellenic Ministry of Agriculture 2001).

The COD is significant where high concentrations of chemicals are in the water (e.g., effluent from factories) (Piesold and others 1999, Adam and others 2001). Moreover, the increased COD/BOD ratios provide a clear indication of the accumulation of nonbiodegradable organic matter, mainly due to industrial and agricultural pollutants. (4) Nitrates—high nitrate burdens of surface water are caused by excess use of fertilizers and by waste water drainage (Tsiouris and others 2002, Adam and others 2001).

The variation of these parameters for Lake Koronia is shown in Figure 2a–c. 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, Liberopoulou 1994). Parameter values were normalized in order to be displayed on a common chart (e.g., pH values were multiplied by a factor of 1000).

Identification of Ecosystem Stressors and Their Interactions

Stressors are defined as anthropogenic factors that pose a risk to ecosystem integrity (Wenger and others 1999). Risk assessment, as applied to ecosystems, is a very complicated task mainly due to the complexity of the ecosystems themselves, as well as the poorly understood manner in which they respond to stress. Moreover, stressors may interact and have a combined effect on the ecosystem. These interactions may have amplifying or diminishing effects upon the stressors and, thus, the presence of positive and negative feedback loops among stressors is evident (Straskraba 2000, Wenger and others 1999, 2000). The study of stressor interactions is crucial since these interactions may cause the ecosystem to shift to an entirely different equilibrium state, perhaps crossing a threshold level from a desired to a degraded state. Any attempt to develop strategies to reduce risk to the ecosystem

Table 1. Ecosystem stressors for Lake Koronia

Number	Stressor
1	Water level decrease—increase in irrigation works
2	Industrial sewage effluents—toxics
3	Pesticides, insecticides, underground pollution
4	Nutrient loading—hypertrophic conditions
5	Domestic sewage
6	Temperature increase
7	Shoreworks—roadworks—landfill operations
8	Introduction of invasive fish species
9	Increase in noise level
10	Recreation activities

should be based on the identification and evaluation of the stressors and their interactions.

The identification of the main stressors for the ecosystem of Lake Koronia was based on research reports (Tsiouris and others 2002, Bobori and Economidis 1996, Liberopoulou 1994) and management plans (Piesold and others 1999, Grammatikopoulou and others 1996, Hellenic Ministry of Agriculture 2001). Not surprisingly, the ecosystem of Lake Koronia suffers from problems similar to those encountered in other lakes in Europe and North America, in regions where intense agricultural activities take place and industrial sewage plant effluents are present (Lemly and others 2000). The main ecosystem stressors are shown in Table 1, sorted in order of significance of their impact on fish production. The significance of stressors was determined in a joint effort of the Greek Ministry of the Environment and the Department of Sanitary Engineering and Environmental Health, National School of public Health. Stressor significance was evaluated according to their impact on the management plans proposed for the rehabilitation of the lake (Piesold and others 1999).

The most likely sources for contamination of Lake Koronia include intense agricultural activities (Piesold and others 1999, Tsiouris and others 2002) and industrial sewage plant effluents from the textile, food, and dairy industries (Piesold and others 1999, Grammatikopoulou and others 1996, Liberopoulou 1994).

The intensification of agricultural activities during the last two decades had a twofold effect on the ecosystem: (1) irrigation works for agriculture were increased dramatically, resulting in a severe water level decrease, and (2) the extensive use of fertilizers, pesticides, and insecticides resulted in the development of hyperthrophic conditions and pollution of the underground water. It should also be noted that, in the absence of a water regulation policy, a shift from wheat cultivation to more water-demanding products such as corn and vegetables took place in the last decades (Piesold and others 1999), resulting in an additional demand for irrigation works.

Industrial development during last two decades around Lake Koronia includes textile, meat, and dairy industries (Piesold and others 1999). Although some of the industries treat their wastes in their own waste treatment plants, there still exists a discharge of industrial wastewater, mainly from the food and textile industries, directly into the lake. These discharges increase the concentration of chemicals, toxics, and heavy metals in the lake water (Piesold and others 1999, Hellenic Ministry of Agriculture 2001, Bobori and Economidis 1996).

Fishing activities in the lake have been severely limited, especially following an incident in the summer of 1995 during which a large number of fish were found dead and fish production dropped (Piesold and others 1999). Recreation activities included wind-surfing, a rowing center, and a number of fish taverns along the lake. The rowing center has closed and most of the recreation activities have ceased since 1995 mainly due to the significant drop in water level (Piesold and others 1999, Grammatikopoulou and others 1996).

An attempt to depict the stressor interactions and their effect on fish production is shown in Figure 3. The diagram of interactions was constructed along the lines presented in Wenger and others (1999), and it is mainly intended to be used as a qualitative tool that displays the amplifying or diminishing effect of one stressor to another. Stressors are displayed in boxes and arrows starting from a box indicate that this stressor affects the stressor at the end of the arrow. It is, essentially, a directed graph (Wenger and others 1999), where the augmenting effect of one stressor to another is denoted by a plus sign and the diminishing effect is denoted by a minus sign. Essentially, an amplifying impact means that an increase in the magnitude of the first stressor leads to an increase in the magnitude of the second and a decrease of the first leads to a decrease of the second. A diminishing impact means that an increase in magnitude of the first stressor leads to a decrease in magnitude of the second (and a decrease of the first leads to an increase of the second). The interactions among stressors are quite complex, as shown in Figure 3, and any attempt to demonstrate all possible stressor interactions on a diagram would result in a very dense and difficult to interpret graph. Moreover, measured data are available for only a few of them, and thus, only the interactions between the most significant stressors are considered in this study. These are shown using darker arrows in Figure 3.

