INTERACTIVE WATER QUALITY SIMULATION IN A REGIONAL FRAMEWORK: A MANAGEMENT ORIENTED APPROACH TO LAKE AND WATERSHED MODELING

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RR-84-12
May 1984

Reprinted from *Ecological Modelling*, volume 21 (1983/1984)

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
Laxenburg, Austria

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Printed by Novographic, Vienna, Austria

FOREWORD

There is a growing awareness in the scientific as well as the policy and decision-making communities that the successful use of systems analysis and formal, model-based research requires special efforts to enhance the communication between technical experts and their clients, and between modelers and model users in particular. The International Institute for Applied Systems Analysis (IIASA) is addressing these topics in various aspects of its research.

Environmental systems analysis of necessity involves a strongly subjective and value-dominated human element, which defies formal representation in any generally accepted way. Only direct user involvement during various phases of the analysis, and the development of interactive methods in which the user plays an appropriate role, can hope to encourage the widespread acceptance and use of new approaches. This direct user involvement, in turn, requires new ways of man–machine interaction.

This report demonstrates one step in this direction. It describes and discusses an interactive simulation model of a lake coupled with heuristic, process-oriented models of the surrounding region. Using a menu-driven conversational control program, extensive input error correction, several levels of output aggregation under full user control, video graphics, and linguistic variables to translate some numerical output into more accessible formats, the model system attempts to provide an easily accessible way of simulating and exploring issues of regional development and environmental management.

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Ecological Modelling, 21 (1983/1984) 209–232
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

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(Accepted for publication 19 October 1983)

ABSTRACT

Fedra, K., 1984. Interactive water quality simulation in a regional framework: a management oriented approach to lake and watershed modeling. *Ecol. Modelling*, 21: 209–232.

A phosphorus-based water quality simulation model for a shallow lake/reed system (Neusiedlersee, Austria) has been coupled with a series of heuristic, process oriented models describing the physical and socio-economic catchment of the lake. Built into an interactive, modular decision support system's framework, which includes simple database management, interactive video graphics, and linguistic output formats, the programs are designed for the simulation and evaluation of regional development, i.e., agricultural landuse, industry, tourism, wastewater treatment, and perceived lake water quality. Special emphasis is put on communication and display through a friendly man–machine interface, including linguistic statements for the description of lake water quality.

INTRODUCTION

The human environment is obviously complex, and environmental problem solving is even more so since it includes socio-political and economic elements with numerous actors, differing goals and perceptions, and more or less pluralistic value systems. As a consequence, models of environmental systems and subsystems have become ever larger and more and more complex, and difficult to handle, understand, and believe in. However, the essence of modeling is simplification and re-scaling to dimensions and a degree of complexity that are easy to manipulate and are directly intelligible. Also, for most practical situations, there is never enough, or there is never the right kind of data to develop, calibrate, and rigorously test complex models.

On the other hand, for most practical applications, the isolation of a

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single subsystem out of any larger functional context is very difficult. One cannot—from a policy or management point of view—reasonably separate a lake from its watershed or use, or the physical system from its political environment, without running into the danger of being irrelevant, addressing the wrong issues, working on politically or economically infeasible solutions, or just pushing problems around, in somebody else's responsibility. The emphasis, however, should be on a comprehensive and integrated view of a system, on the overall "net" environmental effects, together with their social and economic impacts.

For the analysis of a lake and its watershed discussed in this paper, this amounts to extending the "classical" approach to the loading–response modeling of waterbodies, which requires the loading to be specified as an input (e.g., Vollenweider, 1969; Chen and Orlob, 1975; Jørgensen, 1976; Imboden and Gächter, 1978; Park, 1978) towards a more comprehensive study of a lake as an integrated element within its physical as well as socio-economic watershed.

Thus, instead of making assumptions about the pollutant emissions, and then simulating their probable effect on the environment, viz., lake water quality in this example, emissions themselves are simulated together with the processes in the socio-economic domain that cause and control them. These processes are functions of the policies and decisions within the socio-economic system, and are driven by uncontrollable external (e.g., climatic) variables. Also, in the more comprehensive framework, feedback that environmental change may have on the socio-economic system can thus be included. In other words, the boundaries of the system are extended to encompass a convenient causal, management or policy oriented, rather than physical or geographical, unit.

Also, the terms of the analysis are then familiar to the people concerned and involved: there is fertilizer use and agricultural output, area of vineyards and hectoliter of wine produced, the number of hotel beds and the number of visitors, or the degree of sewering of given communities, treatment plant design characteristics and perceived lake water quality as decision and performance variables, instead of mg $P\text{-}P_{04}$ per m^2 of lake surface, and day and mg Chlorophyll *a* per m^3.

Such a comprehensive approach requires a spatial and functional decomposition of the system at the level of the individual actors (in a functional rather than individual sense) in the management or decision making process, which, in a regional study is the sub-regional and local level. Decisions are made (and thus should be simulated) at the level of the individual community, industrial enterprise, or treatment plant. At the same time, however, decisions and resulting management actions are also taken at higher hierarchical levels—treatment associations, the provincial government, or the federal level—defining a corresponding hierarchy of systems and subsystems. Also, physical structures (e.g., watersheds) and political or administrative structures (e.g., communities or provinces) will not always overlap (see Fig. 1). This again results in at least two levels of structural or geographical conceptualization of any larger environmental system.

To cope with the resulting complexity and to make the system comprehensible, its model description has to be built on numerous gross simplifications. Many descriptions of subsystems and processes are based on qualitative expert knowledge, problem perceptions, or simply educated guesswork, rather than on established theories and a body of quantitative data from the respective disciplines. Although the resulting heuristic descriptions of the individual components of the system may appear crude or even naive, and hard to accept as valid models of these elements as such, it is their interaction on the systems level, allowing for a comprehensive and integrated treatment of the overall system, that makes them useful. The degree of resolution and the level of sophistication of the individual modules within the whole system has to be balanced, with special emphasis on the specific problem area addressed in the study, but also as a consequence of data and

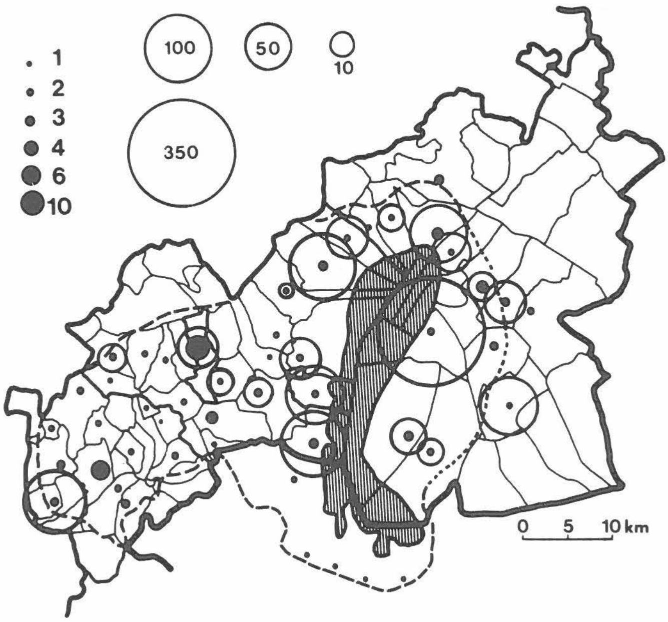

Fig. 1. The Neusiedlersee region: Solid lines of different thickness represent different political boundaries, i.e., state (in the south and east); province (north and west); counties, city limits, and community borders. Broken line represents approximate watershed boundaries. Community center scales are according to resident population (●) and numbers of overnight visitors in 1981 (○); population and visitor numbers in thousands (source: Hary, 1982). Shaded area represents lake/reed area.

