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AUSTRIAN LAKE ECOSYSTEMS CASE STUDY: Achievements, Problems, and Outlook After the First Year of Research

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PREFACE

Among the various fields of research at the Resources and Environment Area of the International Institute for Applied Systems Analysis (IIASA), environmental systems have played a significant role ever since the establishment of the Institute. In 1977, as a result of an IIASA workshop on *Water Quality Modeling*, it was decided to focus particular attention on the water quality problems of natural lakes and man-made impoundments (storage reservoirs). It was felt that IIASA could make an important contribution to the use of models for water quality control and management purposes by attempting to bridge the gap between the natural sciences and policy-oriented disciplines.

Accordingly, two specialized workshops were convened. The first of these was the workshop on *Geophysical and Ecological Modeling of Deep Lakes and Reservoirs* (1977) and the second one was the workshop on *Hydrological and Ecological Models of Shallow Lakes and Reservoirs* (1978). Based on the discussions at these workshops, the needs for methodological developments and for comparative studies involving lake ecosystems in IIASA's National Member Countries were identified. In 1979 a case study on Lake Balaton was initiated as a comparative venture between IIASA and several Hungarian organizations, led by the Hungarian Academy of Sciences. In 1980 the set of IIASA's lake-related case studies was enriched by the initiation of a study on lake ecosystems in Austria. This work was started with the generous support of the Austrian "Fonds zur Förderung der wissenschaftlichen Forschung" and was conducted in close collaboration with several Austrian organizations led by the Institute of Limnology of the Austrian Academy of Sciences.

In this paper, Dr. Kurt Fedra, Principal Investigator for the Austrian Lake Ecosystems Case Study, reports on the project achievements, problems, and plans for further research a seen after the first year of the study. It contains a thorough description of the lake ecosystems studied as well as a discussion of methodological achievements and problems.

IIASA's studies on lake ecosystems are designed to enhance understanding, to extend and develop new methods of analysis, and to assist analysts and decision-makers concerned with the utilization of these systems and the preservation of their natural values. The implementation of these goals obviously calls for establishment of direct contacts, not only with the research community, but also with decision- makers interested in using the results of our analytical work. And this is why particular stress is laid in this paper on expanding collaborative ties with representatives of various scientific' disciplines and decision-making organizations. For the successful continuation of the Austrian Lake Ecosystems Case Study it is essential that we draw upon their joint knowledge.

Dr. Janusz Kindler
Chairman
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INTRODUCTION TO THE PROJECT:

The Austrian Lake Ecosystems Case Study is carried out at the Resources and Environment Area, within the frame of Task 2: 'Models for Environmental Quality Control and Management'. Officially started in January 1980, the study is supported by external funding from the Austrian Research Foundation "Fonds zur Förderung der wissenchaftlichen Forschung". The research program was drafted by the author under the original title "Application of Systems Analysis to Lake Ecosystems", and the final proposal for the research grant was a joint effort of Prof. Oleg Vasiliev, former Chairman of the Resources and Environment Area at IIASA, and Prof.Heinz Löffler, Director, Institute for Limnology of the Austrian Academy of Sciences. The study is a cooperative research effort, where the Resources and Environment area at IIASA provides a broad spectrum of systems analytical techniques and expertise to complement lake research in Austria. Much of this largely limnologically oriented research in Austria was carried out within the frame of international programs such as the "Cooperative Program for Monitoring of Inland Waters (Eutrophication Control)" coordinated by OECD, or the "Man and Biosphere" Project of UNESCO.

The Austrian Lake Ecosystems Study at IIASA, complementary to the above programs, involves several Austrian institutions and individuals, but also succeeded to attract the interest and active participation of several groups and individuals in different countries, among them the USA, USSR, GDR, FRG, and Czechoslovakia (see Appendix for a list of collaborating institutions).

The program aims at a critical application of techniques of systems analysis, in particular numerical modeling, in the field of environmental systems analysis. The main focus is on water quality problems. Lake water quality management and eutrophication control are central issues. Using selected lakes and their watersheds as examples, lake water quality problems of universal importance and interest as well as the methodological problems in there study and analysis are addressed. The major topics of the study can conveniently be grouped into two categories, which are the general and specific environmental issues , and the methodological issues , which arise in the particular application of systems analysis and numerical simulation methods to complex and ill-defined environmental systems.

The following main questions are addressed in the Austrian Lake Ecosystems Case Study:

(a) environmental issues:

-identification of the main factors and pathways in the eutrophication of lake systems, with special emphasis on the role of the watershed, diffuse and uncontrollable sources, and the effect of stochastic inputs and forcings;

-analysis of the main modes and factors of internal nutrient transfers and cycles, with special emphasis on ecological complexity and the interplay of biochemical and physical processes;

-the simulation and analysis of various alternative nutrient loading scenarios, related to feasible management options, for various types of lakes, with special emphasis on the possibilities and limitations of the long-term prediction of the systems response;

(b) methodological issues:

-the inclusion of systems properties and control mechanisms of high hierarchical level such as adaptation and selforganization in process descriptions and model structure;

-the development of methods for model simplification and the linking of model systems of a wide range of complexity and resolution;

-the development of concepts and methods for the quantification of model uncertainty and prediction accuracy, related to data availability and quality, and systems variability;

-the development of techniques for the use of fuzzy data sets and the probabilistic interpretation of model simulations, with special emphasis on the role of models as aids to policy decisions and management.

This rather wide and ambitious spectrum of problems and resulting approaches has to be understood as a guiding framework for the research rather than a rigid program. Also, the project has to be seen within the context of the general research plan of the Task (Environmental Quality Control and Management) and the overall Resources and Environment Area at IIASA, which provides numerous links and partly direct inputs for the Austrian Lake Ecosystems Case Study. Such links and inputs can be expected, for example, from the parallel case study on Lake Balaton (Hungary), the task on Regional Water Management, reasearch on the transport of air pollutants, and the task on Environmental Problems of Agriculture.

Defining the general problem

One basic goal of the study is to provide answers on a systems level to questions which are not only of relevance to the specific lake systems chosen. Generalizable lessons, derived from comparative analysis of more than one system, and from the application of more than one specific set of methods to a given problem, are sought. Generalizing problems and methods should result in answers and solutions that are at least structurally transferable to other similar systems and problems elsewhere. Putting the specific problems of lake eutrophication into a sufficiently general framework, immediately makes obvious that they can very well be illustrations to problems of much wider bearing. Water quality, and in the examples below lake water quality in particular, can be understood as just one out of an increasingly growing set of scarce natural resources. To quote from the research plan of the Resources and Environment Area,

> "... the resource and environmental management problems of the 1980's and beyond cannot ba analyzed adequately by considering resources in isolation. Analyses must be done within a systems framework, integrating environmental considerations with other concerns such as energy supply, economic growth, and regional development.
>
> This will not be a simple task. First, these problems involve a number of variables that cut across physical, economic, and social dimensions of resource and environmental issues. Second, our knowledge of geophysical and biochemical processes is insufficient; for example, much remains to be learned about ecological processes in natural and man-made water bodies. Third, our knowledge of economy and technology is always evolving: the character and extent of resources used are difficult to predict. Moreover, benefits and costs of resources and environmental policies are difficult to measure and often cannot be expressed in monetary terms...."

Within this general programatic framework, a systems framework for water quality as one aspect of environmental quality has to be structured. Figure 1 shows one possible conceptual structure for the relationships of environmental quality within a comprehensive socio-economic or political framework, relating elements like agriculture, industry and -- most important in the case of lakes -- tourism, and the crosscutting sector of human settlements and services in a broad sense.

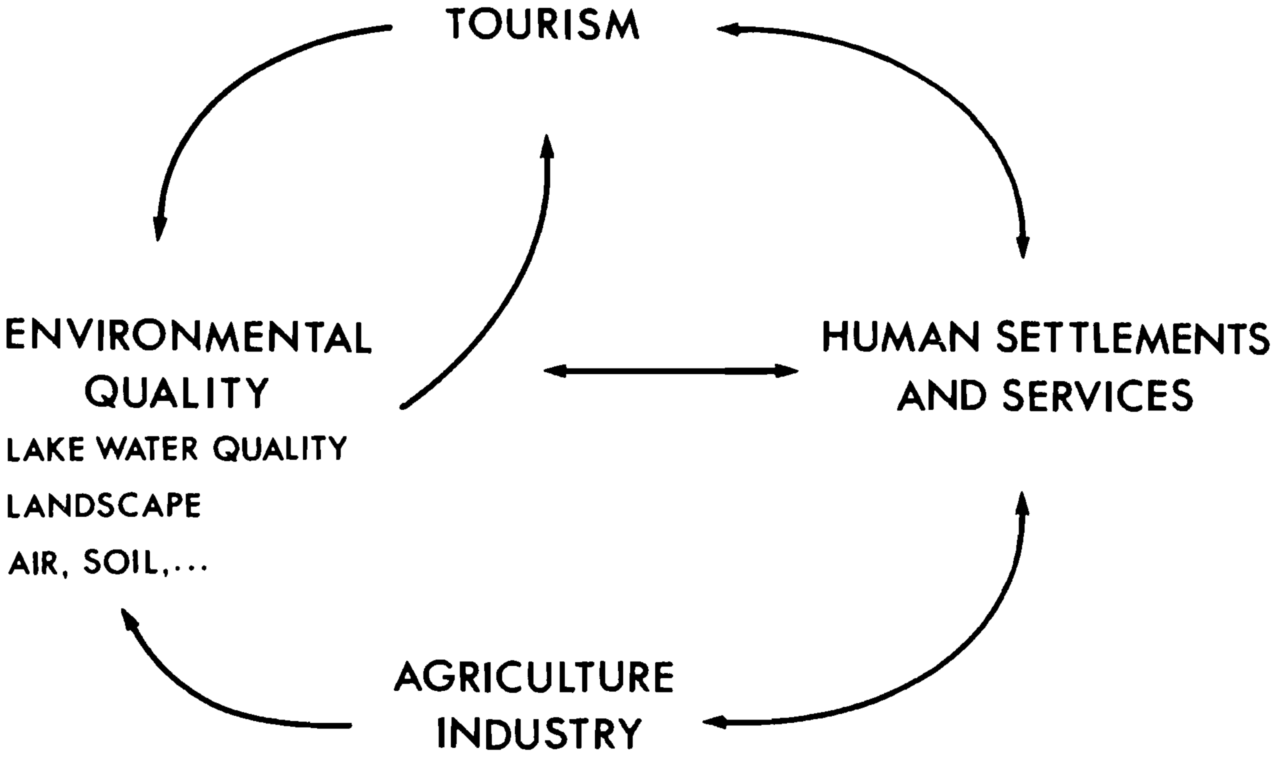


Figure 1: Water quality in a socio-economic and political framework. The arrows indicate directions of major influences and feed-backs between the elements of the overall system.

Within this systems framework, water quality and in particular lake water quality has to be seen in the context of the respective catchment area of any waterbody, which includes the natural physical processes as well as human activities affecting each waterbody. Figure 2 gives an outline of these relationships, using a very general structure. An important point to note here is that water quality not only depends on the loading of a given water body with nutrients (but also organic waste, BOD, suspended solids, dissolved salts, acidity, toxic substances, waste-heat, etc.) and a set of physical and biochemical processes relating these inputs to the relevant water quality variables. Water quality also depends on the criteria and standards used in its definition, which are certainly not absolute values, but related to the socio-economic framework and in particular to the types of use a water body may be subjected to.

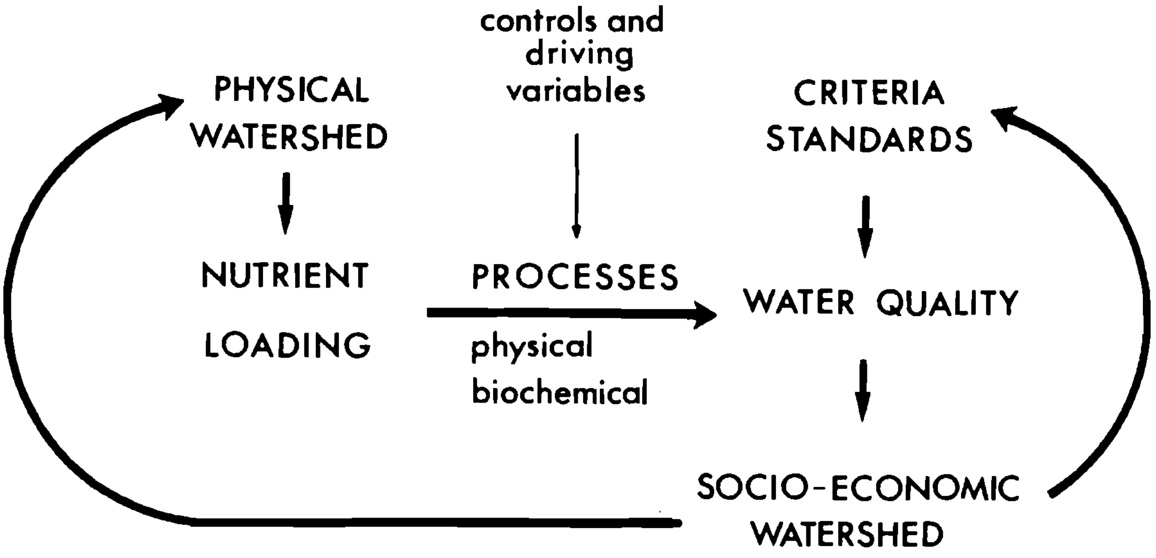


Figure 2: Water quality in a watershed framework. The diagram stresses the interactions between physical and socio-economic dimensions of the watershed.

The problem is thus to arrive at a functional understanding of the major processes, relating a set of goals or objectives through feasible management actions with a set of quality variables, or performance criteria, as an output from the environmental system (Figure 3). This output could also be interpreted as the benefits from the use of the system or resource, whereas the management or control necessary to achieve those benefits would be interpretable as costs. Conflicts and uncertainty, together with the inherent complexity of environmental systems make the problem a non-trivial one.