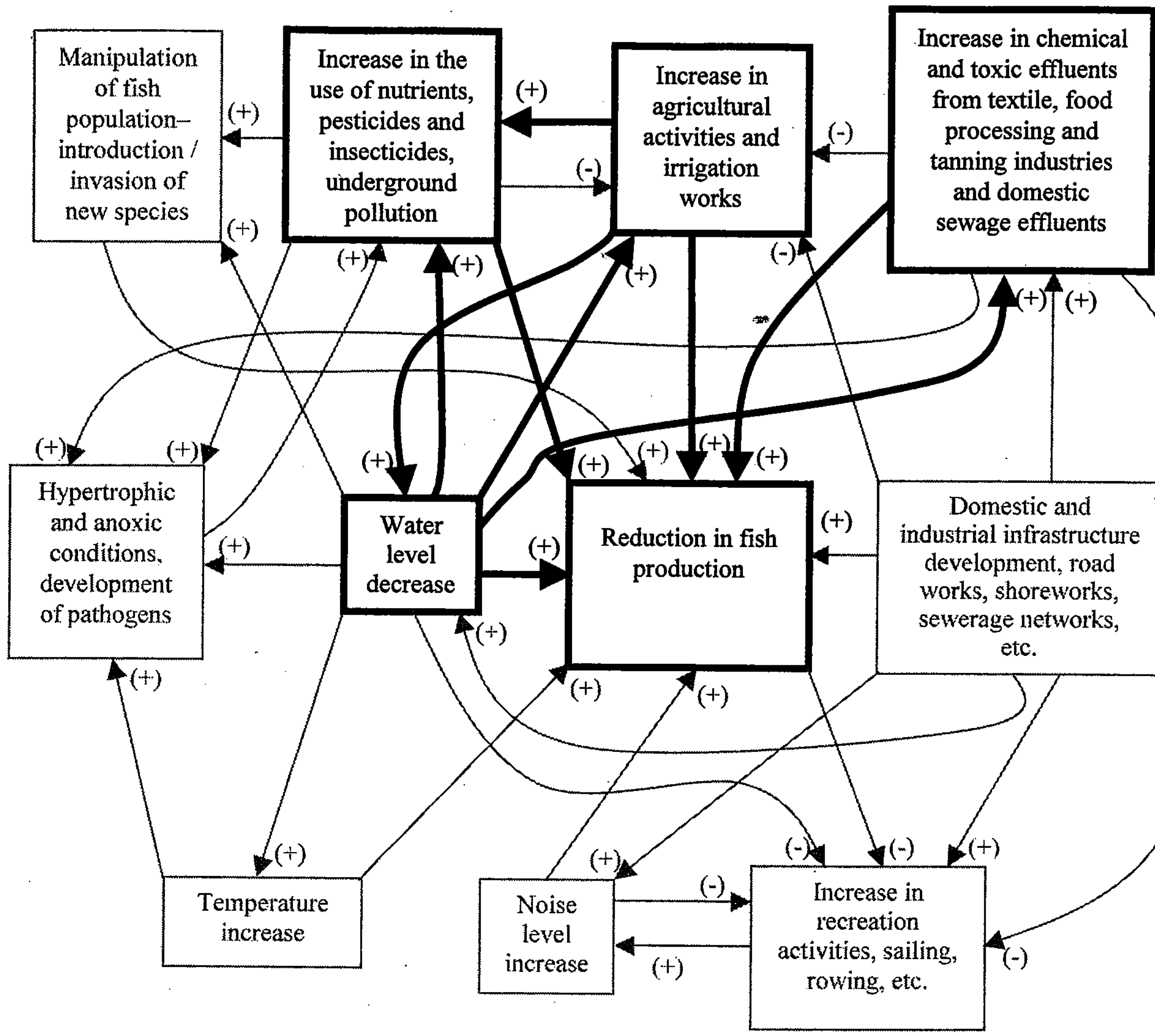

Figure 3. Feedback interactions among stressors in Lake Koronia and their effect on fish production.

By observation of Figure 3 it can be deduced that most of the linkages between stressors are augmenting, and the predominant effect of the stressor interactions is a reinforcing one. A critical issue is the existence of positive feedback loops among stressors. These loops are created when an arrow starting from one stressor has an amplifying influence on another (denoted with a plus sign), which in turn, has an amplifying influence on the first one (denoted with another arrow starting at the second stressor and ending at the first with a plus sign).

For example, a positive feedback loop involving two stressors—an increase in agricultural activities and irrigation works and a water level decrease—is shown in Figure 3. It is clear that irrigation-intensive agricultural activities in Lake Koronia have caused a decrease in water level of the lake over time (Piesold and others 1999, Hellenic Ministry of Agriculture 2001). Additionally, as water levels decreased and more areas were exposed, agricultural activities were expanded to these newly exposed areas (Piesold and others 1999). The effect of positive feedback loops on the equilibrium state of a system is dramatic and usually leads to highly unstable states. In this case, one should consider the effect of this positive feedback loop on the fish production, as shown in the same figure. Evidence of the effect of such a positive feedback loop was seen in the dramatic decrease in fish production in the summer of 1995, when a large number of fish were found dead in the lake (Piesold and others 1999).