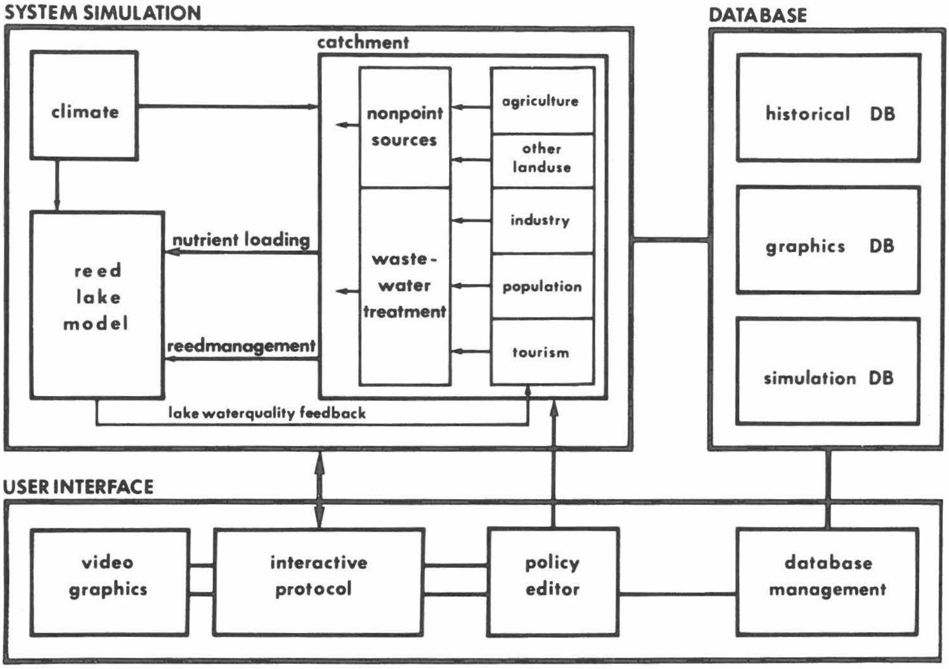

Fig. 2. The structure of the simulation system.

resource limitations. Whenever necessary and justifiable, a given module can be exchanged for a more sophisticated one—but it is of crucial importance for the smooth and interactive development of the system that the necessary linkage is provided in a flexible, easy to modify manner. Thus, to provide a stimulating and friendly environment for experimental learning—a LOGO-turtle environment (Papert, 1980) for systems ecology—the programs have to provide a sufficiently flexible functional, spatial, and temporal resolution. This allows for the interactive construction and modification of a problem oriented and user adequate system's representation, using a variety of alternative but compatible building blocks.

Consequently, the simulation system described below tries to incorporate the major elements of the watershed's nutrient cycle and their linkage to the socio-economic domain with emphasis on agriculture, industry, tourism, and the wastewater treatment system. It is based on extremely simplified descriptions of the individual component elements and processes, and emphasizes their regional and local interaction rather than the individual processes themselves. The basic structure of the program system is shown in Fig. 2. The system of programs is set up in an interactive framework, driven by a conversational control program that provides linkage of the individual modules, a system of databases, and graphical output. The control program allows the user(s) to interactively and dynamically define and simulate management options or policies by changing the values of control variables and parameters (Table I). Also, the controller handles the alphanumerical as well as the parallel graphical display units—in addition to a standard CRT, (geo)graphically organized information, which appears animated during the dynamic simulation, is displayed on a video screen (see Fig. 5). The output is provided at various levels of detail and aggregation, which are again selected interactively, and includes linguistic formats for the description of perceived

TABLE I

Watershed data: database samples for a town/community and a treatment plant

Eisenstadt	/all time-variable data as of 1979/
10424	population
25.0	% unsewered effluents reaching lake/reed
440	commercial/private beds (1979)
5000	visitor capacity (beach/restaurant/etc.)
522.5	woodland (ha)
1095.0	fields (ha)
10.0	% under irrigation
50.0	% intensively fertilized
65.0	average fertilizer kg P/(ha year)
480.0	pastures and meadows (ha)
390.0	vineyards (ha)
15.0	% under irrigation
80.0	% intensively fertilized
70.0	average fertilizer kg P/(ha year)
831	large animals (horses, cattle, pigs)
1400	poultry
90.0	% domestic wastewater collected
1	associated treatment plant No.
75.0	% effluents reaching lake directly
5000	commercial person equivalents
AWV_Eisenstadt	/treatment association/
1	position (town-no.)
10000	design capacity EGW (person equivalents)
1	treatment level
95.0	operational efficiency
1968	year of completion
4	number of modifications:
1975, 19999, 2.	year/capacity/treatment level
1975, 10000, 2.	year/capacity/treatment level
1980, 20000, 2.	year/capacity/treatment level
1981, 20000, 3.	year/capacity/treatment level
1982, 50000, 3.	year/capacity/treatment level

water quality. A description of the philosophical background and the more technical aspects of the interactive approach is given in Fedra (1983).

THE SYSTEM

Lake Neusiedl is an extremely shallow (1.5 m) lake of about 150 km^2 surface area, embedded in a belt of dense reed (Phragmites), covering approximately another 150 km^2. The lake's catchment extends over approximately 1300 km^2 (Fig. 1) in the easternmost part of the country, in a low plane (120 m above sea level) opening towards the Small Hungarian Plane in the east, and bordered in the northwest and west by groups of mountains reaching 748 m. The southernmost part of the lake and its artificial outflow are on Hungarian territory. A detailed description of the limnology of the lake has only recently been published in a comprehensive monograph (Löffler, 1979). The lake is characterized by its extreme shallowness (with a maximum depth of only 1.8 m), and the large extent of the surrounding wetlands, the reed belt. The reed plays an important role in the nutrient budget of the system. These wetlands are also renowned for their rich and unique wildlife, notably birds, and, together with a series of smaller lakes—the "Lacken"—southeast of the main lake (typical of the landscape of the area) they are an important element for tourism.

Lake Neusiedl experienced obvious water quality deterioration, largely as a consequence of a dramatic increase in nutrient loadings over the last decades that were attributed to changes in land use patterns. The catchment is dominated by agricultural land use (46% of the area and about 20% of the region's gross domestic product), and particularly by wine growing around the lake. Agricultural production also includes grain, sugar beets, vegetables, and fruits, in part processed in the local sugar and canning industries. The agricultural sector experienced a strong increase in intensive agriculture, particularly winegrowing (a relative increase of about 50% in the cultivated area from 1966 to 1975, and of 48% from 1970 to 1978), and the development of food processing industries, feedlots, and poultry farms in its catchment. In addition to one major point source, the river Wulka, and a series of smaller, but well identified point sources such as the discharge from the local sewage treatment works (numbering 26 in the catchment), a considerable influence of diffuse sources including atmospheric ones (largely related to wind erosion of fertilized soils), is suspected. An important economic sector in the region is summer tourism, most of it concentrated around the lake, and much of it depending on the direct use of the lake for bathing, boating, sailing and surfing. Again, an average growth of about 10% per year was observed over the last decade (1970–80).