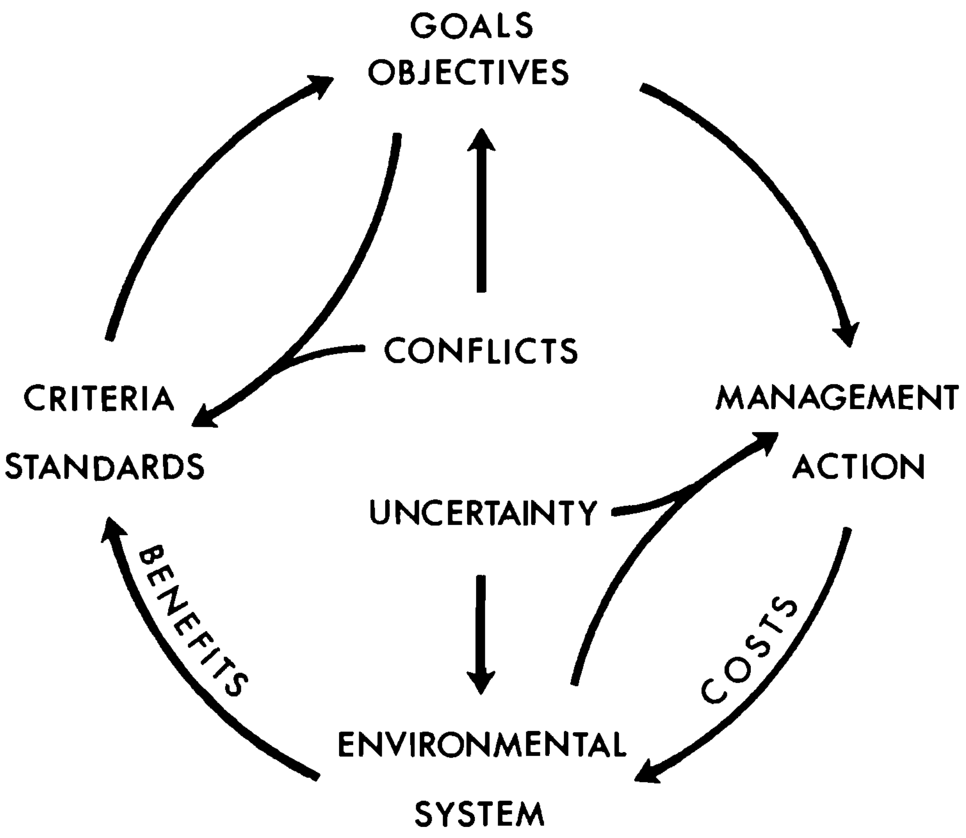


Figure 3: A generalized structure for environmental management problems. In the vertical, the diagram could be structured into a political level (top), an intermediate management level, and the basic scientific level, concerned with the processes and causal relationships within the black box of the environmental system.

Another analogon I would like to adopt is the view of environmental quality not merely as a natural resource, but as a capital stock. The problem is then how to effectively -- and responsibly -- use it, which results in tradeoffs between short term profits and long-term investments, living from the interests and eventually building up capital, or spend it now. All such political to moral considerations require, however, a sufficiently detailed and reliable understanding of the functioning of environmental systems and their responses to our purposeful as well as haphazard attempts at managing them.

The structure of the approach

The approach in the study of the above described issues within the broad framework of environmental systems analysis or natural resource mangement has to be fairly broad as well. This is to say, that a number of possible approaches are used more or less simultaneously, looking at one and the same problem from several (disciplinary) points of view. This interdisciplinary approach certainly requires cooperation to the broadest extent possible. Also, as there is no primary data collection carried out within the frame of this project, it is fully dependent on the cooperation with the respective institutions and individuals, working with the specific systems studied. The approach is therefore, first of all, cooperative. This is considered as the basis for the usefulness of the results of the study. Involving policy makers or at least their consultants and the respective environmental agencies at various government levels from the very beginning, should guarantee the relevance of the outcome in more than academic terms.

Due to the complexity of the systems dealt with, and the inherent ambiguity of the problems addressed, the approach is also adaptive and iterative. Many problems which are under study now were not foreseen in the very beginning, simply because they emerge as the work proceeds. A high degree of flexibility within a loosely defined framework seems to be the only pragmatic solution for a project that aims at breath of comparative analysis rather than at depth and detail.

For the individual problems, however, a general structure of how they are approached can be set up, which in fact holds true for more than one hierarchical level of the analysis. Such a generalized, basic approach would consists of several main steps, which, however, form a continuum rather than distinct consequent units, especially when considering the recursive nature of the analysis. The first and probably also most important step is problem definition: here the problem (in a rather colloquial meaning), which in practice ranges from a diffuse concern (there seems to be a trend towards increasing eutrophication ?) to already well posed questions (what will the relative influence of installing this treatment plant for the nutrient budget of the lake be ?) is translated into a more formal language. That means, that the problem is structured in a set of testable hypotheses, which can be subjected to scientific experimentation. All the aspects of the original problem have to be defined as measurable terms, and their relations have to be specified, at least in a rough preliminary way, formulating specific questions to be answered in the course of the analysis.

Having the problem formulated leads directly into data analysis and model building (in a rather general sense). On the one hand the available information is organized according to the now structured problem, further information needs are identified, and the relevant terms of the problem are extracted from the available information. On the other hand, the causal links connecting the inputs into the system with the answers to be found, or the knowns to the unknowns, are specified in some kind of a formal model, which might be a numerical dynamic simulation model, but also a simple statistical or empirical model.

In the next step, the model adequacy in terms of internal logic, purely technical performance (especially in case of larger computer models), but most prominently in terms of all the assumptions underlying the simplifications necessary in the model building process and their bearing on the original real world problem, have to be examined. This model testing phase again draws heavily on available data, which are the basic test ground for any model.

Given a satisfactory version of a useful model, this will now be used to study the problem at hand, testing the consequences of alternative courses of action, simulating various scenarios of the future, and experimenting with the response of the system to whatever changes. Finally, these findings and predictions have to be interpreted in terms of the real world system again, taking into consideration the limitations and uncertainties in the above procedure.

However, there rarely will be one best model, and the necessary simplification in the analysis and especially in the model building process is always somewhat arbitrary and ambiguous. Non-unique answers and more than one possible approach to any given problem are therefore important to cope with. In many cases, a hierarchical systems of conceptualizations or models has to be used. This leads to a modular approach, where the single steps and elements of the analysis are defined functionally, and by the way they interact. The necessary or unavoidable degree of sophistication, or the possible degree of simplification for any of these modules however, will largely depend on the overall analysis and its objectives; effort and precision have to be well balanced. Each module can than be changed independently, adding more detail or simpifying it, without jeopardizing the coherence of the whole analysis. This is especially important where the analysis is a cooperative effort, involving several groups at different places; a rigid functional framework is essential for coordinating the research without too much prescriptions on the individual contributions.

Also, a hierarchy of conceptualizations and models facilitates communication with groups and individuals of different background and interests. Talking about one and the same real-world system to the limnologist or the regional planner, requires different levels of detail and aggregation. Again, the coherence of such different levels of abstraction or even entirely different points of view requires a hierarchical, modularized approach.

SELECTED LAKE ECOSYSTEMS

In an attempt to illustrate the above described approach and to test the usefulness of different methods and models, a group of specific lake systems was selected for more detailed study. The selection of these lake systems was based on several requirements on the physical nature or the type of the lakes, as well as on the data presumably available on them. As a consequence, and in an attempt to cover a wide range of lakes and typical situations in the development and control of eutrophication, the following systems were selected:

(a) Lake Neusiedl, an extremely shallow (1.5 m) lake of about 150 km^2 surface area, embedded in a belt of dense reed (Phragmites), covering another 150 km^2, is situated south-east of Vienna in the Burgenland; the lake experienced a dramatic increase in nutrient loading and contents, attributed to changes in land use patters (strong increase in intensive agriculture, particularly winegrowing), and a continuing increase of recreational activities around the lake's shore line. Besides one major point source, the river Wulka, and a series of smaller, but well identified point sources such as the discharge from local sewage treatment works, a considerable influence of diffuse sources, including atmospheric sources, is suspected.

(b) A physically quite different example is a group of lakes in the Upper-Austrian Salzkammergut, namely the four major lakes in the catchment of the river Ager: Attersee, Mondsee, Fuschlsee, and Irrsee. These are deep (Attersee: 171 m), stratified, holomictic lakes, which exhibit the full trophic range from more or less eutrophic (Fuschlsee, Irrsee) through mesotrophic (Mondsee) to oligotrophic (Attersee). An increasing trend towards eutrophication is suspected, related primarily to the continuing increase and development of tourism and recreation in the lake district.

TABLE 1:
The range of systems and their morphometric characteristics

Lake System:	surface	depth	volume	retention	catchment
Neusiedlersee	150 km^2	>2 m	250 10^6	5-10 a	1350 km^2
+ reed belt	150 km^2				
Attersee	46 km^2	171 m	3934 10^6	7 a	464 km^2
Mondsee	14 km^2	65 m	510 10^6	1.8 a	247 km^2
Fuschlsee	2.7 km^2	67 m	100 10^6	2.6 a	30 km^2
Irrsee	3.5 km^2	32 m	53 10^6	1.3 a	28 km^2
coupled system			4700 10^6		464 km^2
Wörthersee	19 km^2	85 m	816 10^6	8 a	164 km^2
Millstätter See	13 km^2	140 m	1213 10^6	9.5 a	276 km^2
Ossiachersee	10.8 km^2	52 m	215 10^6	1.9 a	165 km^2

(c) In the Carinthian lake district, three larger lakes, namely the Wörthersee, Millstättersee, and Ossiachersee, provide examples of eutrophication and consequent sanitation of lakes through sewage diversion and treatment. Although the lakes are somewhat different from the lakes of the Salzkammergut in some of their physical characteristics, they can be used as a test case for the simulation of long-term lake response to control and management.

Some additional examples of surface water systems and management problems are provided by a series of connected old branches of the river Danube, in the Untere Lobau. They have no apparent point sources of nutrients, but a strong coupling to the (ground) water system of the Danube, especially through occasional flooding. They are situated in the Nature Reserve of the Lobau in Vienna, where groundwater resources for potable water

supply for the City of Vienna are extracted; these shallow old river arms with considerable fluctuations in their water levels pose an interesting example of surface water quality problems in a rather complex setting.
Finally, another set of examples of lake management by hypolimnic discharge after nutrient diversion, is provided by three smaller lakes in Tyrol, namely Piburger See, Reither See, and Hechtsee. All three lakes were subject to eutrophication, mainly as a result of recreational use. The response of these lakes to the discharge of hypolimnic water, which is rich in nutrients and poor in oxygen, can serve as an interesting test case for models for stratified lakes.

In addition to these examples of Austrian lakes, some of the methodological developments have also been applied to other test cases, as for example the German Bight, Southern North Sea.

Specific problems: lake water quality and eutrophication

Cultural eutrophication of lake systems, resulting from increased nutrient input due to human activities, is a major concern of water quality management. To effectively control eutrophication, we need a detailed quantitative understanding of its causes -- which are the various external sources of nutrients and the internal mechanisms affecting water quality -- as well as an estimate of the consequences of various possible control options in terms of relevant quality measures.

Eutrophication is generally understood as a (undesirable) change in the trophic state of a lake, which is a natural aging process, but can be most dramatically accelerated by increased nutrient loading, in particular of phosphorus compounds. Consequences in terms of water quality can be, to list a few, overgrowth of aquatic weeds interfering with the recreational use of water bodies; mass development of various algae, leading to reduced transparency, and eventually the formation of surface scums, again discouraging recreational use of water bodies; the generation of taste and odor problems, specifically for potable water supplies; sanitary problems through high concentrations of organic material, supporting the development of various disease organisms; and depletion of dissolved oxygen, with adverse effects especially on fisheries.

Since the determining work of Vollenweider (e.g. 1969), much attention has been paid to the analysis of phosphorus budgets and phosphorus dynamics of water bodies, leading to such international attempts like the OECD lake eutrophication program. Data have been collected from numerous lake systems all over the world (OECD Reports) in an attempt to arrive at a generalization of lake ecosystems response to nutrient loading.

A straightforward way to organize the available information on the various sources of nutrients for a given lake system is to compile a nutrient budget, which by inclusion of nutrient exports provides an estimate of the net loading or accumulation of nutrients within the lake system. This net loading is in part transferred to the lake bottom through sedimentation, and in part may add to the nutrient concentration in the water body. The mixing regime and sediment-water interactions as related to geochemical variables and especially dissolved oxygen, have to be considered in estimating the long-term effects of different nutrient loading levels on water quality variables such as maximum or average phosphate concentrations, algae peak biomass, transparency, or yealy primary production of organic material.

However, there are various and in most cases numerous sources of nutrients for a lake system, atmospheric as well as point- and diffuse terrestrial sources, all characterized by a generally high level of fluctuations in time and space. On the other hand, the time and space resolution of measurements to estimate the terms of a nutrient budget is generally low, and considerable measurement and sampling errors have to be suspected. Also, the time span of available reliable observations is generally short in relation to the lake systems response time. Identification of trends, which could then be related to changes in human activities, land use patterns, or more general, the time evolution of potential causes of increased eutrophication, is consequently rather difficult. Therefore, in compiling a nutrient budget for a given lake, considerable effort should be devoted to the estimation of levels of accuracy and relative precision of the individual terms of the budget equation. This is especially important if one keeps in mind that the final analysis should be relevant for supporting environmental decision making, which involves not only great investments but also high risks in terms of possibly irreversible damage to natural resources.

The nutrient budget -- a traditional tool or rather product in eutrophication research -- has now to be linked to the sources of nutrients in the watershed, as well as to the relevant measures of water quality in the lake system:

watershed   lake system

NUTRIENT SOURCES --> NUTRIENT BUDGET --> WATER QUALITY

control and management   socio-economic effects

In the watershed, the individual sources of nutrients constitute also the angles of attack for most forms of management and control. An analysis of the relative contribution and importance of as many individual sources (and thus control options) as possible is therefore desirable. Their contribution, however, has to be expressed in terms of their effect on water quality, requiering a time and space resolution which matches with the structure in the socio-economic domain, allowing for interpretation as e.g. effects on tourism, or cost of treatment for potable water extraction.

LAKE NEUSIEDL:
Eutrophication, Tourism, and Agriculture

Lake Neusiedl is the largest Austrian lake in terms of surface area. It is situated in the easternmost part of the country, at the Hungarian border. The southernmost part of the lake and its outflow are on Hungarian territory. The catchment area covers approximately 1300 km^2 (Figure 4). The lake is characterized by its extreme shallowness (1.5 m), and a peculiar and only partly understood hydrography (Gattinger 1979). Lake Neusiedl is situated in a low plane (120 m above sea level), opening towards the Small Hungarian Plane in the east, and bordered in the west by groups of mountains reaching 748 m. A detailed description of the limnology of the lake has only recently been published in a comprehensive monograph (Löffler 1979).

One of the most conspicuous features of the lake is the large extent of the surrounding wetlands, the reed belt, which not only plays an important role in the nutrient budget of the system (harvesting and exporting reed could be a powerful management option for the lake), but also shapes the typical landscape of the area and is therefore an important element for tourism.

Since the early seventies, a conspicuous increase in the nutrient concentrations (nitrogen, phosphorus) in the lake was observed (Figure 5), (e.g. Neuhuber 1978, Neuhuber et al. 1979), paralleled by an increase in plankton biomasses (Dokulil 1979, Herzig 1979). This development, already resulting in at least local algae blooms, is certainly most undesirable, as it quite obviously endangers the lake's attractivity 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. 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 increased domestic sewage production, and including construction activities, especially in the shorezones of the lake, road building, and the construction of channels, marinas, and bathing beaches to provide direct access to the open lake;

(b) intensification of agricultural production, including the conversion of rangeland into vineyards, and land reclamation, including drainage, land fills, fertilizer use, and irrigation;

(c) the preservation of environmental quality (as an essential resource for tourism), especially lake water quality, but also wildlife and the scenic beauty of the area.