As another example of a positive feedback loop involving three stressors, consider the two stressors of the previous example and their interaction with the stressor relating to the increase in nutrients, pesticides, and insecticides. It is obvious that any increase in agricultural activities induces an increase in the use of nutrients, pesticides, and insecticides. When this increase takes place while water volume is declining, the concentration of pollutants in highly increased. Again, evidence of the effect of such a positive feedback loop was seen in the dramatic decrease in fish production in the summer of 1995. This is also supported by the measurements for the physicochemical parameters shown in Figure 2. One can observe the decrease in water volume and fish production, while measurements for the other physicochemical parameters increase to high levels during that period.

A negative feedback loop example involves the increase in recreation activities and the noise level increase, as shown in Figure 3. As recreation activities increase, the overall noise level is increased and that, in turn, induces a reduction in the number of recreation activities. When combined with the influence of additional stressors, this feedback resulted in the severe limitation of all recreation activities around the lake (Piesold and others 1999, Grammatikopoulou and others 1996).

Since stressors are strongly interrelated, as shown by the large number of arrows in Figure 3, any action affecting one of the stressors is likely to have a considerable impact on the other stressors over time. This indirect impact must be added to whatever direct impact this action may have on the ecosystem itself. Since the effects of these impacts are usually nonlinear in nature, the ecosystem of Lake Koronia and the related stressors acting on it can be considered as a highly dynamic and non-linear system. In this case, a dynamic and spatially explicit model of the ecosystem of Lake Koronia would provide an appropriate basis for assessing the combined effect of stressor interactions. However, due to the model complexity (Straskraba 2000, Chi 2000, Gaff and others 2000, Bain and others 2000), such a model for the assessment of the impact of stressor interactions cannot even be constructed. Any effort to create a model for a single stressor [e.g., water level management and hydrological alterations (Piesold and others 1999)] requires sophisticated computational and mathematical approaches, and it is time-consuming and computationally expensive.

Development of the Fuzzy Inference System

A new, fuzzy inference system that models stressor interactions for the ecosystem of Lake Koronia is presented in this paper. Fuzzy inference can generate models that encapsulate both the knowledge provided by the experts as well as the available measurements for a system. Fuzzy inference defines fuzzy sets as those whose confinements are not precise but vague (Zadeh 1965). Fuzzy logic is able to represent the concept of vagueness that natural languages use for pointing out qualitative variables, such as warm, cold, low, high, much, etc.

Especially for ecosystems, there is often difficulty in obtaining accurate values since we are usually sampling small parts of patchy environments, whereas the significance of the observed results or damages can be easily assessed. Fuzzy logic facilitates such an assessment. Additionally, there is a lack of consensus about what different damage levels mean. 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 zero and one. Thus, the membership value denotes the degree that an object belongs to a fuzzy set.

The relationship between an environmental variable x and its membership value $\mu(x)$ can have different forms. In this paper, 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:

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

where 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:

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

with $\tilde{\sigma}$ being the standard deviation and c a parameter specifying the shape of the distribution (Mathworks Inc. 1999, Kosko 1997). These membership functions were chosen because they can approximate the shape of a variety of different functions by simply changing their parameters. This attribute is quite important in our case, since the parameters of the membership functions were varied considerably in order to satisfy not only the qualitative criteria, but also the set available measurements.

Table 2. Characteristic rules of the fuzzy inference system

		Water level drop		Industrial pollution		Agricultural activities		Fish reduction
1	IF	*small*	AND	*low*	AND	*low*	THEN	*insignificant*
2	IF	*small*	AND	*low*	AND	*significant*	THEN	*small*
…		…	…	…	…	…	…	…
11	IF	*small*	AND	*significant*	AND	*significant*	THEN	*large*
…		…	…	…	…	…	…	…
16	IF	*excessive*	AND	*significant*	AND	*low*	THEN	*critical*
17	IF	*excessive*	AND	*significant*	AND	*significant*	THEN	*borderline*
…		…	…	…	…	…	…	…
24	IF	*significant*	AND	*excessive*	AND	*excessive*	THEN	*nonrecoverable*
…		…	…	…	…	…	…	…
27	IF	*excessive*	AND	*excessive*	AND	*excessive*	THEN	*nonrecoverable*

In most situations, more than one environmental variable is important. In the context of this paper, one needs to develop ways of combining the membership functions of different stressors to obtain a measure of their augmenting or diminishing effect. Usually, the appropriate combination is a standard fuzzy relationship that is formulated as a fuzzy relation or "rule." The process of combining the effects of several fuzzy relations is called fuzzy inference.