Since the early seventies, a conspicuous deterioration of the lake's water quality could be observed. A rapid increase in nutrient concentrations (nitrogen, phosphorus) in the lake was reported, paralleled by changes in plankton composition and an increase in plankton biomass (see e.g., Löffler, 1979). This development, resulting in at least local algae blooms, is certainly most undesirable, as it quite obviously endangers the lake's attractiveness for recreation. Recreational use of the lake, however, or the income from tourism, is one of the most important elements in the economy of the region. Only recently, apparent water quality problems and several controversial development projects around the lake have triggered a heated political debate. The specific problems in the management of the lake system have to be understood as resulting from three major conflicting objectives in the development of the region, namely:

(a) Development of tourism, leading to construction activities and affecting landscape and biota, especially in the shore zones of the lake, together with the construction of channels, marinas, and bathing beaches to provide direct access to the open lake; it also involves increased domestic waste and sewage production.

(b) Intensification of industrial and agricultural production; this involves pollution from industrial plants, wastewater and the production of excess manure from animal husbandry and feedlots; it also includes fertilizer leaching, wind erosion of fertilized soils, or the enhancement of erosion resulting from the conversion of rangeland into vineyards, or from land fills, and irrigation.

(c) The preservation of environmental quality (as an essential resource for tourism, and especially lake water quality.

These objectives, which are obviously conflicting, have to be seen in the context of the region's overall development within Austria; situated at the "closed" border towards Hungary, the industrial and infrastructural development of the Burgenland had a late and slow start in comparison with the overall Austrian development.

MODEL REPRESENTATION

The simulation programs describing the region introduced above are organized around a dynamic, phosphorus mass balance model for the lake and the surrounding reed belt. A group of additional programs generates and transports nutrients to the lake as a function of landuse, agricultural and industrial activities, wastewater treatment, and tourism, the latter in turn being influenced by lake water quality (Fig. 2).

In the model representation, the catchment is disaggregated into 45 communities, grouped into three districts within Austria, and one in Hungary.

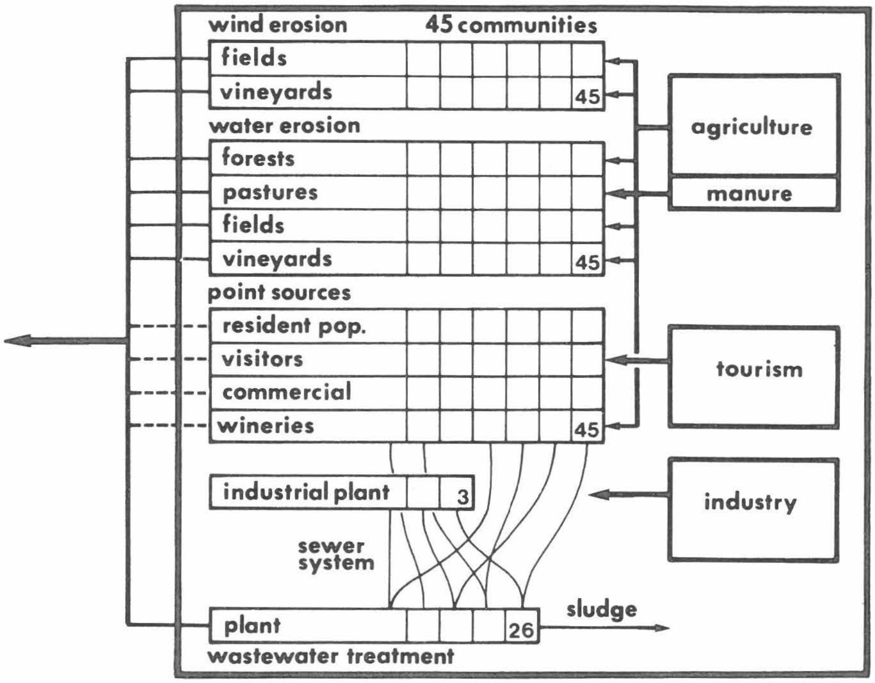

Fig. 3. Flowchart for the watershed models. Output from the watershed constitutes the nutrient input to the lake/reed system.

Together with these communities, 26 treatment plants and three major industries (food processing and canning, and sugar production) are treated explicitly. Figures 2 and 3 show generalized flow charts for this system of models.

Watershed modeling

A major element of the simulation is the estimation of nutrient release from the watershed as a function of the climatic variables and the landuse characteristics, and is based on the obvious but not necessarily sufficient assumption that it is these nutrients that primarily affect water quality. Since very few data are available on most of these processes, their description is based on expert opinion and problem perceptions rather than on physical theory. The resulting modules, describing the physical (e.g., erosion) and socio-economic (e.g., tourist behavior) processes included in the watershed modeling are thus examples of heuristic programming, and resemble rule-based expert systems of artificial intelligence. Processes in the watershed are described on a monthly timescale using simple difference equations.

Diffuse waterborne pollution is made a function of runoff, each community's drainage situation (described by one lumped parameter describing slopes, drainage density, and geology), and landuse. The latter also includes fertilizer application and irrigation. In addition a specific monthly weight, depending on the distribution of groundcover and farming activities throughout the year, is applied. Wind-driven erosion of fertilized soils is again made a function of the above landcover information, as well as on each community's position towards the lake. For each month, an erosion and transport-relevant wind-rose is generated, using eight main directions, which is used to convey particulates to the reed and lake system.

Domestic wastewater estimates are based on the resident population, commercial population equivalents, and the number of tourists estimated for each community. The latter is estimated from the capacity for overnight stays (i.e., the number of available beds in hotels, second homes, etc.), and the capacity for short-term visitors (beaches, restaurant places etc.). A monthly weight for each type of visitors is used, derived from the available statistics on tourism (e.g., Amt der Burgenländischen Landesregierung, 1980). The resulting estimate is then corrected for the deviations of the monthly temperature from the long-term average, i.e., more visitors are assumed in warmer than average (summer) months; for the previous month's water quality, i.e., water quality classifications below average (see below) cause a slight negative feedback on the attractiveness of lakeshore communities; for crowding, i.e., the ratio of last month's number of visitors to the total capacity, causing a slight negative feedback for communities with ratios of less than one; or for the case when the lake is frozen and available for skating. Total domestic sources are summed for each community. According to the percentage of the community sewered, the respective part is routed to the corresponding treatment plant. From the unsewered part a certain fraction, depending on the drainage situation, is routed to the lake system. As a specific feature of the area, wastewater produced in connection with wine harvesting and production, concentrated from October through December, is added to the domestic wastewater (proportional to the estimated harvest) which is determined from the area of vineyards, climatic variables, and fertilizer application rates. Similar to the estimation of domestic sources, the contributions of the main industries are determined using monthly weights that specify wastewater output relative to average or peak load. Total sewered point source contributions are then routed to the treatment plants. The inflow to each plant is then treated according to the plant's capacity, the treatment level installed, and operational reliability. If the inflow exceeds capacity, as may happen particularly during the summer tourist season or during harvest and campaign times, the operational efficiency of the plant is temporarily decreased. The effluents after treatment are then added to the input to the lake and reed, respectively, depending on the plants' locations.