The rapid development of tourism (Figure 5) together with a remarkable development in agricultural activities, especially wine growing (relative increase of about 50% in the cultivated area from 1966 to 1975), are obviously paralleled by an increase in nutrient loading and the observed deterioration of waterquality. The catchment area (estimates of its size vary from slightly more than one thousand to almost 1400 km^2) is dominated by agricultural land use. Fleckseder(1980) gives the following figures (as of 1976): 51% fields, 25% woodland, 10% vineyards, 9% meadows and pastures, 1% gardens and orchards, with about 5% residual uncultivated area. According to his estimate, more than 60% of the cultivated land are intensively fertilized. Also there is a considerable amount of livestock in the area, with approximately 80,000 larger animals (cattle, pigs, horses) and poultry (chicken, turkey, geeth, ducks) numbering roughly 300,000.

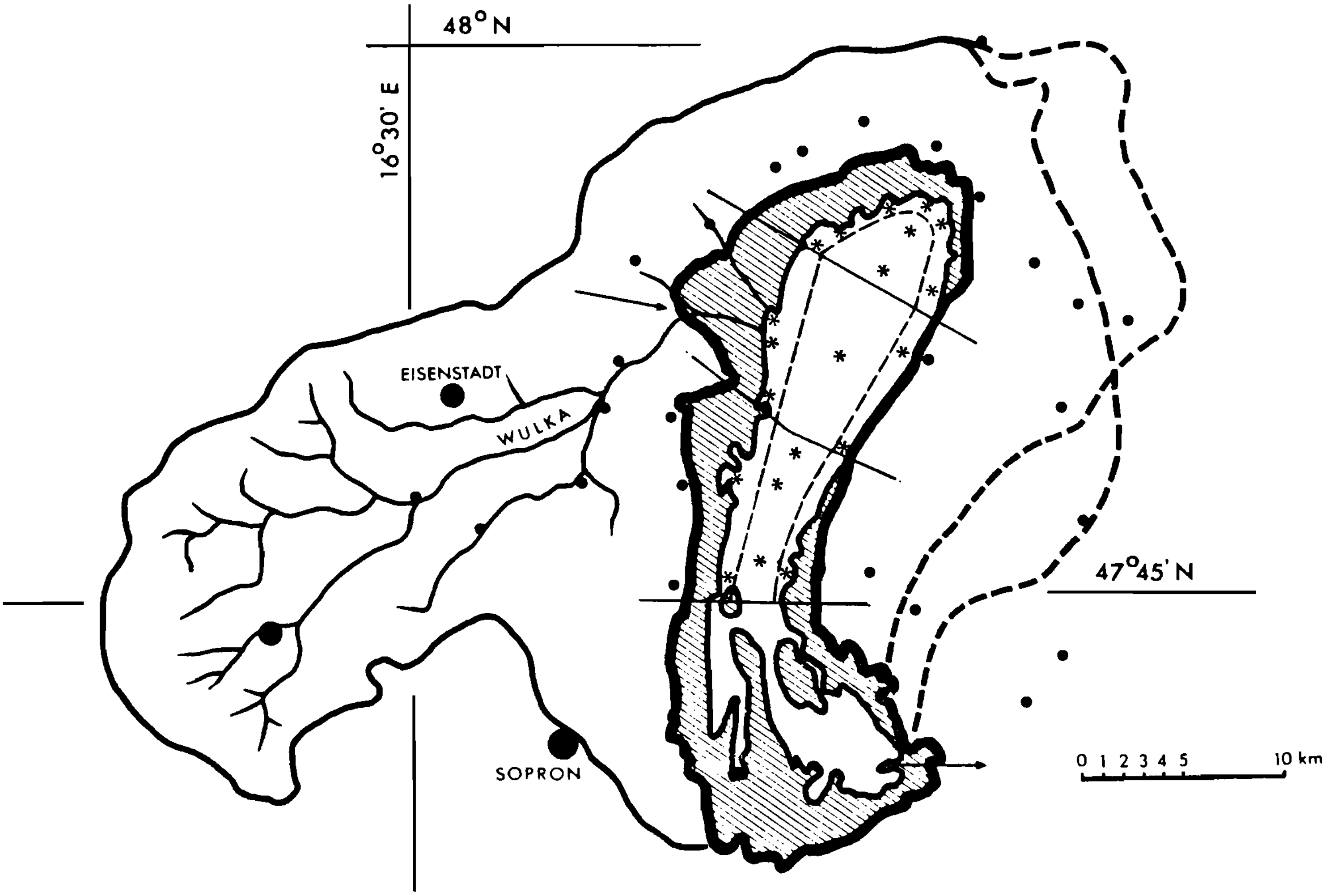


Figure 4: Lake Neusiedl in its watershed. Shaded area indicates the extension of the Phragmites reed belt; watershed boundary corresponds to the geomorphological recharge area given in Gattinger (1978); note the broken lines in the eastern part of the watershed, showing several alternative delimitations of the catchment by different authors. Dots mark major settlements. The figure suggests four main segments, split into a nearshore and an open water zone, for the spatial disaggregation of the lake and reed system, considering the position of the major point source of the Wulka (arrow), the structure of the reed belt, and the position of sampling points (asterisks).

From a rough estimate of a phosphorus budget (Table 2), based largely on data given in Fleckseder 1980, the prominent role of domestic wastewater is obvious. Tourists will contribute to the gross release on the order of 10 t $P_{tot.}$ per year corresponding to about 1.5 10^6 overnight-stays and a minimum of 10^6 additional visitors days. This source, however, is characterized better by its behavior in time, with approximately 10^5 visitors on a hot summer Sunday. According to Fleckseder(1980), about 65% of the domestic sewage was collected and treated in 1976/77, with about 80% undergoing biological treatment (average phosphorus retention 25%).

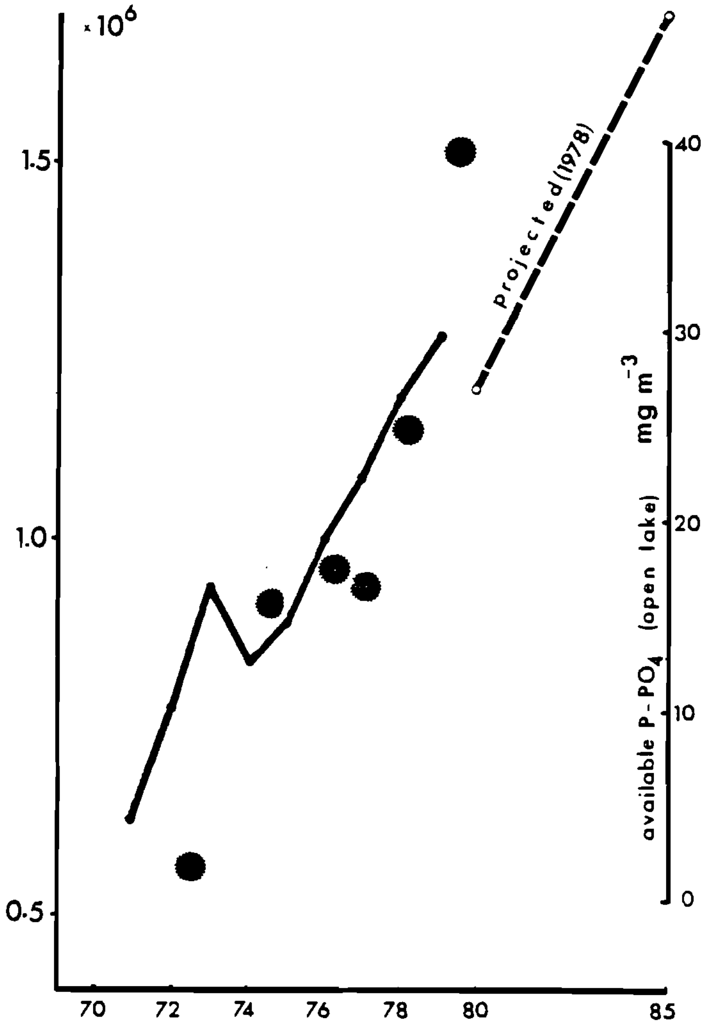


Figure 5: Development of tourism (measured as number of overnight-stays) for the lake district (source: Fremdenverkehrskonzept Burgenland, Raumplanung Burgenland 1980/2), and the annual mean of available phosphorus in the open lake, average of six mid-lake sampling stations (phosphorus data courtesy of F.Neuhuber).

TABLE 2: a preliminary phosphorus budget for lake Neusiedl
units: tons of total Phosphorus per year;
(estimates based largely on Fleckseder,1980; alternative estimates (atmospheric contributions) in parentheses from Neuhuber, pers.comm.)

Source:	gross release	entering the lake	relative importance
Industry (food)	?	4.	2%
Urban runoff	4.		
collected and treated	3.	2.	1%
Domestic wastewater	200.		
collected and treated	130.	60.	28%
TOTAL POINT SOURCES		66.	31% (47%)
contribution from river Wulka		(30.)	
Urban runoff (diffuse)	1.	1.	
Domestic wastes (diffuse)	> 10.	> 10.	5% (7%)
Agricultural runoff			
animal husbandry	480.	10. ?	5% (7%)
soil erosion	?	22. ?	10% (16%)
Groundwater exchange		?	?
Atmospheric sources			
wet deposition (rain)	?	57. (15.)	26% (11%)
dry deposition	?	> 50. (15.)	23% (11%)
TOTAL DIFFUSE SOURCES		> 150. (73.)	69% (53%)
TOTAL INPUTS		216. (139.)	100% (100%)
Outflow		< 10.	
Fisheries		4.	
Reed harvest			
current		0.5	
potential		< 250.	

The second major source of nutrients seems to be the atmosphere, with wet and of course also dry deposition of nutrients, where the current estimates of phosphorus in the rain only range from 15 to about 60 tons a year on the lake (+reed), corresponding to 0.5-2.0 kg per hectare and year. Dry deposition of nutrients has to be assumed in the same order of magnitude (Runca, pers.comm.). Wind erosion of fertilized soils from the surrounding areas of intensive agriculture must be suspected as the most likely source for phosphorus in the atmosphere.

As discussed above, this nutrient budget (which is in no way fully established, but rather a collection of uncertain guesses), has to be related to water quality criteria of socio-economic relevance. The first step would be to split the total phsophorus loading into a directly available fraction, (this, in terms of the sources is mainly due to domestic sewage and animal wastes), and a non-available fraction, which has to be mineralized before it can be used for primary production. This available fraction directly relates to the basic waterquality variables. For the main direct use of the lake system, namely water recreation -- swimming, boating, sailing and wind surfing, and fishing), total organic material, algae biomass, or primary production of the open lake may all be used as first approximate measures. These variables have to be estimated on a time scale and with a spatial resolution sufficiently detailed to estimate their potential effects on the lakes attractiveness for visitors. A daily time scale, and the disaggregation of the lake in various segments with special emphasis on the shore zone where bathing beaches, marinas, or camping grounds are situated, seems appropriate (compare Figure 4).

Considering the special role of the reed belt, the basic processes relating nutrient inputs into the lake to water quality could be summarized as follows (Figure 6): nutrients in soluble (which could roughly be taken as directly available) and particulate forms reach the reed belt through the river Wulka, several smaller creeks, and various channels; according to the local structure of the reed and the resulting distances towards the open lake, the particulate fraction will at least in part sediment, whereas the soluble one will build up concentration gradients. Both fractions will also eventually directly reach the open lake through channels in the reed. Wet and dry deposition of nutrients from the atmosphere will reach the open lake as well as the reed belt directly.

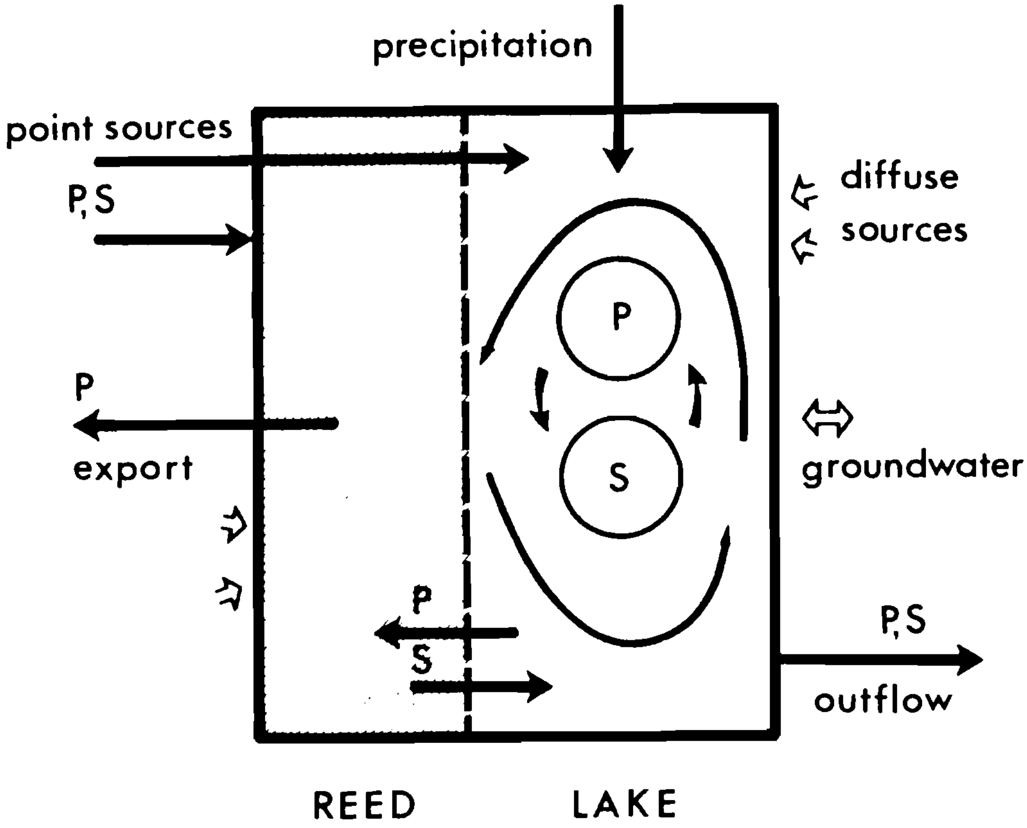


Figure 6: Basic processes in the nutrient system of lake Neusiedl. Arrows indicate inputs and outputs, transport, and transformations; P: particulate fraction of nutrients; S: soluble fraction.