The Mamdani type of fuzzy inference was used in the proposed system. The Mamdani inference for N relations R^1, R^2, $\cdots R^N$ of two fuzzy variables A, B is defined as:

$$R^N = \vee_k R^k \qquad (3)$$

where $k = 1,2, \cdots N$ and

$$\mu_R^N(x,y) = \vee_k[\mu_A^k(x) \wedge \mu_B^k(y)] \qquad (4)$$

where $\mu_A^k(x)$ and $\mu_B^k(y)$ are the membership functions for the fuzzy sets of variables A and B respectively, symbol $\vee$ denotes the *max* operator and symbol $\wedge$ the *min* operator. The Mamdani inference was chosen due to its simplicity and low computational power requirements with respect to other fuzzy inference methods (Kosko 1997). However, the Mamdani inference does not permit weighting of different factors that may not have equal importance. In the proposed system, the relative importance of the parameters is implicitly reflected in the number and width of the fuzzy membership functions. Moreover, the proposed system allows for different weighting of the fuzzy rules. Basically, the fuzzy rules express the experts' knowledge about the ecosystem under study. Table 2 presents some fuzzy rule examples, where the antecedents of a rule are connected with the logical AND operator and the different rules are implicitly connected with the logical OR operator. The qualitative criteria used for the formulation of the fuzzy rules were derived from the experts' knowledge, as it was expressed in the joint, multidisciplinary report of the Greek ministries of the Environment and Agriculture, for the rehabilitation of the lake (Piesold and others 1999). The main findings can be summarized as follows:

1. The current state of the lake is a result of the combination of two parameters: water level decline due to agricultural activities and the deterioration of water quality.
2. The lack of a waste treatment plant and the increasing number of textile and food industries contributed significantly to the deterioration in water quality.
3. The excessive used of fertilizers and pesticides has contributed large pollutant loads.
4. Changes /improvements in any of the parameters alone cannot lead to significant improvements in the state of the lake as far as fish production is concerned.
5. Deterioration in any of the parameters leads to a significant reduction in fish production.
6. The combined deterioration in any two of the parameters will lead to a critical state.
7. The combined deterioration in all three parameters, even if it is only to a small extend, will lead to a non-recoverable state with respect to fish production.

Additionally, it is also reported that any feasible solution proposed for the rehabilitation of the lake must aim at improving all the parameters in combination. These qualitative criteria were supported by the variations in the measurements for the critical parameters that are shown in Figure 2.

As much as fuzziness helps rule formation and evaluation, the final desired output for a variable is generally a single number. Since 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 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 μ_y (y), as follows:

$$\hat{y}_{COA} = \frac{\int_s y\mu_y(y)\,dy}{\int_s \mu_y(y)\,dy} \quad (5)$$

where S denotes the range of y values covered by the combined output surface [it is called the S support of μ_y (y)]. It has been shown that this method provides satisfactory results, especially in fuzzy process control applications (Altrock 1995). The COA method, when combined with the Mamdani inference, takes into consideration even the smallest influence of a rule since this is accounted for in the combined output area (in contract with other defuzzification techniques such as the mean of maxima). The aim of the proposed fuzzy inference system was to model the experts' knowledge about the ecosystem while satisfying the quantitative measurements available for the basic system variables.

The proposed fuzzy inference model assesses the combined effect of the interactions among the most important stressors of the ecosystem of Lake Koronia, i.e. (1) water level decrease (input *water level drop*), (2) industrial sewage effluents (input *industrial pollution*) and (3) pesticide and nutrient usage due to agricultural activities (input *agricultural activities*), on the fish production of the lake (output *fish reduction*), as shown on the stressor interaction diagram in Figure 3. Apart from the experts' knowledge, as expressed in the relevant studies and management reports (Piesold and others 1999, Grammatikopoulou and others 1996, Hellenic Ministry of Agriculture 2001, Tsiouris and others 2002, Bobori and Economidis 1996, Liberopoulou 1994) and formulated in a set of fuzzy rules, the variation of pH, conductivity, biochemical and chemical oxygen demand, and nitrate concentration for Lake Koronia, (Figure 2) were used as quantitative stressor indicators. More specifically, a fuzzy combination of the variations in conductivity, pH, COD, and BOD was used to determine the fuzzy sets for industrial pollution. Additionally, a fuzzy combination of the variations in nitrates, conductivity, pH, and water losses was used to determine the fuzzy sets for agricultural activities. The conductivity and pH are used as measures of both industrial pollution and agricultural activities as they are very important factors. Exceeding the limits in pH will not permit fish and other aquatic organisms to survive whereas increasing salinity alone could result in dramatic changes in fish abundance and community composition.

The number of fuzzy membership functions for each input and output variable 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 the set of fuzzy rules, as well as the quantitative parameter variation (Figure 2). Thus, the fuzzy combination of the variations in the parameters measuring industrial pollution was used to calibrate the fuzzy sets for that variable and, similarly, for agricultural activities. Additionally, the construction of the fuzzy membership functions and rules reflects the relative importance of stressor interactions through the positive feedback paths (Figure 3). In this sense, whenever a critical threshold value is crossed, even small variations in the input levels lead to terminal variations in the output. Further care was taken in order to keep the number of membership functions of the inputs small. A large number of input membership functions very quickly leads to the "dimensionality curse" (Kosko 1997, Altrock 1995) of fuzzy logic (i.e., to a combinatorial explosion in the number of possible rules). Although the use of three, five, and seven membership functions for the input and output variables was investigated in several alternative design attempts, it was found that a fuzzy inference system with three membership functions on each input and seven membership functions on the output, of the form described in equations 1 and 2, was capable of encapsulating the dynamics of stressor interactions without leading to a very large number of rules. The fuzzy sets for the input and output variables are shown in Figure 4, whereas some characteristic rules of the fuzzy inference system are shown in Table 2. The variation of the system input/output variables is normalized within the range [0,1] and can be interpreted as a percentage variation.