In addition to this dynamic nutrient budgeting, the programs keep track of revenues from tourism, the (operational) costs of wastewater treatment, and reed harvesting, which is specified on a monthly basis. All prices and wages used in the model always represent actual values at simulation time, i.e. basic figures are corrected yearly to reflect inflation and price increases, and used, undiscounted, on a real-time basis.

Most of the estimates used in these models also include some stochastic perturbation in an attempt to account for uncertainties and natural fluctuations in the processes and relationships considered. After compiling the nutrient inputs reaching the reed-belt and the lake directly for a month, and completing the financial accounting, the lake program is called to update the water quality status of the lake.

The reed / lake model

In the core of the simulation system is a phosphorus based model of the lake and its surrounding reed belt (Fig. 4). The model uses available and particulate (detritus) phosphorus in the open water, in the water in the reed system, and in the sediments of the reed system, to describe the dynamics of phosphorus, algae, and reed biomass. The latter can be exported from the system by harvesting, which not only reduces reed biomass, but also affects (depending on the technology used) the diffusion between the sediments and the water of the reed system (by pore squeezing due to heavy machinery), the mixing between reed and lake, and reed mortality. In addition to nutrient uptake and growth, mortality, respiration, and mineralization, various forms of mixing and transport are included.

The reed/lake system is described by a set of differential equations, with partly stochastic parameters and stochastic forcings. A short discussion of the model is given in Kamer (1983). The equations are solved by a fifth-order Runge Kutta method. As in the case of the watershed models, the reed/lake system is simulated with a monthly timestep. It is represented by two adjacent, connected cells, coupled by various transport mechanisms. Nutrients are transported through the reed zones to the open lake to balance the outflow from the lake, and also by eddy diffusion along the border between reeds and open water. Since the latter process is considered to be largely wind-driven it is made a function of average wind velocities. Under ice, the mixing coefficient is correspondingly set to values of molecular diffusion. In addition to the settling of detritus (largely in the calm reed zone), adsorption and settling of phosphorus in the open lake is included as a governing mechanism in the model. A summary of the model constants, initial condi-

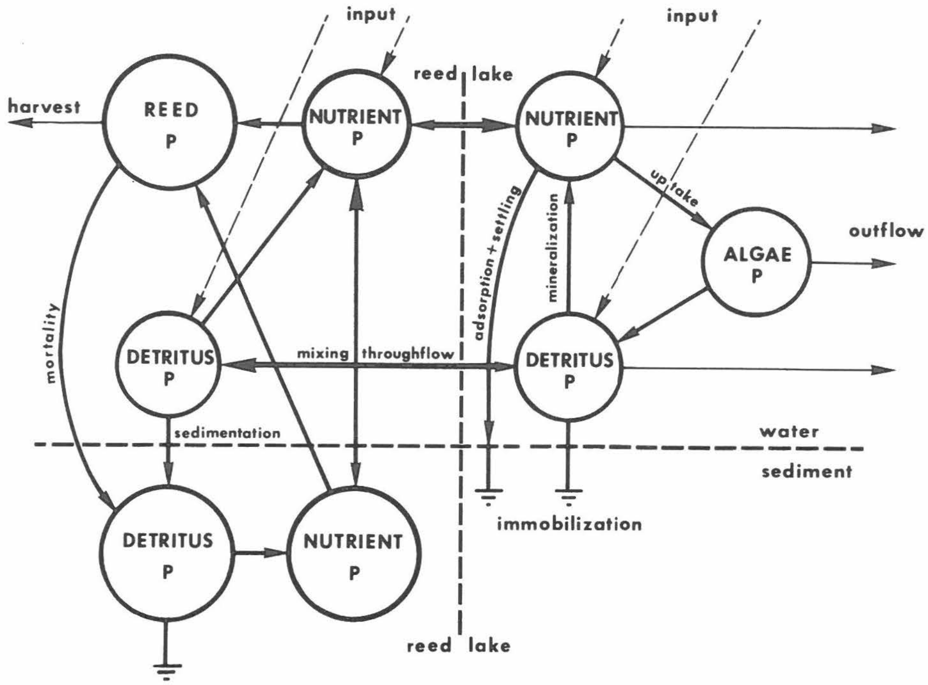

Fig. 4. Flowchart of the lake/reed model. Size of arrowheads indicates dominant flow direction for exchange processes.

tions and parameters, as well as the model's structure, is given in Table II.

Nutrients from the catchment (in directly available as well as in particulate, mineralizable form) reach the reed system as well as the open lake directly, depending on the respective source's (viz., community or treatment plant) location and drainage system. The latter, for communities bordering the reed/lake system, accounts for the major channels through the reed zone, allowing part of the inputs to reach the open lake directly. In addition to the nutrient inputs, the model is supplied with a value for the lake's outflow, average wind velocity, air/water temperature, solar radiation, and information on reed management. The reed management information (area harvested, technology used) will determine an export term in the reed biomass equation, and will also invoke small adjustments in some of the model parameters for reed mortality (if cut underwater); there is also the exchange between sediment and water in the reed zone (representing pore squeezing from the use of heavy machinery), and finally the exchange between reed and the open lake (which will increase proportionally to the area of reed cut).

The state variables of the model (all in terms of phosphorus) are reed biomass, detritus (particulate P) and available P in the water of the reed zone; detritus and available P in the upper layer of the sediment of the reed zone (supposedly affected by exchange processes and assumed to be 1 m, roughly corresponding to the rooting depth of Phragmites); and detritus, available P, and algae biomass in the open water of the lake, the latter again in units of P. Assuming a constant P : Cl ratio of 1, algae biomass could alternatively be interpreted in units of Chlrophyll.

Primary production of reed biomass uses a production rate that is made a linear function of the product of irradiance and temperature, and is limited by space competition, i.e., a carrying capacity set in terms of areal biomass. The model includes seasonal variability in the biomass/phosphorus ratio of

TABLE II

Lake model constants and parameters

100.0	area reed in km^2		
150.0	area lake in km^2		
50.0	water volume reed in ml m^3		
150.0	water volume lake in ml m^3		
15000.0	initial cond.:	reed biomass P (January)	(mg/m^2)
100.0	initial cond.:	detritus P reed system	(mg/m^3)
100.0	initial cond.:	available P reed system	(mg/m^3)
15000.0	initial cond.:	detritus P reed sediment	(mg/m^2)
10000.0	initial cond.:	available P reed sediment	(mg/m^2)
100.0	initial cond.:	detritus P lake system	(mg/m^3)
50.0	initial cond.:	available P lake system	(mg/m^3)
10.0	initial cond.:	algae P lake system	(mg/m^3)
0.30	p (1) **	sedimentation in reed	/month
0.018	p (2)	mineralization in reed	/month × degree C
0.60	p (3)	reed production rate	/month × degree C × kW
18000.0	p (4)	reed carrying capacity	mg P/m^2
0.01	p (5) *,**	reed mortality (base rate)	/month
0.50	p (6)	ratio reed nutrients from water	
10.0	p (7)	mm constant reed water	mg/m^3
1000.0	p (8)	mm constant reed sediment	mg/m^2
0.033	p (9) **	sedimentation in lake	/month
0.025	p(10)	mineralization in lake	/month × degree C
0.50	p(11)	algae mortality rate	/month
0.60	p(12)	algae production rate	/month × degree C × kW
10.0	p(13)	Michaelis–Menten constant algae	mg P/m^3
0.0033	p(14)	particulate P immobilization	/month
0.0025	p(15)	mineralization detritus sediment	/month
0.0022	p(16) *,**	mixing reed sediment/water	m^2/month
0.01	p(17) *,**	mixing reed/lake	m^2/month × m/sec

* Value affected by reed harvesting.