In the lake, there are transformations between particulate and soluble fractions in the aquatic foodweb, as well as interactions with the sediment. Wind-driven horizontal transport will build up horizontal patterns of concentrations (Dokulil 1975)-- which are nonlinearly related with the biological processes. Also, transport phenomena will lead to the exchange of water and material between the reed belt and the open lake. In extreme simplification, we can assume that particulate matter will tend to be deposited in the stagnant water of the reed, whereas the soluble fraction will be transported according to its concentration gradients, from the reed towards the open lake. Within the reed system, nutrients will be incorporated into reed biomass -- which can be exported from the system. Also, particulate material will remineralize, and further increase the concentrations of the dissolved nutrients. This system is driven by meteorological variables such as light and temperature, the wind, and also controlled by variables such as dissolved oxygen (controlling mineralization and nutrient release from the sediments), or suspended solids, which adsorb dissolved nutrients (Gunnatilaka 1978).

This systems is rather complicated, especially when taking into account the nitrogen cycle, which has been neglected sofar. However, atomic ratios of nitrogen to phosphorus have dramatically changed only recently in the lake water (Neuhuber,in press), indicating a transition from phosphorus limitation to nitrogen limitation. Consequently, both groups of nutrients will have to be considered. Also, there arises the biologically interesting questions, why there is no mass development of blue-green algae in the lake, which would be capable of fixing atmospheric nitrogen and utilize the enormous pool of available phosphorus. The high degree of turbulence, or mechanical stress, might be one potential explanation for this peculiarity.

To study this system, a sufficiently detailed dynamic and spatially disaggregated description of a mass balance of nutrients, and their relation to the water quality variables (algae biomass, primary production, and dissolved oxygen, which explicitly includes the role of the reed belt and its potential for nutrient export), will be necessary. This, however, cannot be accomplished by one single simulation model, as the characteristic dimensions in time and space of the major governing processes span too wide a range. Rather, for this complex system a set of coupled sub-models, oriented along the lines of the major processes, is used (Figure 7). This system is composed of four major elements, or submodels, describing horizontal transport, vertical transport, biochemical transformations in the open lake, and in the reed belt.

(a): The two-dimensional transport model.
This submodel describes the watermovement and mass transport for the dissolved and particulate nutrient fractions in the open lake and the reed zones, using a regular grid with 250 m point distances. The model is based on the simulation model developed by Ramming (1978), which has to be modified through the inclusion of the appropriate transport equations, and the inclusion of source-terms at all the grid points. This will allow for a dynamic description of any arbitrary number of individual sources of nutrients, including the atmosphere. The model is driven by a dynamic wind field over the lake, and utilizes bottom topography. A constant windstress coefficient is used for the open lake, whereas for the reed zone a spatially variable stress coefficient, related to reed density and structure, will be used. Bottom friction, which is the second important parameter of the model, can also be related to reed structure; also, a reduction of mass transfer according to reed density has to be taken into account, using an explictly prescribed reduction or a virtual depth. For a better resolution of the channels through the reed system, allowing for a better description of the role of the channels in the movement of nutrients through the reed, a nested grid system with higher resolution for the channels can be used in the numerical scheme of Ramming's model (Ramming, pers.comm.).

(b): The 1-D vertical model of erosion and sedimentation.
Using dynamic wind intensity, this model generates a vertical profile of turbulence, and estimates a shearstress coefficient at the sediment surface, determining erosion or resuspension of sediments (e.g. Sheng and Lick, 1979; Szomlyody, 1979; Kvon et al., in prep.). Apparent sedimentation will be determined by turbulence and particle size of the suspended matter. The resulting vertical distribution of suspended matter will control the light climate, and nutrient removal by adsorption.

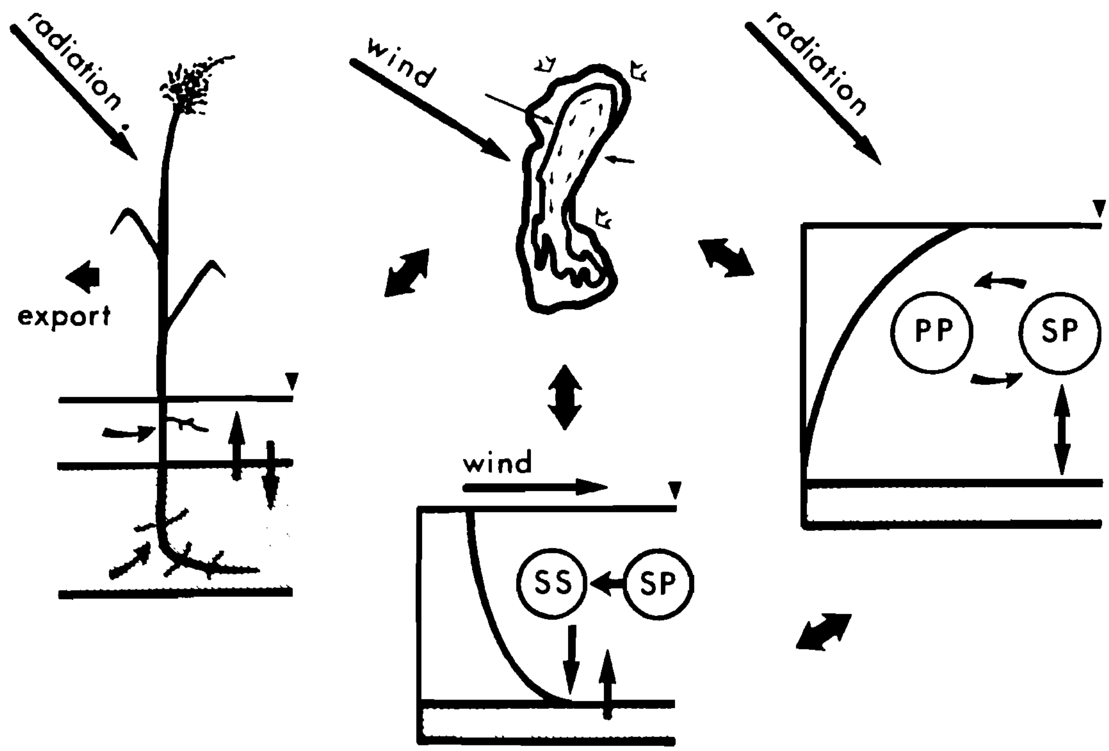


Figure 7: System of coupled models for the description of a dynamic, spatially disaggregated mass balance of nutrients and water quality for lake Neusiedl. For a detailed description of the individual models see text.

(c): The 1-D vertical model of the open lake food web. Driven by light and temperature, this model determines the transformations of nutrients into planktonic biomass and vice versa for several segments of the lake (compare Figure 4). Basic processes are primary production, and the decay and mineralization of organic material, both processes coupled with the oxygen cycle. The model is structured as a multi-layered water body over a uniform sediment layer, using a vertical profile of eddy diffusivity for vertical mixing, and advection for horizontal exchange between the segments. The latter can be estimated from the two-dimensional transport model. Due to the vertical structure of the model, it can describe the effects of ice cover or short-term stratification under calm summer conditions on the biological processes and especially on dissolved oxygen concentrations.

(d): The biochemical model of the reed system.
This model estimates the incorporation of nutrients into the reed biomass, driven by light and temperature, and including the effects of light- and space competition by the reed. In the aquatic and sediment phase of this model, sedimentation of particulate material, its mineralization, and the release of nutrients from the sediments under low oxygen conditions are described. The model also includes an ice-cover routine. Exchange of nutrients with the open lake and the harvest and removal of reed are important features of the model.

From the above description of the individual modules, the way they interact is already obvious. The coupling of the modules is a technical rather than a conceptual problem, which arises from the different time steps and different spatial structure. For example, the horizontal transport model (time step about 100 sec) will have to be integrated in time as well as in space for providing the necessary information to the biochemical modules (time step 1 day). This requires, that the models either run "within each other, but at different speeds", or where appropriate, are solved sequentially using pass files. In both cases, the problem is facilitated by the fact that the simulation periods of interest are in the order of a few days, characterizing typical weather situations. Using such typical episodes, probability distributions of the parameters to be estimated for the coupling can be established, which again allows to finally describe the waterquality variables in terms of probability distributions. A typical example would then be a probability distribution for e.g. particulate organic material concentrations for each of the segments simulated for a typical hot summer day and a specific loading history. Such information can directly be interpreted in a meaningful way for the comparison of planning or management alternatives. Such alternatives can be different strategies of reed harvesting, or various alternative designs in the wastewater system (e.g. von der Emde et al. 1978), or further projects of develpoment of tourism, or the implications of regulations for agriculture, or any combinations of the above.

The information from the simulations must be directly translatable into "costs" -- for controls, regulations, sanitation effort on the input or export side, and in "benefits" from maintaining certain standards of water quality. However, it must be kept in mind that the ultimate goal can only be the comparison of alternatives rather than quantitative predictions of the outcome of any of them.

Achievements, Problems, and Outlook

Sofar, much of the data available on lake Neusiedl has been collected and incorporated into a computerized data base. This applies mainly to the chemical and biological observations in the lake (up to 22 stations), covering the years from 1975 onwards (Neuhuber, Dokulil, pers.comm.). An example for these data sets is given in Figure 8, showing a scattergram of available phosphorus for the years 1975 to 1978, where open lake stations and nearshore zone are distinguished by different symbols. The extreme variability of the data should give an idea of the problems encountered in the data analysis process. Also, meteorological data from several stations around the lake as well as one station on the lake are available (Neuwirth, Dobesch, pers.comm.). Hydrometeorological background data including data on the outflow through the Hansag or Einser-Kanal for the years 1966 to 1975 have been taken from Baranyi and Urban (1978), and additional data on precipitation, flows (Wulka), lake levels and groundwater are expected from the Austrian Hydrographic Service. In addition, occasional measurements on loadings, including concentration measurements from the rain, are available. Some background information on the watershed, mainly on tourism and agriculture, were made available by the Regional Planning Office of the provincial government in Eisenstadt.

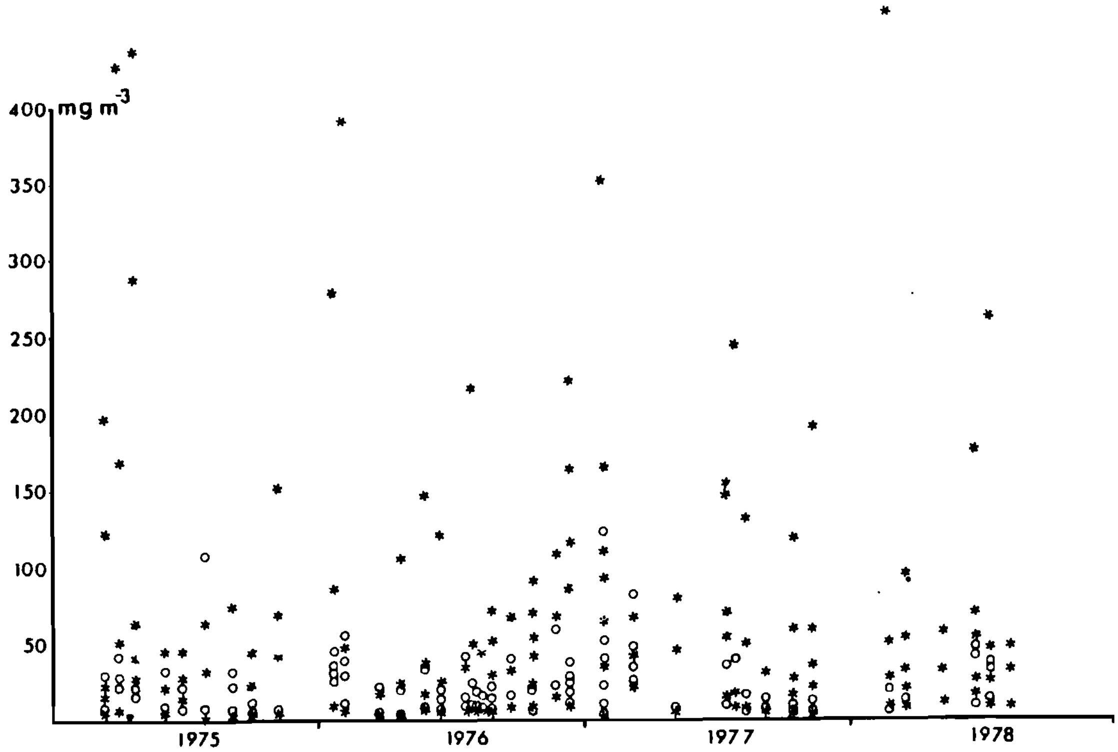


Figure 8: available phosphorus (P-PO_4) for the years 1975 - 1978; nearshorezone samples are represented by *, open lake samples by o.

Lacking, however, are data on currents, and a detailed bottom topography of the lake and especially the reed zone. A recent mapping of the reed structure would be most desirable. Little or no information is available on the nutrient dynamics of the reed, so that information from the literature had to be used to structure the reed model. One basic open question is where the nutrients incorporated into reed biomass actually are taken from: the water or the sediments, and in which proportion, and from which depth in case of the sediments. At the same time, the depth-age structure of the nutrients deposited in the sediments, the depth of reworking or bioturbation, and the vertical nutrient fluxes in the sediment are of crucial importance. Only the removal of recent nutrients coming from the lake or retained from external sources on their way to the open lake will be of significance for the nutrient budget and consequently the water-quality situation of the lake. A detailed understanding of the role of the reed in nutrient retention and removal for the lake system is of crucial importance for the planning of reed harvesting as a possible control strategy (compare Table 2). Also, an operational model of reed-nutrient dynamics would be of interest for the lake Balaton study with respect to the Kis-Balaton project, where the restoration of extensive wetlands for nutrient retention is planned.

Also, reliable information on the temporal and spatial distribution of nutrient loading is lacking, especially with respect to the diffuse sources. For example, estimating 2% diffuse losses from livestock breeding leaves unclear where the remainder of 98% of this wastes will go, which is still an estimated 470 tons a year. Also, contributions from industrial sources totaling 4 tons a year are certainly a conservative estimate. The identification of the individual sources of the nutrients, and especially the relative importance of their available fractions, is crucial for the design of any management scheme for the watershed (compare Fleckseder 1980 for alternative designs of a wastewater diversion and treatment plan). It is therefore planned to eventually use auxiliary simulation models to estimate some of these contributions, especially from agricultural sources. Models for estimating, for example, erosion and fertilizer leaching from agricultural areas are available (e.g. Knise 1980), and much of the data necessary to use them is available in principle. As a first step into this direction, a numerical model for the estimation of groundwater recharge (Guglia et al. 1977), (spatially disaggregated on a square kilometer grid) is currently prepared for use on the Neusiedlersee catchment area. Using this model to estimate groundwater recharge and runoff on a yearly as well as monthly basis should allow one to identify potential pathways from diffuse sources. Also, the use of simple watershed models to estimate erosion and nutrient runoff on a rough scale might be appropriate.