The Mamdani inference used for the creation and implementation of the fuzzy rules, in accordance to equations 3 and 4 is demonstrated graphically in Figure 5. Each row of membership functions corresponds to a rule relating input and output variables and the vertical straight line crossing all membership functions depicts a certain system input (in the example shown, water level drop = 0.3, i.e., a 30% increase; industrial pollution = 0.5, i.e, 50% increase; and agricultural activities = 0.6, i.e., 60% increase). Each rule that is activated by an input contributes to the output to a degree that is

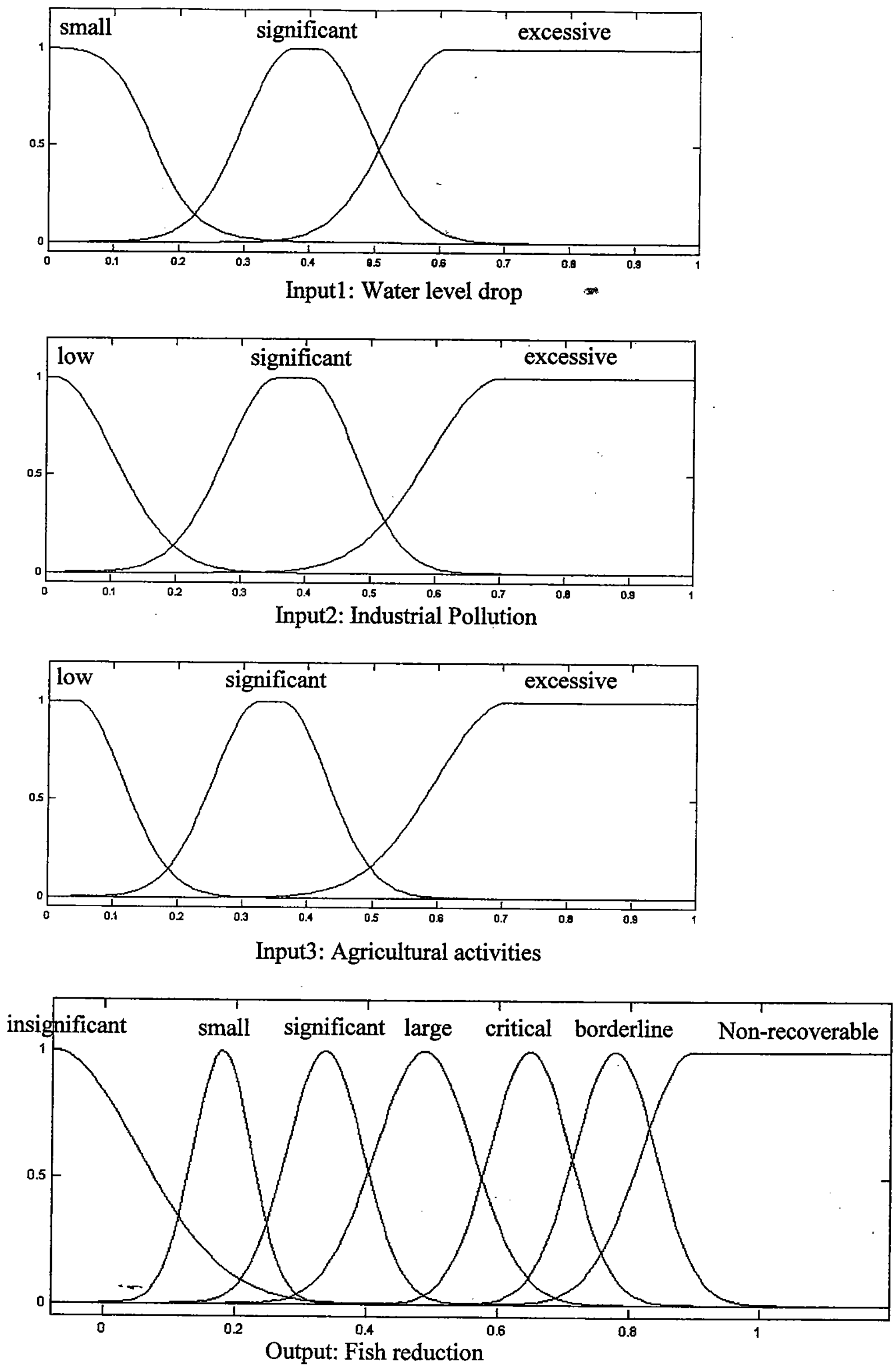

Figure 4. Fuzzy membership functions for the input and output variables of the proposed fuzzy inference system.