** Value affected by step functions triggered by ice cover, strong wind, or temperature.

TABLE II (continued)

System structure: input/output matrix; reed: reed biomass; PSrw: nutrients in reed water; PPrw: detritus in reed water; PSrs: nutrients in reed sediment; PPrs: detritus in reed sediment; PSlw: nutrients in lake water; PPlw: detritus in lake water; APlw: algae biomass; Outp: exports through outflow, harvesting, and immobilization

to from:	reed	PSrw	PPrw	PSrs	PPrs	PSlw	PPlw	APlw	Outp
reed	××××				**				**
PSrw	**	××××				**			
PPrw		**	××××				**		
PSrs	**	**		××××					
PPrs				**	××××				**
PSlw		**				××××		**	**
PPlw			**			**	××××		**
APlw							**	××××	**
Input		**	**			**	**		××××

the reeds in estimating carrying capacity as well as the export through harvesting. Harvesting, of course, is specified on an areal basis, and not in units of P. A nutrient limitation term uses multiple Michaelis–Menten expressions for the available fraction in the water and the sediments of the reed zone. The half saturation constants used, however, are about an order of magnitude lower than the average concentrations observed. Only under extreme conditions therefore, would nutrient limitation affect reed production, and the term is largely a protection against unrealistic behavior far outside the range of feasible values. Under normal—non-limited—conditions, the proportion of nutrients taken from the two possible sources, viz., water and sediment, is determined by an arbitrary coefficient, which, in the absence of any more detailed information, is set to 0.5. Reed mortality is described as a first-order process, affected by average windspeeds and air temperature, which triggers a step function with higher values in fall and winter.

Detritus in the water of the reed system receives inputs from the watershed as well as from exchange processes with the lake. Losses are due to net throughflow to the lake, settling (first-order), and temperature dependent mineralization. Eventually the mixing with the open lake may also cause exports of particulates. Detritus in the sediment is supplied by settling of the detritus in the water of the reed zone, and by reed mortality. The latter, in order to account for the different speeds of remineralization of very coarse material, and, in fact, whole leaves and stems, is directly passed to the sediment compartment. Losses are due to immobilization at the lower end of the 1 m sediment layer considered for exchange processes, and the temperature driven mineralization.

Available P in the reed zone is exchanged between water and sediment in a diffusion-type equation, and is proportional to the concentration difference. Under ice (when anoxic conditions are likely to occur), or after the use of heavy machinery for reed harvesting, this coefficient is increased. The exchange of available P between the reed zone and the open lake is also described by a diffusion-type equation (which, on the monthly timescale employed, also incorporates advective processes due to seiche motion and circulation), with the eddy diffusion coefficient linearly coupled to the wind velocities. Under ice, this mixing is reduced to very small (molecular) levels.

In the open lake, primary production is again described as a linear function of the product of irradiance and temperature, and corrected for average turbulence (cf. DiGiano et al., 1978), described as a randomly perturbed quadratic function of average wind speed. Nutrient limitation is expressed in terms of Michaelis–Menten kinetics. Since the lake is so shallow and usually vertically mixed, there is no settling term for the algae compartment. Mortality is described as a first-order reaction, which is again made temperature dependent as in the case of the reed. Detritus settles (although with a very low rate as a result of the extreme turbulence of the lake) in a first-order process, and is mineralized as a function of temperature. Dissolved nutrients, i.e., phosphate, are adsorbed to mineral turbidity (which is generated as a randomly perturbed function of the wind velocities, based on the observed statistics of turbidity), are settled out, and are immobilized in the sediments. The latter process seems to be most important in the nutrient budget of the lake, since it is the only plausible mechanism to account for the phosphorus inputs while maintaining the observed in-lake concentrations. All the above processes' descriptions have to be seen in light of the monthly time-step employed, that averages over many of the more transient short-term dynamics of the system.

THE INTERACTIVE FRAMEWORK

These models of the catchment and the lake/reed system are incorporated into an interactive control program (see Fig. 2) that allows the user to simulate the evolution of this system for an arbitrary number of years while exploring the consequences of (again interactively defined) management or policy alternatives. For the period from 1970 to 1979, historical data on most of the external driving variables (i.e., temperature, wind velocities, inflow and outflow from the lake) are available. Simulations can only be started within this period, and the respective values are supplied from a simple database connected to the simulation system. Whenever the simulation is extended outside the period of available data, synthetic time series are generated on the basis of the available data. Similarly, other time-variable elements of the system (e.g., number, size and level of treatment plants, landuse patterns, number of hotel accommodations, etc.) are supplied from this database or from simple submodels fitted to the historical observations. However, if so desired, the user can override the default development for any year and supply his own version of the management and control variables.

TABLE III

Sample output from the interactive model system

INPUT TOTALS for: July 1970
REGION: Region aggregated

Number of visitors	(1000):	800.856	
overnight stays	(1000):	258.022	
short term visitors	(1000):	542.834	
Pollution load in metric tons:			
Nonpoint:	forests and pastures	0.157	1.9%
Nonpoint:	agricultural fields	0.687	8.2%
Nonpoint:	vineyards	0.893	10.7%
Nonpoint:	atmospheric sources	1.312	15.7%
Point:	domestic wastewater	4.503	53.9%
Point:	industrial sources	0.797	9.5%
Total phosphorus input in tons:		8.349	100.0%
Input to reed system:		5.656	55.8%
Input to lake system:		3.693	44.2%

To list the respective values of a sub-region,
type its number, followed by "RETURN",
for a list of sub-regions, "−1." "RETURN",
to continue, "RETURN" only.

RESIDUAL SUMMARY:

	current:	cumulative:	
Total Wastewater generated:	836987.	4709457.	m^3
Effluents after treatment (P)	1.	4.	tons
sludge + solids for deposition	9.	53.	tons
Total solid waste for deposition	2090.	14630.	tons

date: 1970 7 simulation month: 7.
WATER QUALITY STATUS: good – moderate

to print a monthly nutrient mass budget for the lake,
type "1.","RETURN",
to skip the printout;"RETURN" only.