However, data collection in the field continues, and more and more appropriate data for the analysis are to be expected during the coming year, especially as first results of the analysis already allow to identify specific data needs.

Also, the study of lake Neusiedl can benefit very much from the ongoing case study on lake Balaton; due to the similarities of the two lake systems -- in terms of their physiography as well as their eutrophication problems -- much of the developments and findings of the Balaton case study are also relevant and most helpful for the work on lake Neusiedl.

The continuing and more and more obvious deterioration of water quality of Lake Neusiedl, and its consequently decreasing attractiveness for tourists has not only recently led to a series of critical comments in the media, but also led to political action. The provincial government initiated a comprehensive research effort focussed on the lake, involving numerous Austrian scientists. This initiative has led to the establishment of a working group "Arbeitsgemeinschaft Gesamtkonzept Neusiedlersee"; following an invitation of government representatives, two research proposals were submitted to the working group by the author. The two proposals are structured as a two phase extension and direct continuation of the Austrian Lake Ecosystems Case Study. The first of the proposals concentrates on the relationships of the lakes nutrient budget to lake water quality, along the lines described above. Emphasis is placed on the representation of individual sources of nutrients and the effect of control strategies such as the increased harvest of reed on ambient water quality. This should allow one to directly interpret the results of the proposed detailed analysis in terms of environmental management action.

The second, more comprehensive project aims at an analysis of the interactions between environmental quality (including lake water quality but also aspects of the typical landscape) and the development of tourism and agriculture on a regional scale. The regional system is structured as proposed in Figure 1. For this second research proposal, a top-down hierarchical approach of adaptive environmental assessment and management (e.g. Holling 1978) will be used. The research, embedded into an open, interactive planning process, is structured as a series of informal workshops, emphasizing multi-objective decision making and conflict resolution. The major tools of such an approach are environmental impact analysis, cost-benefit analysis, and conceptual simulation modeling and comparative scenario analysis. The proposed set of techniques includes several standard methods of environmental impact analysis and cost benefit analysis, as well as new approaches in the field. These include, among others, checklist and matrix methods (e.g. Leopold matrix), systems simulation (ranging from KSIM to complex simulation modeling), and multi-objective evaluation procedures.

The expected results of this study, planned for a two years period of research, include a comparative analysis of alternative strategies or scenarios of development; the formulation of guidelines for regional development under environmental quaility constraints; and finally a conceptual comprehensive regional environmental simulation model. Besides these formal results, the open interactive planning process has to be understood as an important learning process for all parties involved. This should result in a better understanding of the interdependencies and tradeoffs in a complex multi-purpose system with conflicting objectives.

The realization of these projects, which however are depending on partial external support and funding, would certainly lead to a most desirable extension of the scope of the Lake Neusiedl case study, building on the work done in the ALECS sofar.

THE SALZKAMMERGUT LAKES:
Lake Water Quality in a Watershed Framework

In the Upper-Austrian Salzkammergut, a system of four coupled lakes, namely Attersee, Mondsee, Fuschlsee, and Irrsee provide an example of a similar problem within a geomorphologically quite different region (Figure 9).

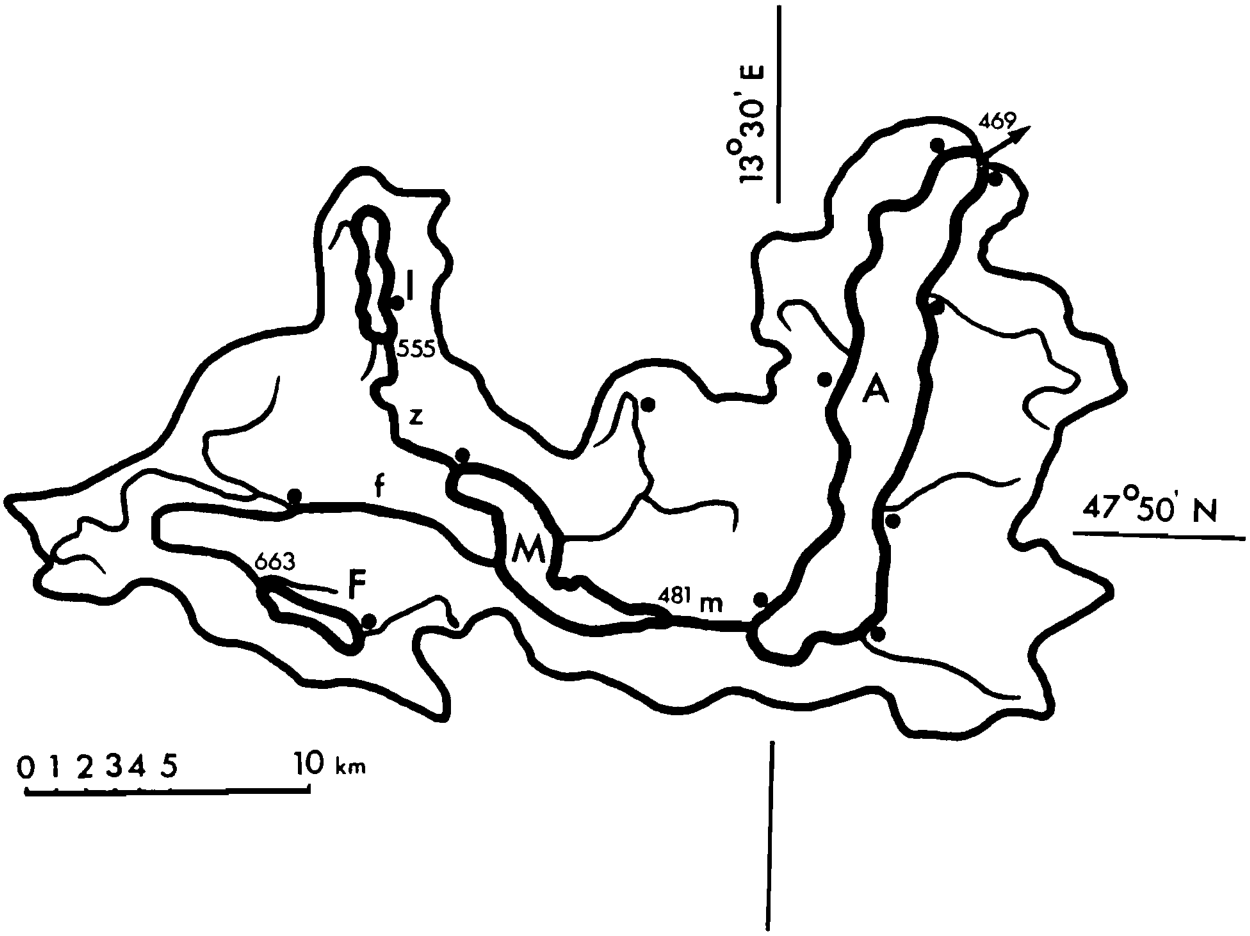


Figure 9: Catchment area of the river Ager (arrow), with Attersee (A), Mondsee (M), Fuschlsee (F), and Irrsee (I) and the connecting river system with Mondseeache (m), Fuschlerache (f), and Zellerache (z); dots mark major settlements; numbers indicate altitude above sea level in meters.

The area is of mountainous character (up to 1700 m alt.), and the lakes are deep and stratified. Landuse patterns differ from the situation in the Neusiedlersee catchment area (compare Figure nn), with woodlands, rangeland and uncultivated areas dominating. The recent development of tourism, its pattern within the year (Figure 10), and the consequent problems with domestic sewage however, are of a very similar nature.

The lakes of the Salzkammergut are not only of considerable importance for tourism and consequently for the regional economy, they also constitute large reservoirs (compare Table 1) of relatively clean water; in case of the Attersee, the cool water of the hypolimnion would be of potable quaility, and about twenty years ago, even the water of the now eutrophic lake Fuschl would meet drinking water standards. Considerable increase of tourism and a change in the composition of domestic sewage in the last two decades however result in a conspicuous deterioration of lake water quality, most pronounced in the Fuschlsee, but also the Irrsee and Mondsee. Several algae blooms were observed during the last years. This development has led to the initiation of sanitation measures, namely sewage diversion and treatment. Due to the specific situation of the Salzkammergut lakes -- forming chains of coupled lakes -- any sanitation has to consider the whole system of lakes and their watershed. For the catchment basin of the river Ager -- the outflow of the Attersee -- one treatment plant with tertiary treatment in Mondsee is already in operation since 1974 (Flögl 1976), a sewage-diversion system for the Attersee is operational since 1976, diverting the domestic sewage of the communities around the Attersee through a canal system to a treatment plant at the river Ager (Flögl 1976). Treatment plants for Fuschl-Hof (at the outflow of the Fuschlsee) and in Thalgau (on the Fuschlerache, connecting the Fuschlsee and the Mondsee) are under construction. At present however, only part of this wastewater system is operational yet, and the continuing excess nutrient loading of the lakes is reflected in a continuing eutrophication process. Also, deep lakes react slowly, and an observable improvement of the current situation cannot be expected immediately.

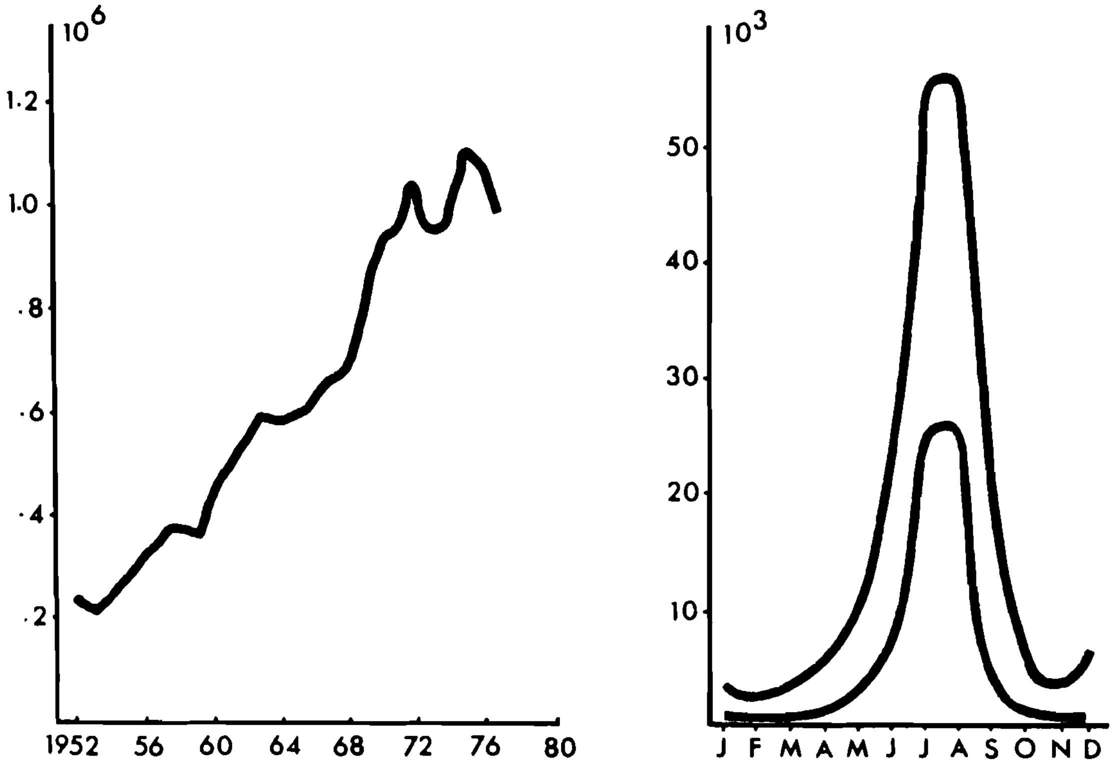


Figure 10: Development of tourism in the Attersee region, overnight stays per year (left), and the average in-year pattern of overnightstays (envelope for six shore-communities) at the Attersee, averaged for 1977 and 1978. (after Siakala, 1979, and Moog, Pers.comm.).

One basic problem in designing a rational strategy for lake water quality management in this system is to determine the actual sources of the nutrients responsible for eutrophication, determining available versus unavailable and controllable versus (technically) uncontrollable sources. In a mountainous watershed like the Attersee-region, stormwater contributions to the loading may be of significance. Their importance, as compared to the domestic sources, is essential in designing control strategies. Also, the high degree of variability from year to year and the difficulty to arrive at reliable loading estimates with such a high number of individual small tributaries and the high degree of connectedness in this system are additional problems. These problems, however, are of quite universal nature, and to quote from the recent conference on "Phosphorus Management Strategies for the Great Lakes":

> "The existence of at least 3 separate estimates of the total load of phosphorus to the Great Lakes requires clarification. The compatibility of these estimates has yet to be demonstrated,....... Important differences also exist with respect to the calculation of tributary loads and the variations attributable to natural variations in the hydrological cycle. These variations may be important, especially when viewed in the context of the loading reductions achievable through further remedial programs. Thus, these variations must be explained adequately before commitments for further reductions can be expected." (Slater and Bangay, 1980).

Besides the necessary degree of effort on the sewage diversion and treatment side, it is its geographical distribution which also matters in a geographically complex situation of coupled lake systems. Due to the natural function of each of the lakes as a nutrient retention basin, trapping part of the load into the sediments, the spatial design of any control strategy is of importance. Consequently, for the study of the coupled lake system, a high degree of spatial resolution was attempted, limited only by the number of individual sampling and measurement stations. A discretization of the total watershed as shown in Figure 11, into 19 sub-basins, the four lakes, and the connecting river reaches (Figure 12), is used as the basis for data organization. This structure is also used as the framework for the overall system of models describing this complex system of coupled lakes, consisting of a watershed runoff module, a nutrient load module, a module for the river reaches, a lake hydrodynamics-module (to describe stratification and internal nutrient transport), and finally the lake water quality module.