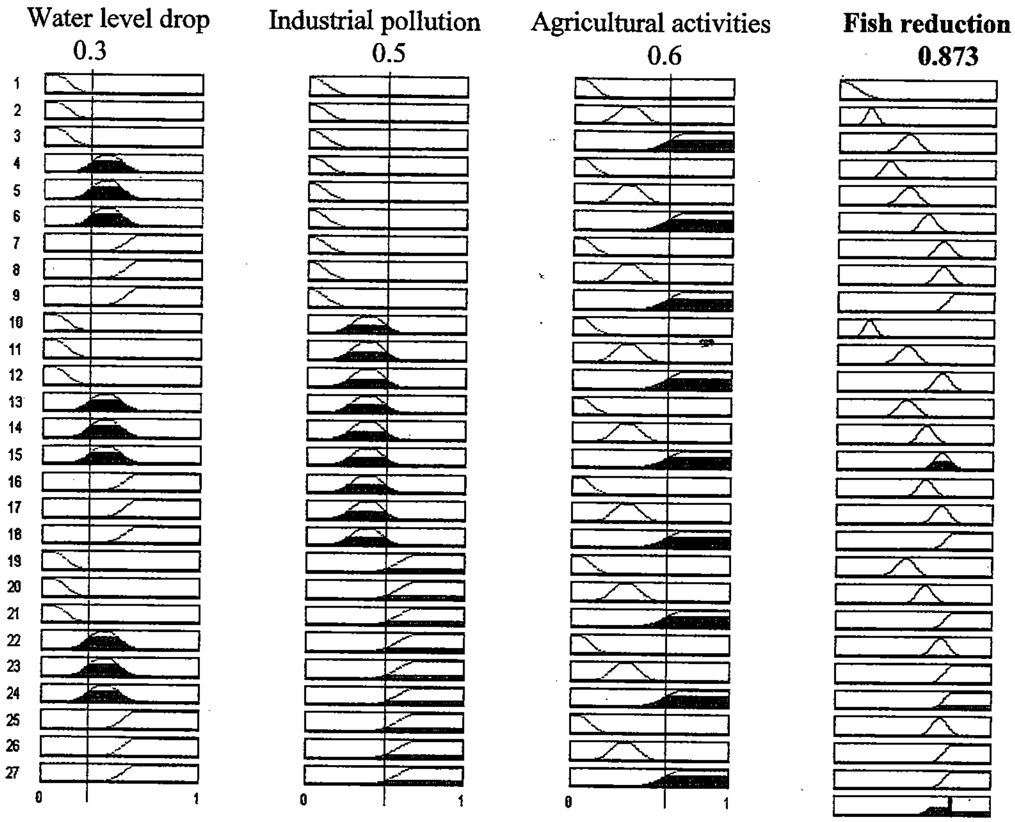

Figure 5. Typical example of operation of the proposed fuzzy inference system.

calculated as the minimum of the membership degrees of the inputs (as suggested by equation 4). The fuzzy inference system output is the combined membership function (as defined in equation 3) that is defuzzified according to equation 5 and produces a result of fish reduction = 0.873, i.e., 87.3% reduction of the fish production.

Results and Discussion

The input/output behavior of the proposed system can be investigated on the three-dimensional graphs shown in Figure 6, where one of the inputs is fixed and the three- dimensional graph displays the variation of the output with respect to the rest of the inputs. Although the overall performance of the system, with respect to all three inputs, cannot be represented graphically since it would require a four-dimensional space (one dimension for each of the inputs and one for the output), a large number of three dimensional plots were created for different levels of the fixed input and have shown similar characteristics. The interactions and feedbacks between all three inputs and their respective effect on the system output were investigated using the graphical simulation tool shown in Figure 5. The activation of the rules due to variations in all of the inputs (achieved by placing the vertical line on a different position for each input on Figure 5) results in specific outputs for fish production, as it was explained in the previous section.

The variation of the inputs shown in Figures 6a–c produces a monotonically increasing variation of the output. Thus, the surfaces produced are increasing functions of their inputs and have a form that is difficult to model analytically (Figures 6a–c). It should be noted that for high output values there exist flat areas, where the output does not change in response to small changes in the inputs. In this case, at least one of the inputs has risen considerably and leads the system almost to its terminal state. Thus, it is expected that small changes around the other inputs will not affect the output. A considerable change in any other input leads the system to an even higher terminal state (this is partly an artifact of the way in which the membership functions were defined for the terminal states). Additionally, the measurements for the basic parameters that are shown in Figure 2 correspond to points on these surfaces. In this sense, the proposed fuzzy infer-