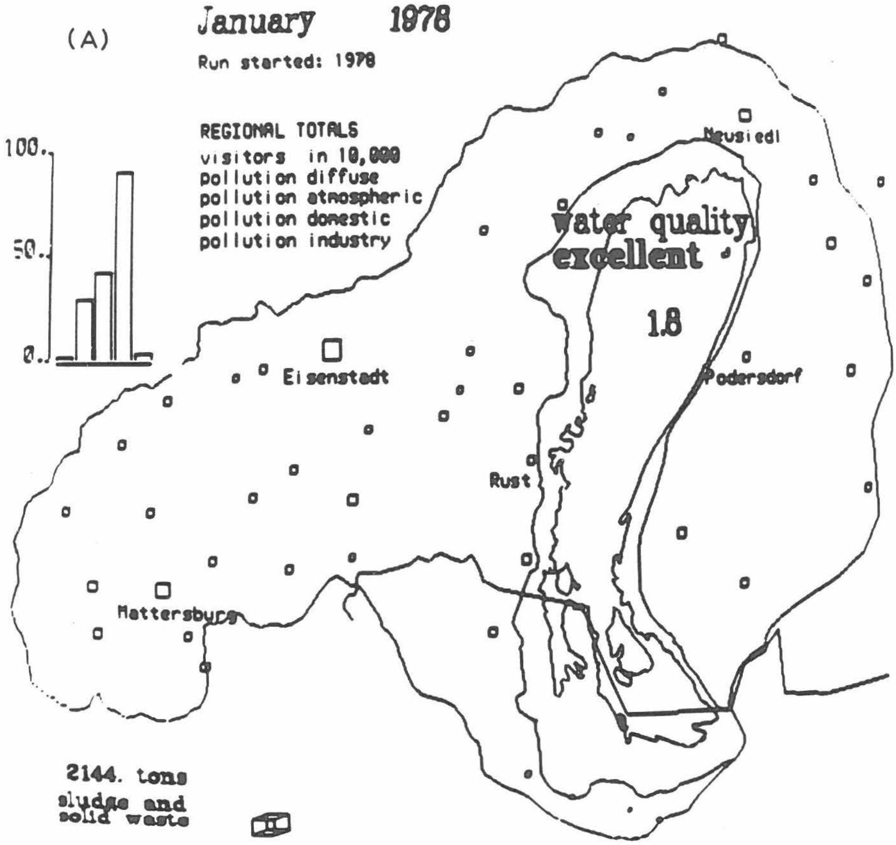

Fig. 5. Video display of the regional map. (A) Basic map with watershed boundary, lake and reed contours, and towns/communities; histogram summarizes number of visitors and pollutants for the region; note water quality classification and water temperature indicated in the lake. (B) Small histograms represent number of visitors and pollution from different sources for individual communities; bold treatment plant names indicate loads above design capacity; (C) Note increase in the number of visitors around the lake and parellel increase in domestic wastewater; (D) Distribution of yearly totals of P effluents after treatment from domestic sources.

For example, one can increase the area of vineyards around the lake, change the fertilizer use per landuse category and community, build hotels in individual communities, upgrade treatment plants, connect communities to existing plants, etc. In addition, reed harvesting (i.e., the area to be harvested and the technology to be used) can be specified on a monthly basis.

The model system, however, includes numerous random disturbances, many of them affecting the management variables specified. Most of the processes, such as for example treatment plant operation, are described with

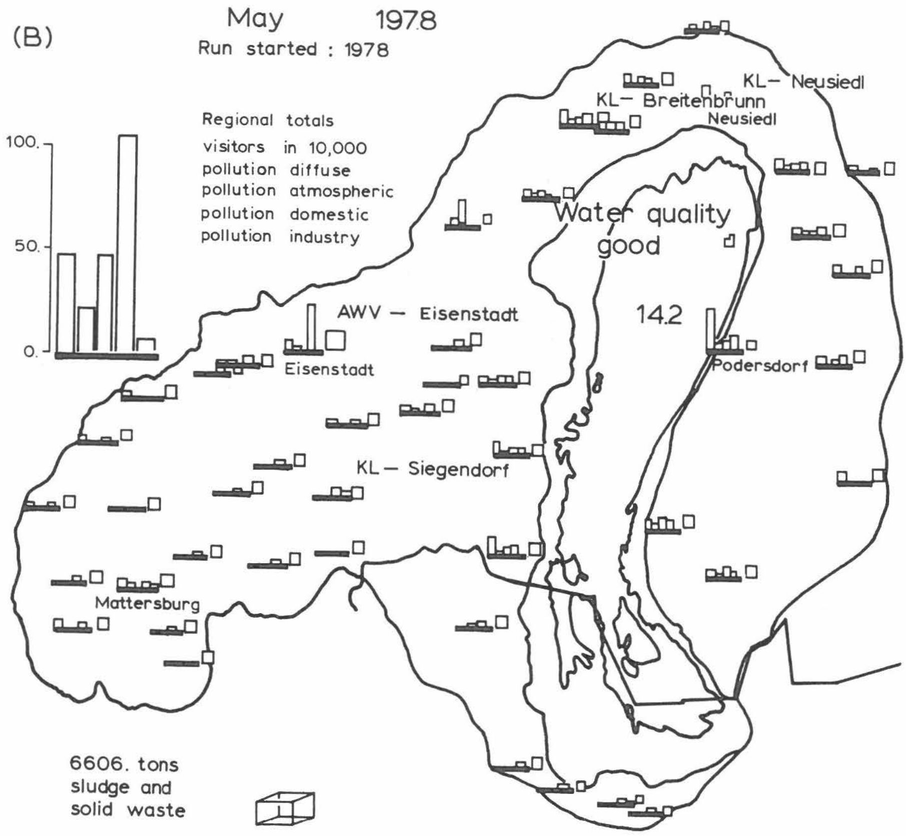

Fig. 5 (continued).

the help of stochastic parameters, allowing the user—quite realistically—to exert only partial control over the system. To facilitate the use of the fairly complex simulation system, the control program offers a system of menus for the selection of options, and checks the feasibility of inputs wherever possible. Also, the model-generated output is offered at several levels of detail; by default, only summary regional statistics are displayed at each time-step. The user can, however, choose to print and display more detailed information on a community/treatment plant level, or on the level of individual processes (see Table III). This is particularly useful for the detailed study of the nutrient flows in the lake/reed system, where monthly flows and the values of all state variables at the end of a month can be displayed.

Parallel to the alphanumeric display on a normal screen terminal (Table III), the system also includes a graphics monitor, which displays a map of the region (Fig. 5). On this map, the summary statistics of the major