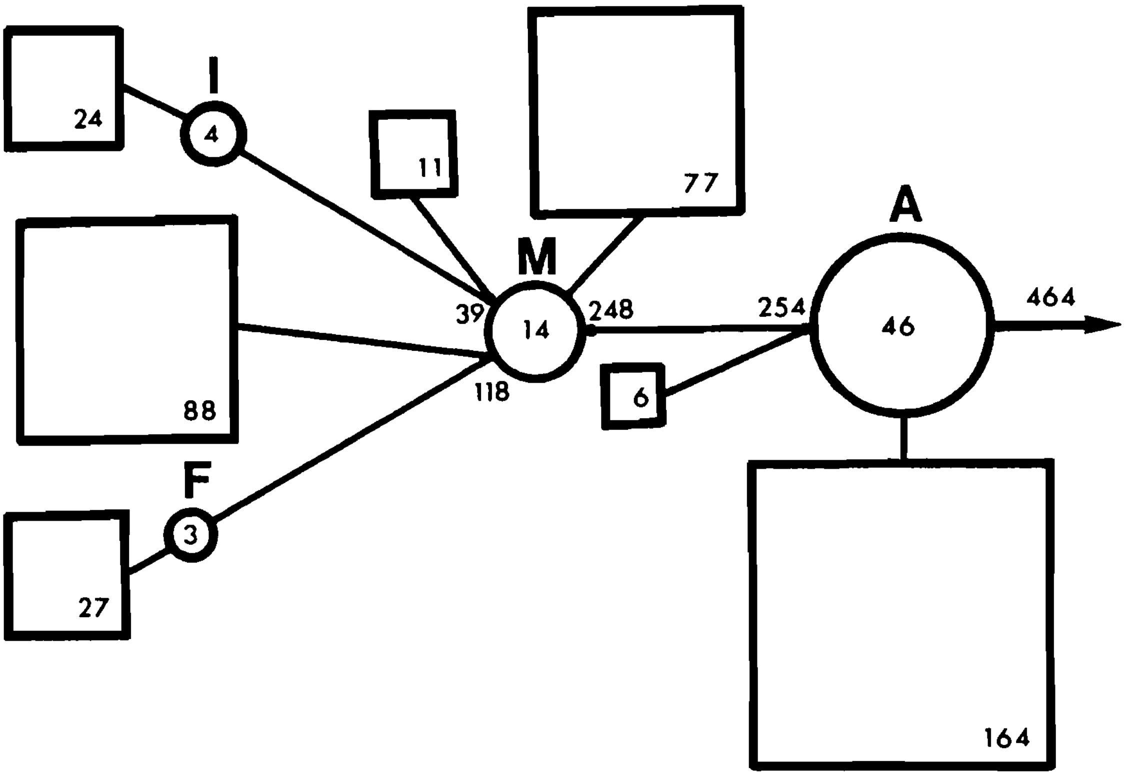


Figure 11: The Attersee system: catchment of the river Ager with the four major lakes (cycles) and a minimum-structure for the watershed system. Areas of lakes and individual catchments are drawn in scale, numbers indicate square kilometer values for the areas (compare Figure 9). (From Fedra and Moog, in prep.)

For each of these sub-basins, runoff and nutrient load are estimated, based on the field measurements of river flows and nutrient concentrations. In parallel, simple watershed models attempt to predict on a daily basis runoff and nutrient loads based on precipitation, sub-watershed characteristics such as size, average slope, soil properties, land use and vegetation, population, livestock etc.. These individual sub-basins are coupled, providing via appropriate routing of the flows and a description of the intermediate reaches of running water, the hydraulic and nutrient inputs for the lake water quality models.

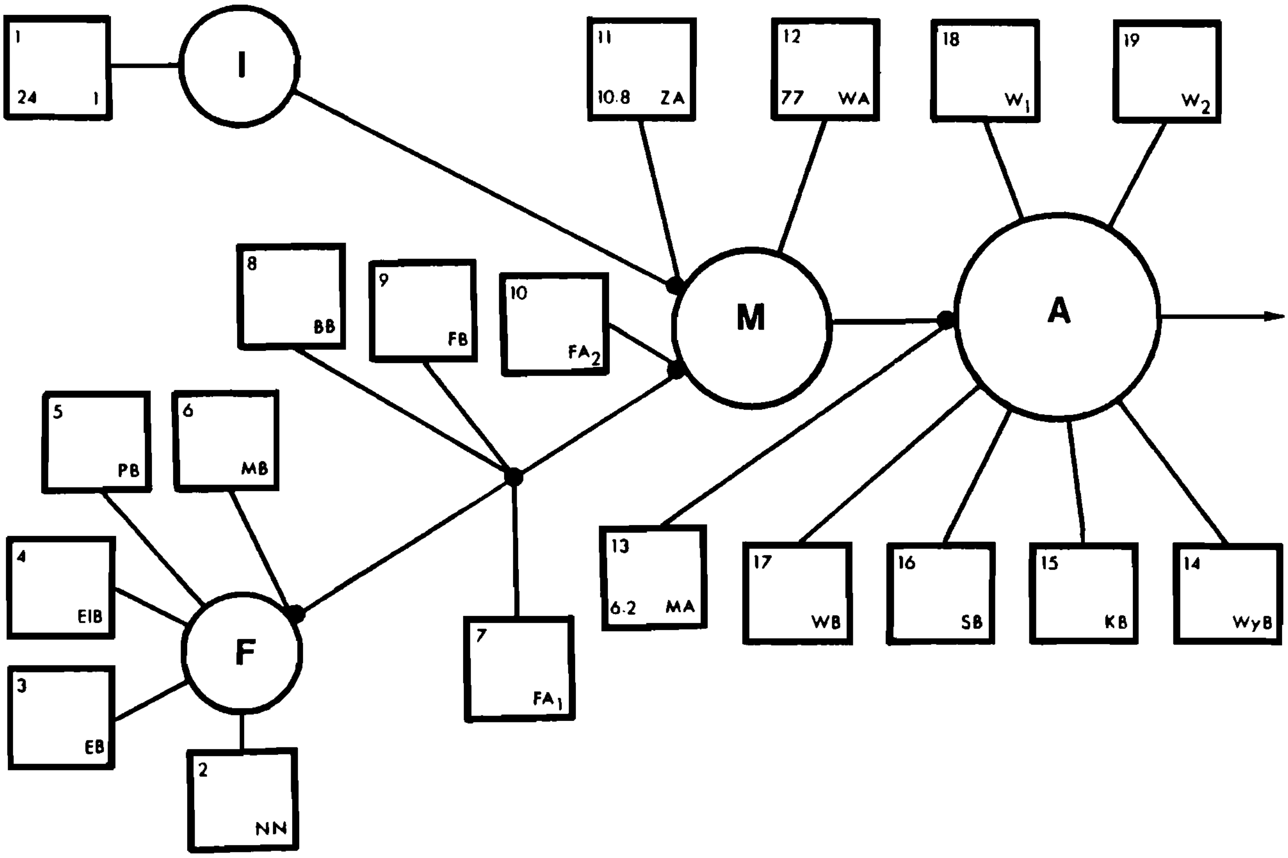


Figure 12: The Attersee system: catchment of the river Ager with the four lakes (circles) and a system of 19 subwatersheds. (From Fedra and Moog, in prep.).

These lake water quality models link the watershed and its runoff with the relevant waterquality variables. Again, these are primarily related to tourism, so that nutrient concentrations, algae biomass, primary production, and dissolved oxygen can be used as approximate measures. For the deep and generally clear lakes of the Salzkammergut, transparency of the water may also be used as a quality variable. The models of in-lake processes relate the inputs of available as well as non-available nutrients to the above variables through a ecologically detailed description of primary production (driven by light and temperature), herbivore and eventually carnivore predation and, secondary and tertiary production, respiration and excretion, mineralization of organic material, and the sinking of particulate organic material. Again, as in the biochemical model for the Neusiedlersee, these nutrient transformations (which in these lakes can be described in terms of the limiting phosphorus only), are linked to the oxygen cycle. The basic physical processes in this system are inflow and outflow of water and materials, and the complex processes of vertical transport and mixing.

These physical processes are extremely important for the understanding of deep, stratified lakes, which can generally be assumed to be horizontally homogeneous, but exhibit marked vertical gradients (compare Figures 16 ff, 26 ff). The problems of vertical transport of nutrients in the deep lakes, including the transport through the seasonal thermocline, are determining for the in-lake processes governing lake water quality. Similar to the processes in the watershed, where a discrimination between controllable and virtually uncontrollable sources of nutrients has to be made, the nutrients available in the productive upper zone of a deep lake, the epilimnion, are supplied from two major sources. They can be grouped accordingly into the external loading -- from the watershed -- and the internal loading. The latter is determined by the flux of nutrient rich water from the deep part of the lake, the hypolimnion, and eventually the sediments, through the thermocline into the productive zone. This flux is controlled by the concentration gradient, the vertical movement of the thermocline, and by diffusion through the thermocline. Understanding the role of this internal loading in the overall nutrient cycling in the lake has important implications on the longterm aspects of control strategies and lake response, as changes in the hypolimnetic concentrations of nutrients occur rather slowly, related to the average retention time of the lake. To study this phenomenon in more detail, and also to provide methods to link any detailed description of the hydrophysical processes responsible for the internal nutrient loading to the ecological processes, the coupling of an appropriate version of the MIT vertical stratification model (e.g. Octavio et al.1977) is planned in cooperation with the Ralph M.Parsons Laboratory of Hydrodynamics, MIT. The general problems in this approach of linking models of quite different purpose, scale, and resolution into a comprehensive modularized system of models to describe a large and complex environmental system with the necessary detail and the possible simplifications, are quite similar the those discussed for the Neusiedlersee above.

The Attersee

The Attersee is the largest of the four lakes under study, and it is also the cleanest one. The lake is under intensive study since 1974 within the frame of the OECD Lake Eutrophication Program, project: Alpine Lakes, and the Man and Biosphere program, and there also exist a few historical records. Figure 13 shows the lake with 12 main tributaries, indicating their (estimated) relative contribution to its nutrient loading, averaged over the last few years. From this figure, the dominant role of the Mondseeache, connecting the outflow of the upstream Mondsee and a small subwatershed of about 6 km^2 with the Attersee, is obvious. The 254 km^2 drained by the Mondseeache contribute slightly more than 50% of the total nutrient load of the lake. The remainder stems from the direct catchment of the Attersee with 164 km^2, and the atmosphere through dry and wet deposition of nutrients. Although the relative contribution from the atmosphere is much smaller than the one estimated fo Lake Neusiedl (see Table 2), it is still a considerable fraction, when keeping in mind that the area is non-industrialized. The study of sources and pathways of these atmospheric contributions to lake eutrophication provides another link to ongoing research within the Resources and Environment Area.

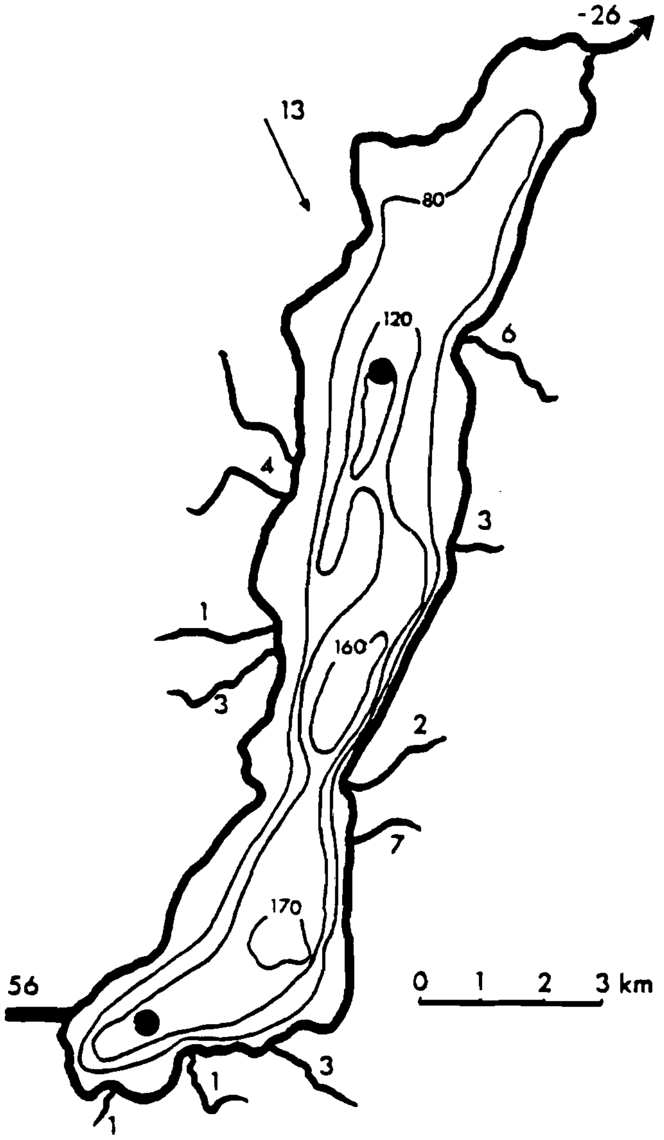


Figure 13: The Attersee and its main tributaries. Numbers indicate relative contributions of the individual tributaries in percent, averaged for the period 1974 to 1979 (data from Müller 1979, and Moog, 1980). The two dots represent sampling stations for chemical and biological variables.

The first step in the analysis was to arrive at a nutrient budget for the lake, extending previous attempts by Müller (1979) and Moog (1980). In parallel, a simple dynamic simulation model capable of translating this nutrient budget into water quality variables was used. Figure 14 gives an indication of the variability of the available data, showing a timeseries of volume-weighted estimates of the total phosphorus content of the lake from 1975 to 1979 (compare also Figure 15). Obviously, this variability obscures any potential trend during the observation period. To estimate all the other terms in the budget equation, and some measure of their precision or reliability, a threefold approach was selected (Fedra et al., in prep.).

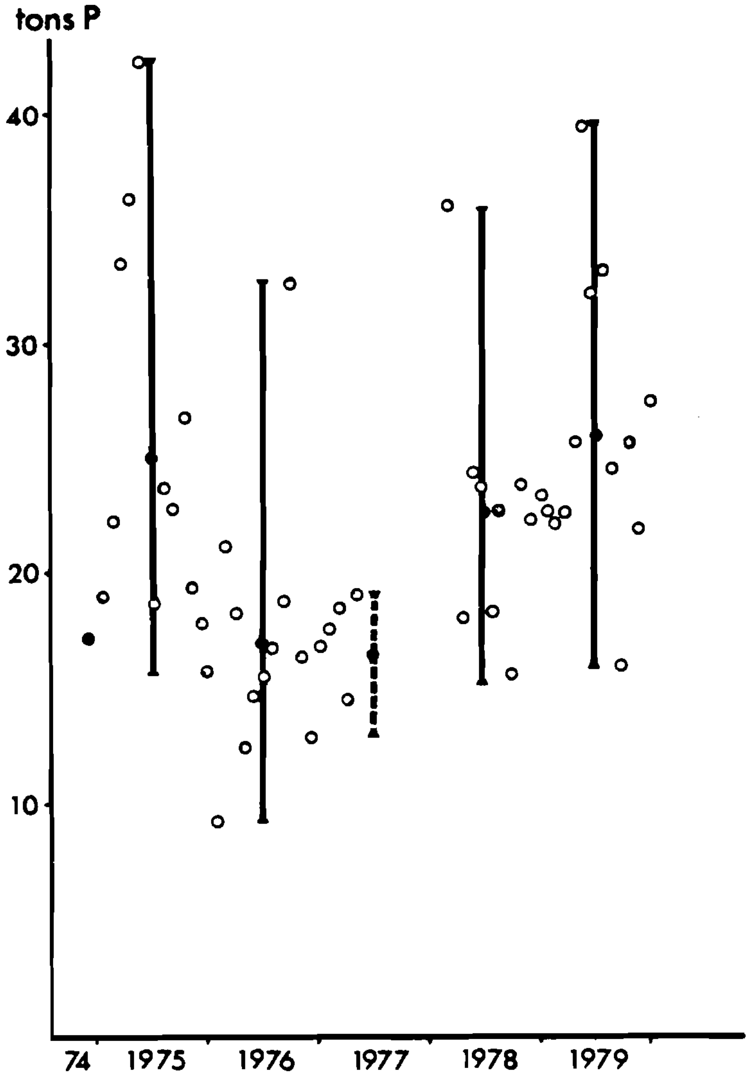


Figure 14: Time series of volume-weighted estimates of the total phosphorus content of Lake Attersee for the years 1975 to 1979, averaging two sampling stations and 11 depth layers. (Raw data from F.Neuhuber, pers.comm.).