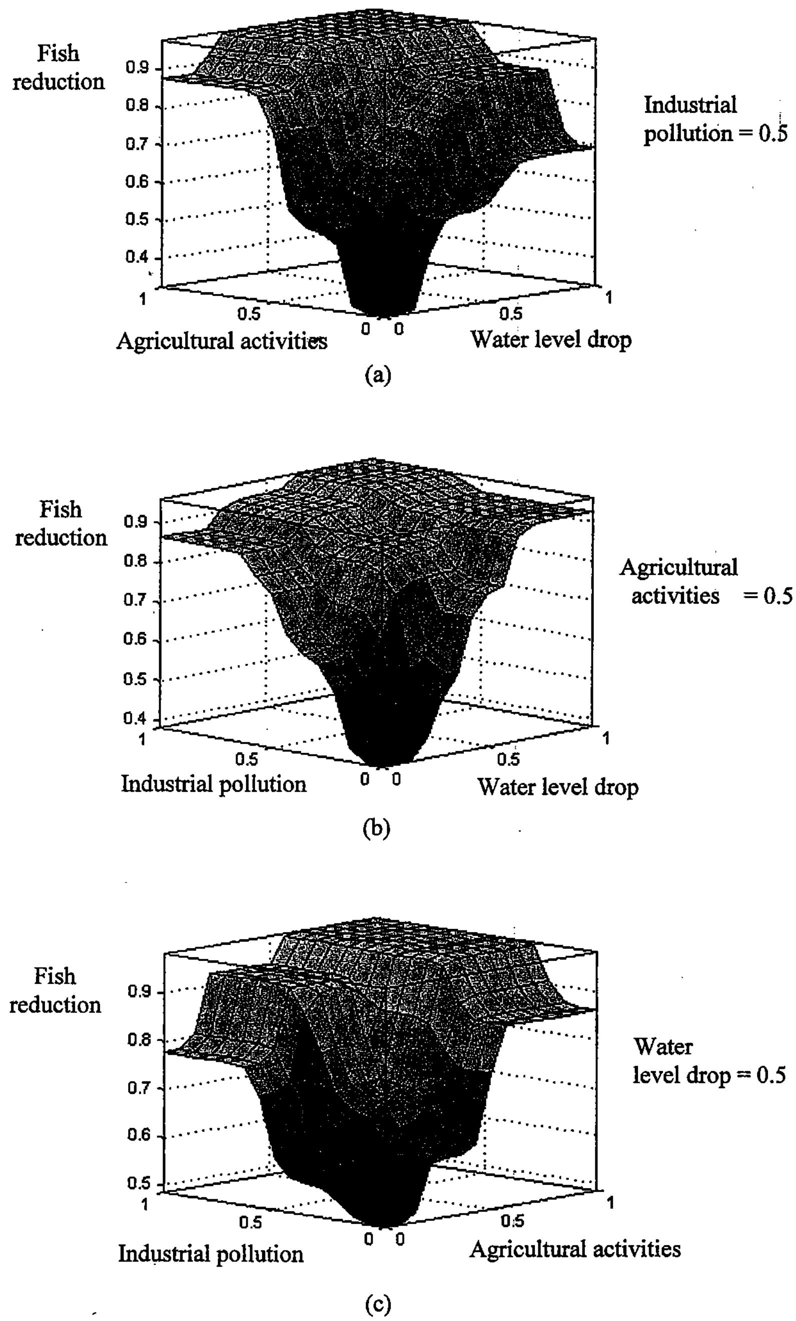

Figure 6. Fuzzy inference system performance. On each three-dimensional plot, one of the input variables is fixed and the variation of the output with respect to the other two input variables produces the corresponding surface plot. (a) Variation of the fish reduction with respect to water level drop and agricultural activities, for a level of industrial pollution fixed at 0.5 (i.e., 50%). (b) Variation of the fish reduction with respect to water level drop and industrial pollution, for a level of agricultural activities fixed at 0.5 (i.e., 50%). (c) Variation of the fish reduction with respect to agricultural activities and industrial pollution, for a level of water level drop fixed at 0.5 (i.e., 50%).

ence system encapsulates the set of available quantitative data for the ecosystem.

The positive feedback dynamics of stressor interactions in the proposed fuzzy inference system are depicted along the steep slope variations that transfer the system from one state to another. Even for small input variations around some critical values, the output is varied considerably (Figures 6a–c). Additionally, there exist slopes and abrupt output transitions even if one of the two varying inputs is held constant (e.g., if agricultural activities are held at zero, the continuing water decline results in increased values of fish reduction; Figure 6a). However, the slopes are steeper and the fish reduction reaches higher values when both of the input components are varying at the same time. This is an indication of the system dynamics since, for this example, the effect of increasing pollution in less water volume has an amplifying effect on fish reduction (Fig-

Table 3. Fuzzy inference system simulation results[a]

Row no.	Time period	Model Inputs (% variation) Water level drop	Industrial pollution	Agricultural activities	Model output (% variation) Fish reduction	Measured data (% variation) Fish reduction
1	1988–1989	14	16	7	8.5	9
2	1988–1990	25	25	10	41	42.6
3	1988–1991	50	30	40	71	69
4	1988–1993	60	50	50	89	85.3
5	1988–1995	90	80	80	99	100
6	—	60	80	80	99	—
7	—	90	50	50	92	—
8	—	50	50	50	86	—

[a]The fuzzy sets for industrial pollution were calibrated with respect to pH, conductivity, COD, and BOD. The fuzzy sets for agricultural activities were calibrated with respect to pH, conductivity, nitrates, and water losses. Percentage variations are based on the scale of Figure 2 and not on absolute values.

ure 2), due to the interaction between the two factors. Similar observations can be made for Figures 6b and 6c. Finally, it is evident that for increased input values, the proposed fuzzy inference system is eventually driven to the terminal state of maximum fish reduction.