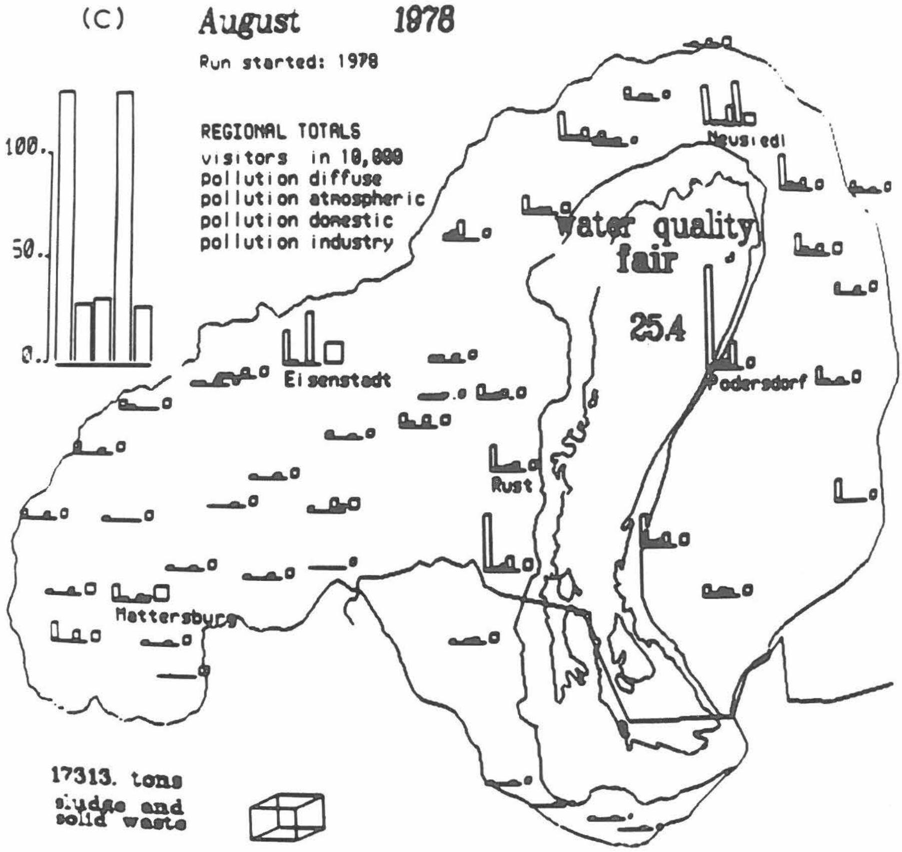

Fig. 5 (continued).

processes, as well as the lake water quality status are shown (Fig. 5a). If a more detailed level of output is selected, statistics for the individual communities and treatment plants are shown with graphical symbols, resulting in an animated display during the simulations (Fig. 5b,c). Also, when control variables are edited, the position and names of the affected communities are temporarily indicated. At the end of each simulation year, several yearly statistics (such as total number of visitors, revenues from tourism, erosion of fertilized soils, or wastewater generated) can be displayed on the map with simple symbols, for a comparative evaluation of regional patterns (Fig. 5d).

If the simulation is continued for another year, the system again offers the optional use of the policy editor. Here, the watershed parameters and control variables (see Table I) can be edited, reflecting changes in the regional development, or policy. If no changes are made, the system follows its default evolution for time-variable values (e.g., prices, trends in landuse patterns such as increase in vineyard area at the expense of pastures, or the

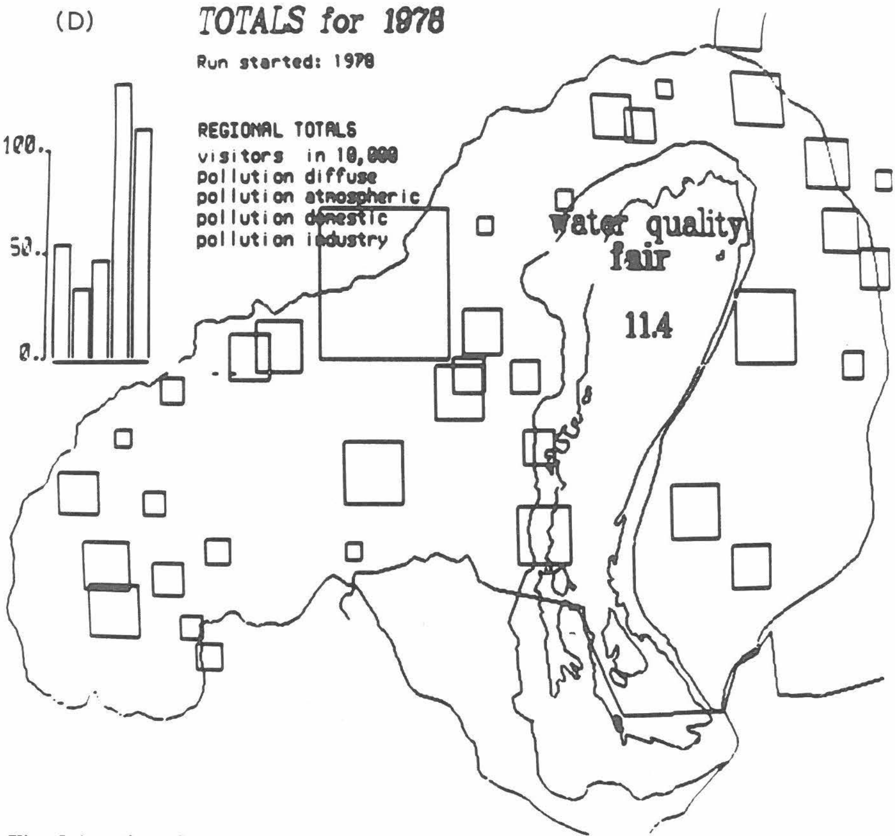

Fig. 5 (continued).

degree of sewering for the communities). These changes in the default case are either based on the historical development (as captured in the systems databases) or extrapolated outside the range of historical data, or estimated using simple models, such as logistic growth equations, again based on observed trends. Other modifications are based on the simulated regional development. The increase (or possibly decrease) in the number of beds in a given community, for example, depends on revenues from tourism (or the average occupation of these beds) in the previous simulation year. The system thus includes several feedback mechanisms, which are designed to keep its behavior (if alternative or even extreme policies are simulated) within plausible limits.

Statistics from any simulation year are stored in the simulation data base, and, for multi-year simulations, can be used for year to year comparisons, or for the display of the time series and trends of these values. Since all the database files are permanent disk-files, these records can then be compared and analyzed at leisure, using whatever analysis programs are desired.

DISCUSSION

The data set available on lake Neusiedl, although covering several years, many chemical compounds and biological variables sampled at roughly monthly intervals at up to 22 stations over the lake's surface, is poor when one attempts to calibrate a simulation model with it. Extreme short-term and spatial (i.e., horizontal) variability result in an extreme scatter of the observational data. As an example, there is no (statistically significant) trend in phosphorus concentrations or chlorophyll values that is obvious from the data covering the period from 1972 to 1979, although the biological indicators (e.g., species composition)—obviously more sensitive since integrating and the sheer appearance of the lake strongly suggest increasing eutrophication. The lack of sufficient and appropriate data, however, is quite typical for sampling programs that are the result of partly uncoordinated individual efforts, with little or no overall planning or regard to a later analysis of the accumulated data.

Also, there are several processes of potential importance that are not included in the model system: cutting reed to provide access to the open lake, beaches, and marinas (which will influence the exchange processes between reed and open lake); a strong growth of bathing huts at the fringe of the reed system; or the introduction of Tilapia sp., which potentially disturbs the macrophyte-related nutrient cycling in the lake; or the effects of massive stocking and commercial fisheries. Further, the model is based on a single nutrient, which may or may not be limiting. It lumps all primary production in a single compartment, and disregards the higher trophic levels. Although being quite site- and problem specific in its treatment of the lake/reed coupling, the model is extremely simple in comparison with some other lake water quality models (e.g., Park et al., 1975; Jørgensen et al., 1978; Nyholm, 1978; Jørgensen, 1980). Nevertheless, the available data allowed only a calibration in terms of feasible parameter ranges (see Fedra, 1982).