First, a detailed analysis of the loading and the export is made, where the yearly totals have to be estimated from continuous measurements of the flows and occasional (generally monthly) measurements of the concentrations. In case of the smaller creeks, estimates of the flows are also on a monthly basis only. From these data (Figure 15), the yearly total is estimated by several techniques, including Monte Carlo based interpolation techniques. The results are given in terms of probability distributions, or mean estimates and their range and variability. Second, based on these estimates, several steady-state black-box models (e.g.Vollenweider 1975, Kirchner and Dillon 1975, Larsen and Mercier 1975) are used, relating the empirical terms of the budget equation and estimating sedimentation or apparent settling.

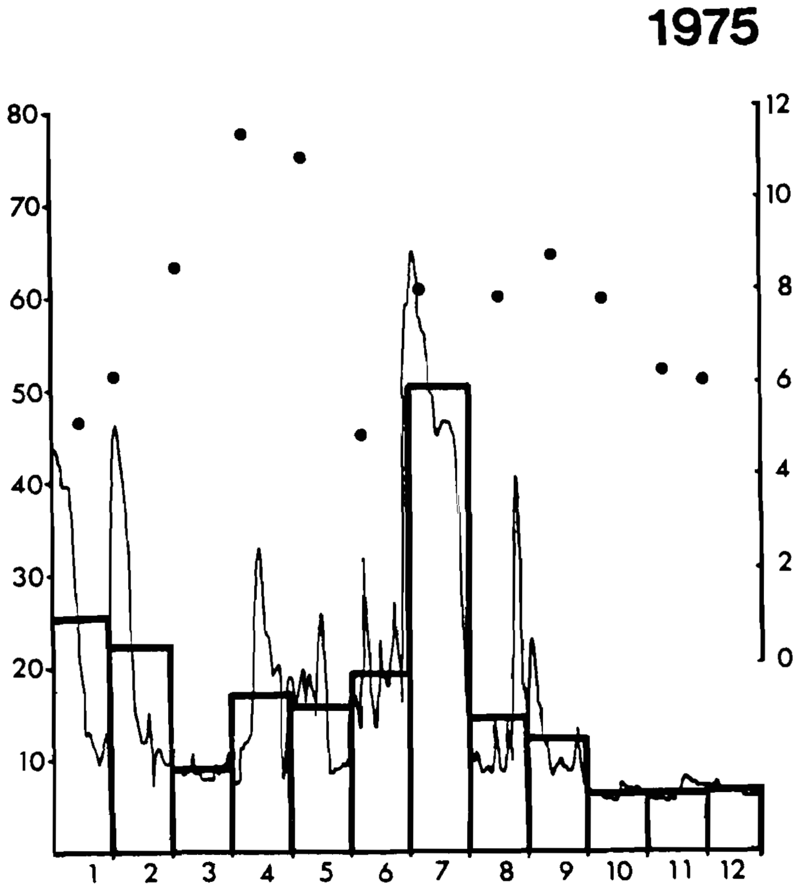


Figure 15: Outflow from Attersee through river Ager, showing daily values and monthly means, and surface layer (0 -10 m) concentrations of total phosphorus in the Attersee (flow data from O.Moog, pers.comm., chemistry from F.Neuhuber, pers.comm.).

And third, a dynamic simulation model was used to simulate the nutrient dynamics of the lake (Figure 16), which was integrated to estimate a yearly nutrient budget (Fedra et al, in prep.). Casting this model into a Monte Carlo framework, again allowed to estimate probability distributions for the individual terms of the nutrient budget (compare also Figure nn). These problems of scarce data and data uncertainty lead to methodological developments on stochastic approaches to model and data uncertainty, probabilistic interpretation of modeling results, and estimation of model reliability and prediction accuracy (e.g. Fedra 1980, Fedra et al.1980, Fedra in press a,b).

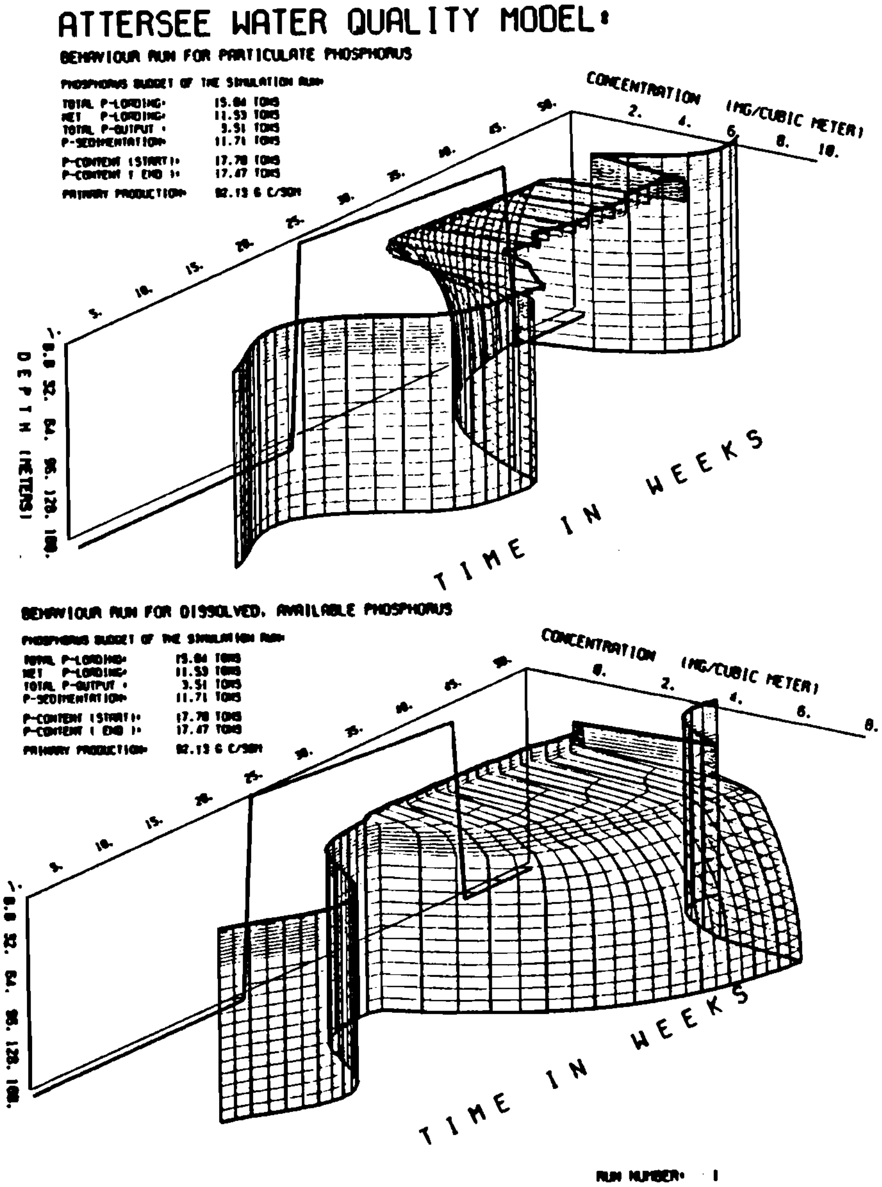


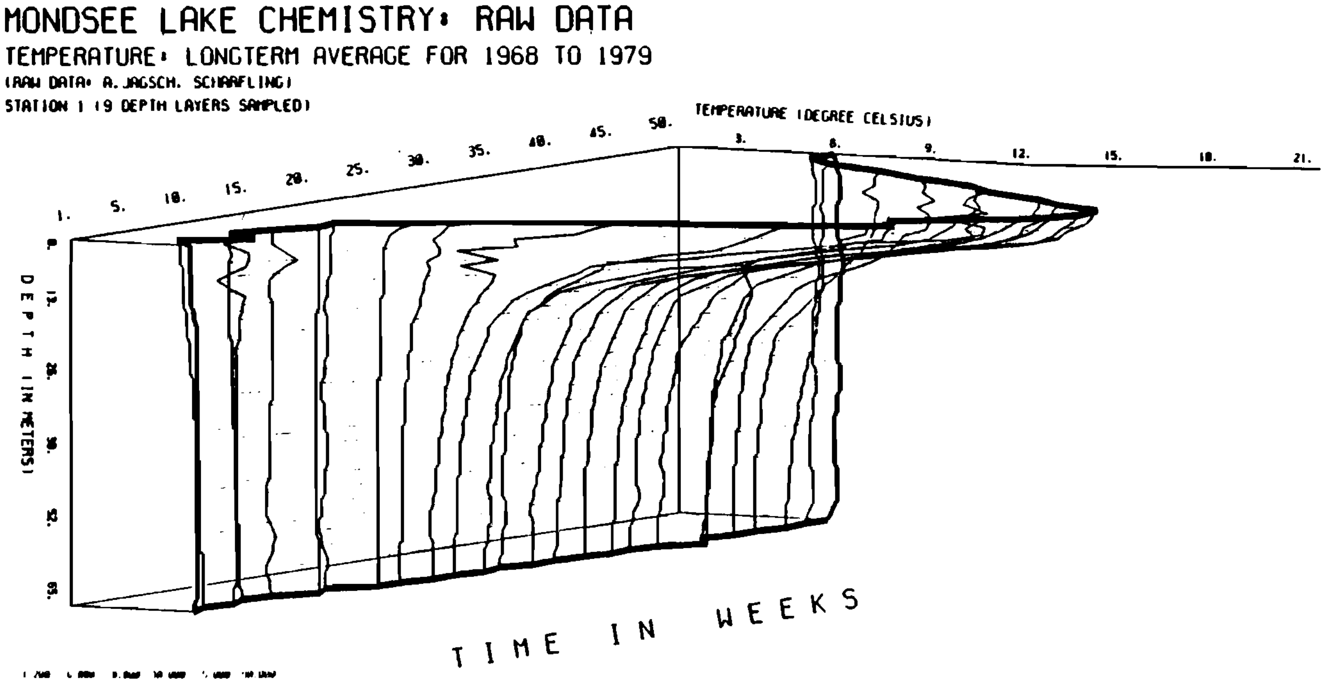
Figure 16: Attersee Water Quality Model: graphic output from a simulation run showing time/depth distribution of particulate phosphorus, representing algal biomass, and available phosphorus (phosphate). Thick line on the reference plane indicates depth of the thermocline. Note the proportions of epilimnion and hypolimnion, drawn in (depth) scale.

A detailed discussion of these methods and findings is given in a later section (pnn ff), and the Appendix (p nn ff). This model was also used to estimate the longterm response of the lake to changes in the nutrient loading, extending the simulations up to ten years, which allowed the system to reach a new dynamic equilibrium. Again, probability distributions were estimated for relevant measures of water quaility in time and related to changes in the nutrient loading (compare Figure nn).

The Mondsee

The second largest lake of the system studied, the Mondsee, is connected with the Attersee through the 2.5 km long Seeache, with a mean flow of about 8 m^3 sec^{-1}. In contrast to the oligotrophic Attersee, the Mondsee must be considered as being mesotrophic at least. With about 13% of the volume of the Attersee, and an average retention time of 2 years as compared to 7 for the Attersee, the Mondsee received an estimated 22 tons of total phosphorus in 1979 (Moog, 1980). This is more than what reaches the Attersee (about 19 tons in 1979), which demonstrates clearly the function of the Mondsee as a nutrient retention basin for the Attersee. The Mondsee, however, is severely affected by the high loading, with its hypolimnion going anoxic in the summer (Figure 17). As a consequence, redissolution of nutrients from the sediments has to be suspected. Figure 18 substantiates this assumption by showing remarkable concentrations peaks above the sediment.

Although a sewage treatment plant, including tertiary treatment, has only recently started operation in the town of Mondsee, estimates for phosphorus loading have doubled from 1978 to 1979. Paralleling the situation of the Attersee, the major part of nutrients entering the Mondsee is coming from the Fuschlsee and the 88 km^2 additional catchment of the Fuschlerache (compare Figure 11).