The procedure of testing and evaluating the agreement between the fuzzy results and observations is described as follows: the sets of input and output data shown in Figure 2 were divided into two subsets: (1) a training subset used to design the membership functions and to create the rules so that the system output fits the observational data, and (2) a testing subset (approximately 20% of all data samples), on which the system was not trained, was then presented to the inputs and used to evaluate how well the system predicts the outputs. The testing subset was chosen so that it is both representative of the data the trained model is intended to emulate, yet sufficiently distinct from the training data set so as not to render the validation process trivial. This is an approach similar to that used in neural networks and hybrid techniques (Mathworks Inc. 1999) in order to avoid the problem of the model overfitting the data. When training for very small errors, the model begins overfitting the training data set. In this case the system learns the training examples, but it has not learned to generalize to new situations. The testing subset extends the generalization capabilities of the fuzzy inference system. The system parameters (shape and overlapping of the membership functions and rules) were modified, in several design iterations, until the difference between predicted and observed output data was minimized to a mean value of less than 5%.

Some characteristic results obtained by the simulation of the proposed fuzzy inference system are shown in Table 3. It should be noted that the percentage variations for the input and output parameters shown in Table 3 are based on the scale of Figure 2, and not on absolute values. Modeling 90% of the water level drop, for example, does not equate with a 90% reduction in the water level of the lake, but to a 90% reduction with respect to the maximum value shown in Figure 2 (and, similarly, for the other parameters). The values on the first row of Table 3 correspond to small stressor variations, similar to those that took place in Lake Koronia from 1988 to 1989 (in percentage variation), as shown in Figure 2. The output of the proposed fuzzy inference model is very close to the actual fish reduction that occurred for the same period, as shown on the last column of Table 3. Similarly, the values on the second row of Table 3 correspond to stressor variations for the period of 1988 to 1990, the values on the third row correspond to stressor variations for the period of 1988 to just before 1992, values on the fourth line correspond to variations for the period of 1988 to 1993 and values on the fifth row correspond to variations for the period of 1988 to 1995, as they are displayed on Figure 2. These variations are an indication of the cumulative burden inflicted on the ecosystem of Lake Koronia. The fuzzy inference system output for each of the time periods is very close to the actual measurements for fish reduction presented in Figure 2a and in the last column of Table 3. Moreover, the proposed fuzzy inference system incorporates very satisfactorily the most critical situation, with respect to environmental risk, that occurred in 1995 (Piesold and others 1999) and resulted in the minimization of fish production (fuzzy inference system output = 99%). Finally, as it can be observed on Figure 2, the fish production did not decline in a consistent manner in the years prior to 1988 and it was even increased in the period 1986–1987. However, these years were not considered in the proposed model because the uncontrolled introduction of fish spawn in 1984–1985 and the insufficient time given for fish reproduction after this period has caused unstable fluctuations in fish production (Piesold and others 1999).

The simulation results shown on rows 6–8 of Table 3 correspond to some scenarios of stressor impact reduction. For example, if only the water level drop is decreased to 60%, while industrial pollution and agricultural activities are maintained at 80%, then there is no change in the percentage of fish reduction, as shown in row 6 (fish reduction = 99%). On the other hand, if a large reduction in industrial pollution and agricultural activities occurs (their values reduced to 50%), while the water level drop is kept at very high values (90%), only a small mitigation of fish reduction is achieved (fish reduction = 92%), as shown in row 7. Finally, if a major improvement of fish production is to be achieved, then all of the input parameters have to be reduced considerably (all inputs at 50%, fish reduction = 86%), as shown on row 8 of Table 3. Although there is no evidence of such an improvement during the last years, these positive changes could increase fish production in the long term (however, increasing water level could decrease fish production in the short term, by flooding critical habitats). These results are in accordance with the management actions proposed in Piesold and others (1999) and Grammatikopoulou and others (1996), where it is stressed that the improvement of the ecosystem by changing a single parameter alone is impossible and that a combination of parameters must be improved to achieve ecosystem rehabilitation.

Thus, the proposed fuzzy inference model can be used as a tool for the investigation of the behavior of the aquatic ecosystem under a large number of hypothetical environmental risk scenarios. In this sense, it would be very useful in a decision support system that will aid the selection and application of appropriate management plans (Havens and Aumen 2000), within the bounds of the training data and its generalization capabilities. Additionally, the proposed fuzzy inference system can be used for environmental education and training, since its operation is based on a number of easily understood fuzzy rules.

Conclusions

This paper presented the development of a fuzzy inference model for assessing the interaction of stressors in the ecosystem of Lake Koronia. More specifically, the proposed model 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 fish production of the lake.

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. Its operation was successfully verified on a variety of environmental conditions, including critical states for the lake. Additionally, the proposed fuzzy inference model can be used as a tool for the investigation of the behavior of the aquatic ecosystem under a large number of hypothetical environmental risk scenarios, within the bounds of its generalization capabilities.

It was found that the application of the proposed model was quite simple and fast. The model provides well-defined predictions of the ecosystem state, as it is based on a well-defined set of assumptions. These predictions can be easily understood, since they are based on fuzzy linguistic descriptions. Since the proposed model combines qualitative analysis with quantitative data, it is expected that its predictions can be scrutinized with a higher level of confidence than quantitative assessment alone.

The proposed fuzzy inference model is relatively generic and its basic principles can be used under different circumstances and even for different types of ecosystems. Finally, it should be noted that the model's predictions are quantitative and testable, allowing for comparisons of predictions with on-going observational research and ecosystem monitoring.

Although the model has a number of advantages, the basic limitations to its use are the quality of data used and the level of expertise reflected in the fuzzy rules, which are both crucial for making accurate predictions.

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