All these sources of uncertainty suggest that the lake model as such is at best conditionally useful. However, when seen in the framework of the entire watershed, and accounting for all the sources of uncertainty there, the problem gains another perspective. As part of a regional development problem, a rather coarse description of the lake system is quite sufficient. The questions to be answered at this level are, e.g., whether a given development policy will result in an improvement or a deterioration of lake water quality; what effects these levels of water quality might in turn have on regional development through effects on tourism, property values, etc.; and how any modifications of these policies may change these patterns. Given the considerable uncertainty in the relationship between the classical water quality indicators, apparent water quality, and its feedback on tourism, lake response can obviously be measured with a very crude yardstick indeed. In this specific example, much of the lake's attractiveness is due to: (a) its vicinity to the population center of the capital, Vienna; (b) its gentle beaches and high water temperatures; and (c) its scenic and enjoyable surroundings. None of these characteristics are affected by water quality. Thus, within the above framework, a qualitative assessment of the lake's response to various scenarios of nutrient loading will suffice.

To be relevant in the management- and policy oriented application, the output from the lake model has to be "translated" into meaningful indicators: rarely will these be chlorophyll or phosphorus concentrations directly. In the framework of the regional development problem, the lake water quality problem is directly related to tourism, and thus to perceived water quality. Here macroscopic features like appearance, taste, and odor are of importance. From a long term perspective and for the prediction of a general trend in water quality evolution, it is the overall nutrient budget, i.e., the amount of net nutrient loading, that is of importance. Appearance, taste and odor are, of course, functions of the classical water quality variables treated in the model, but this relationship is neither straightforward nor well known. However, it is in terms of tourist reactions (or from a more general point of view, apparent environmental quality, a deliberately fuzzy notion), that the success or failure of any lake-related management strategy has to be assessed.

As a first step towards accounting for this discrepancy between what can be modeled with a mass-budget approach, and what is relevant in the application-oriented framework, the water quality status of the lake (simulated in terms of phosphorus and algae concentrations) was translated into a verbal quality scale.

Each of the calculated values of the water quality variables is basically a sample from a probability distribution of possible outcomes over the ensemble of possible inputs and parameters (Fedra, 1982), and in fact is generated by largely stochastic models. It is thus associated with a certain variability, or it comes as a distribution: a set of numbers. Using fuzzy algebra (Zadeh, 1973), this translates into the linguistic statement describing water quality.

This serves several purposes: (1) It provides an easy to understand user interface, for which the decision maker can develop an intuitive feeling, and which he can merge into his set of mental models;

(2) It interfaces nicely with the stochastic simulation techniques used. When the water quality variable comes as a discretized distribution after running the respective model more than once in a Monte Carlo scheme (Fedra, 1982), this distribution can again be described by a fuzzy set. With a fuzzy relationship between the water quality variable and the quality class, the support levels or values of the membership functions for the individual

quality classes can be computed (Jowitt and Lumbers, 1982). The result can then be displayed by just indicating the respective verbal classification (cf. Fig. 5), a range of classes (e.g., good to moderate, Table III), or by using a simple graphical display method (Fig. 6). The size of the window, moving along a quality scale, represents the uncertainty in the water quality forecast; its position on the quality scale is given by the composition of prediction uncertainty (represented as a fuzzy set describing the water quality forecast) and classification uncertainty (the fuzzy relationship between values of the water quality variable and the quality classes).

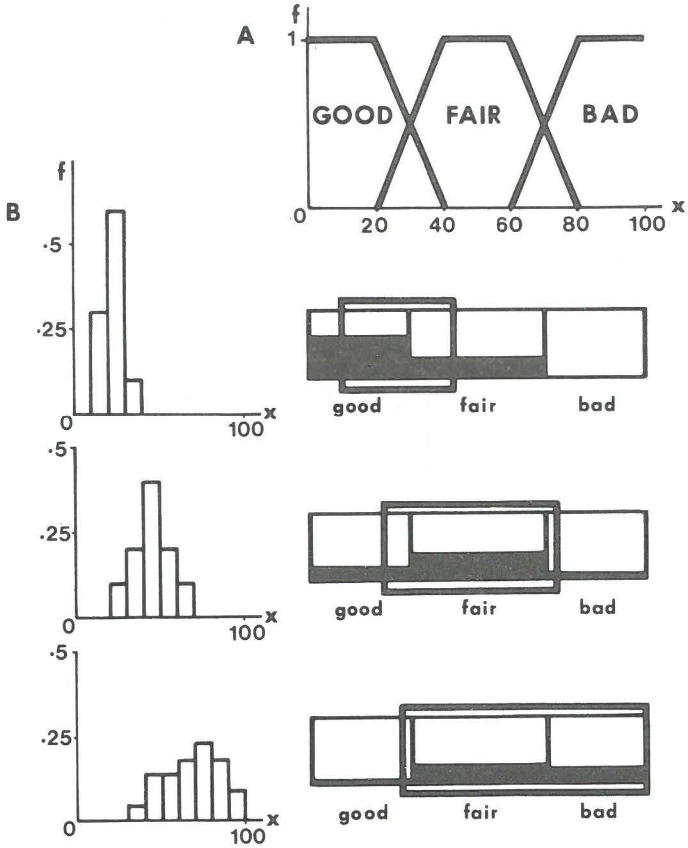

Fig. 6. Water quality classification using fuzzy sets. (A): Fuzzy relationship R between a continuous water quality variable, x, and three water quality classes; (B): Examples of translating the composition of a water quality forecast of increasing uncertainty (expressed as a frequency distribution of the water quality variable x, interpreted as a fuzzy set) with the fuzzy relation R into a simple graphical symbol, i.e., the window over the quality scale. Dark areas represent support levels for the individual quality classes.

(3) It can easily be backed up by a more elaborate description in terms of probability distributions (displayed graphically) when requested;

(4) It can be quite easily calibrated, even if there is only partial consensus in a group of people; in fact, it can be understood as representing partial consensus.

(5) The linguistic statements can easily be combined into policy oriented classifications, conclusions, or fuzzy inferences of the sort: if water quality is fair or better, and tourism is constant or slowly increasing, then the policy is a success; otherwise, it's a failure.

This already sounds very much like the language of a certain level of policy making, as this quotation from a state law, containing a development program, should demonstrate: "Tourism as an important economic factor shall be continually developed. The unique environmental potential [of the Neusiedlersee region] forms the essential basis for tourism. For this reason, it has to be maintained. Every individual action for the development of tourism has to be examined according to this principle" (Landesgesetzblatt Burgenland, 1982). But now there is a direct link provided to simulation modeling, which bridges the gap between the language of the non-technical user, or the real-world application, and the numbers of the model. Lists of such statements combined through fuzzy relations can define objectives and criteria at a relatively abstract level of conceptualization, and appealing from a policy oriented point of view. At the same time, the direct link to the numerical, strictly quantitative (though stochastic) methods of simulation and analysis is maintained. Obviously, this can be used for the automatic screening of very large numbers of alternatives, and as a preprocessor for the interactive approach.

Also—and this is probably the most valuable aspect of the whole approach—it places much of the critical ambiguity in the user interface, where it is obvious, easy to inspect and criticize, and capable of provoking judgement. After all, the idea is to provide decision support for more informed judgement, not to replace this judgement by an algorithm. It is certainly a very effective vehicle for communication, and its purpose is to make otherwise inaccessible, overwhelming, and forbidding simulation models interesting, attractive, more educational, more useful and, hopefully, used.

ACKNOWLEDGEMENTS

The research described in this paper was supported by the Austrian Research Foundation, Grant No. 3905, and completed while the author was at the Massachusetts Institute of Technology, Cambridge, MA, under a Fellowship from the Max Kade Foundation.

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