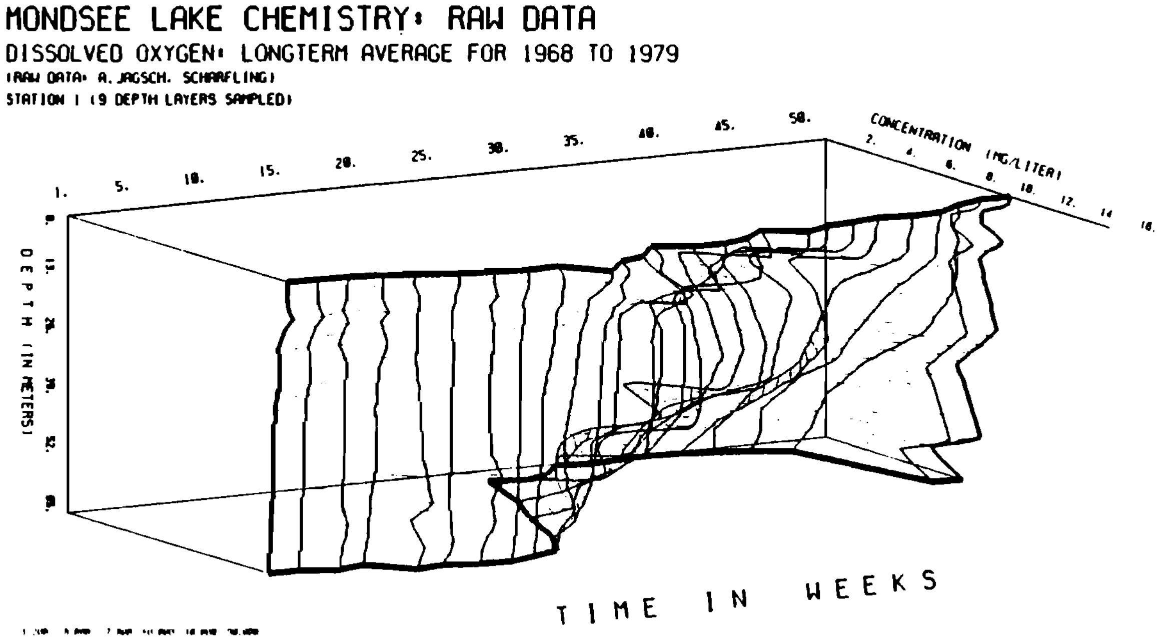
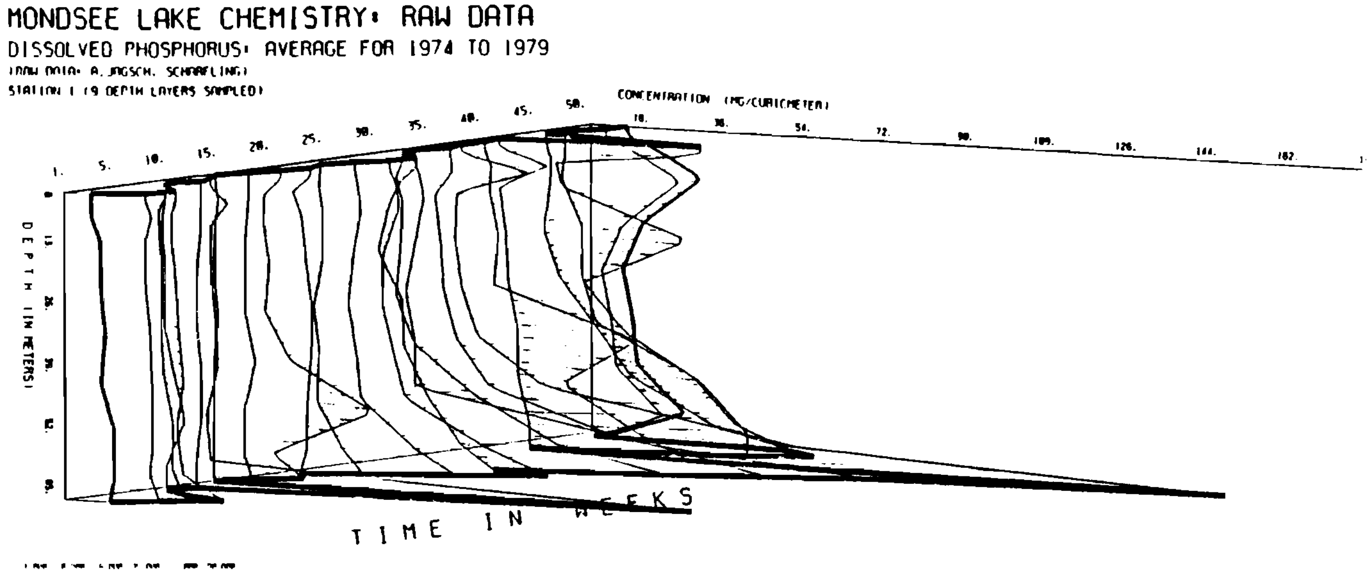


Figure 17: Mondsee Lake Chemistry: temperature (top) and dissolved oxygen (bottom), yearly patterns averaged for the years 1968 to 1980; (raw data from A.Jagsch, pers.comm.).



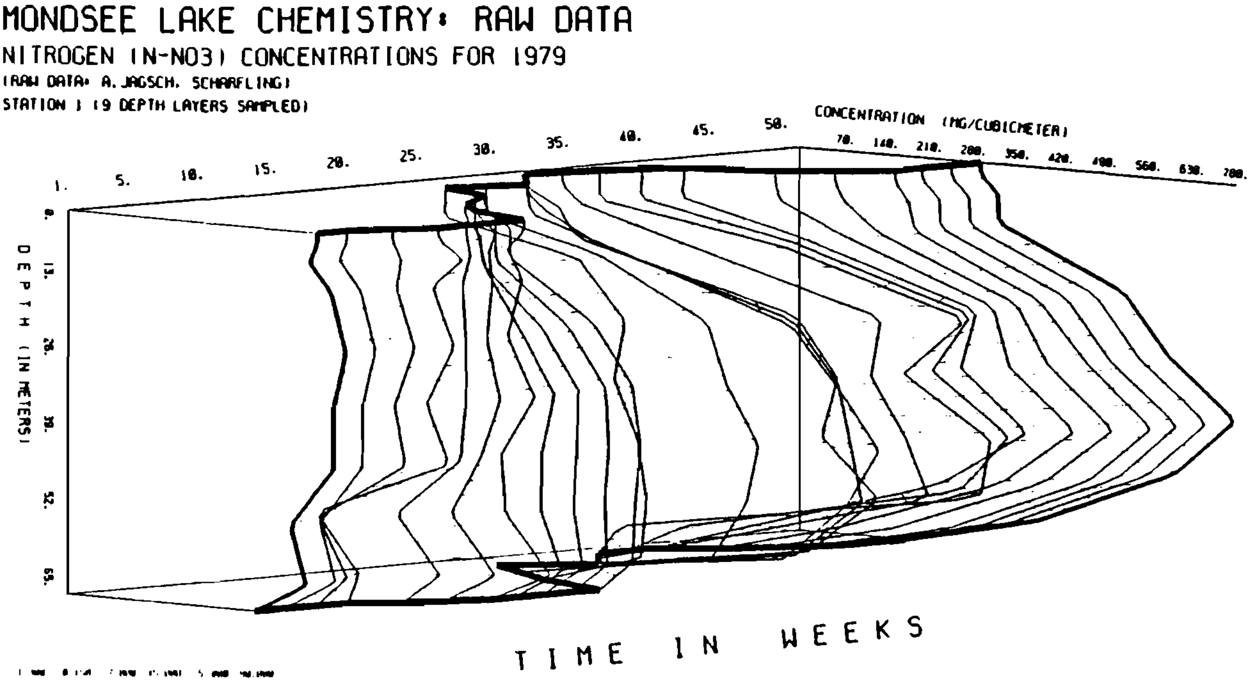
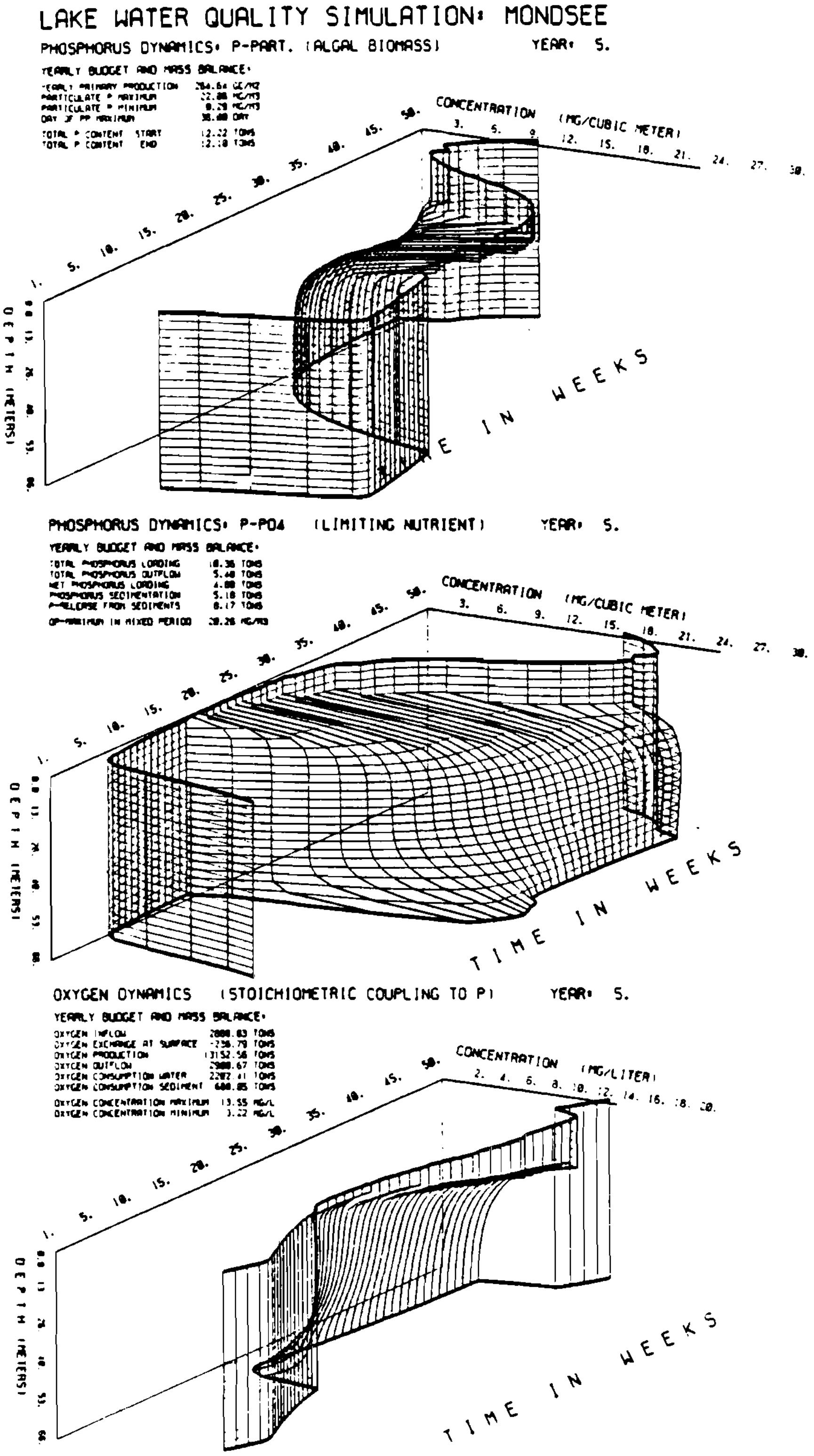


Figure 18: Mondsee Lake Chemistry: soluble phosphorus (top) and nitrate (bottom); yearly patterns averaged for the year 1979 ($N-NO_3$) and 1974 to 1979 (soluble P); (raw data from A.Jagsch, pers.comm.).

The problem of redissolution of nutrients from the sediments during the summer stratification of the lake makes obvious that the problem of lake sanitation is not a problem of phosphorus alone. Controlling the redissolution of phosphate, the dissolved oxygen above the sediment is of determining importance for the internal nutrient fluxes. For the study of lake Mondsee, a lake model including oxygen was therefore developed (Figure 19). Longterm simulations of the lake behavior in terms of oxygen and phosphorus can now be made to study the response of the lake to changes in the loading. This loading is split into two components, namely in available phosphorus and BOD (in phosphorus equivalents, representing organic material to be oxidyzed and mineralized). The model also allows a biochemically based estimation of phosphorus backflux from the sediments, which may play an important role in the recovery of the lake following effective nutrient diversion. An example of the output from this model is shown in Figure 19, which approximately represents the loading situation of the year 1978.

Due to the installation of the sewage treatment plant in Mondsee and the connection of a growing number of domestic sources to this plant (for a discussion of the legal and institutional aspects of current sanitation measures see below), the effects of nutrient retention should slowly become obvious. However, due to the long lead time for effective operation of the diversion and treatment systems, and the continuing increase in nutrient release in the watershed, a quick, conspicuous recovery cannot be expected. The models developed allow to estimate not only the effort necessary, they also indicate what the respective response times of a lake might be.



```
YEARLY BUDGET AND MASS BALANCE:
YEARLY PRIMARY PRODUCTION    284.64 GC/M2
PARTICULATE P MAXIMUM         22.88 MG/M3
PARTICULATE P MINIMUM          0.29 MG/M3
DAY OF PP MAXIMUM             38.00 DAY
TOTAL P CONTENT   START       12.22 TONS
TOTAL P CONTENT   END         12.18 TONS
```

```
YEARLY BUDGET AND MASS BALANCE:
TOTAL PHOSPHORUS LOADING      10.36 TONS
TOTAL PHOSPHORUS OUTFLOW       5.40 TONS
NET PHOSPHORUS LOADING         4.88 TONS
PHOSPHORUS SEDIMENTATION       5.10 TONS
P-RELEASE FROM SEDIMENTS       0.17 TONS
OP-MAXIMUM IN MIXED PERIOD    20.26 MG/M3
```

```
YEARLY BUDGET AND MASS BALANCE:
OXYGEN INFLOW                  2808.83 TONS
OXYGEN EXCHANGE AT SURFACE     -256.79 TONS
OXYGEN PRODUCTION             13152.56 TONS
OXYGEN OUTFLOW                 2988.67 TONS
OXYGEN CONSUMPTION WATER       2282.41 TONS
OXYGEN CONSUMPTION SEDIMENT     608.85 TONS
OXYGEN CONCENTRATION MAXIMUM     13.55 MG/L
OXYGEN CONCENTRATION MINIMUM      3.22 MG/L
```

Figure 19: Lake Water Quality simulation for the Mondsee; graphical output of lake simulation model for dissolved, available phosphorus, particulate phosphorus (representing algal biomass) and oxygen. Loading corresponds approximately to the estimates for 1978, the lake is in dynamic equilibrium (cyclically stable) after five years of simulation.

This lead time for any improvement (compare Figure 2?) is certainly an important element in planning; being aware of these time lags, it becomes obvious that a purely reactive approach to management is inappropriate for systems with comparatively long lead times. For the technical and construction aspects of lake management, time necessary may directly be translated into investment or capital costs. On the other hand, the analysis described here allows one to estimate the effects of late, slow or insufficient management action, or the additional effort necessary to compensate delayed action. Taken together, this provides the basic requirements for an economic analysis, where expected costs and benefits of environmental protection and environmental quaility can be compared.

Fuschlsee, Irrsee

The two smaller upstream lakes Fuschlsee and Irrsee constitute the upstream elements in the chain of lakes in the Ager catchment area. The Fuschlsee[1], which in terms of surface area is the smallest of the four lakes studied, is situated only 18 km east of the city of Salzburg. It therefore provides a very convenient possibility for water based recreation. Its catchment of less than 30 km^2 is dominated by woodland (80%). The area is non-industrialized, domestic sewage and agriculture constitute the basic sources of nutrients to the lake.

The lake is also of interest as a potential drinking water reservoir for the city of Salzburg; occasional investigations on water quality have therefore been carried out since 1948, describing the lake as a crystal clear, oligotrophic body of water. Only since 1966 first increases in nutrient concentrations could be documented, indicating a rapid deterioration of water quality since the mid seventies (Figure 20).

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[1] The discussion of the Fuschlsee is largely based on material from the yet unpublished Ph.D. thesis of J.Haslauer (Haslauer, pers.comm.).

Again, water quality deterioration is paralleled by the development of tourism. However, one should not forget that during the same period average lifestyle has also changed, resulting in an increasing phsoshorus release per capita, at least in part du to phosphate detergents. Tourism in Fuschl, the main settlement at the lake,experienced a more than tenfold increase since 1960, which is far above the average for most settlements even in the Salzkammergut region. In parallel, changes in agricultural practices lead to a more intensive use of former rangeland.

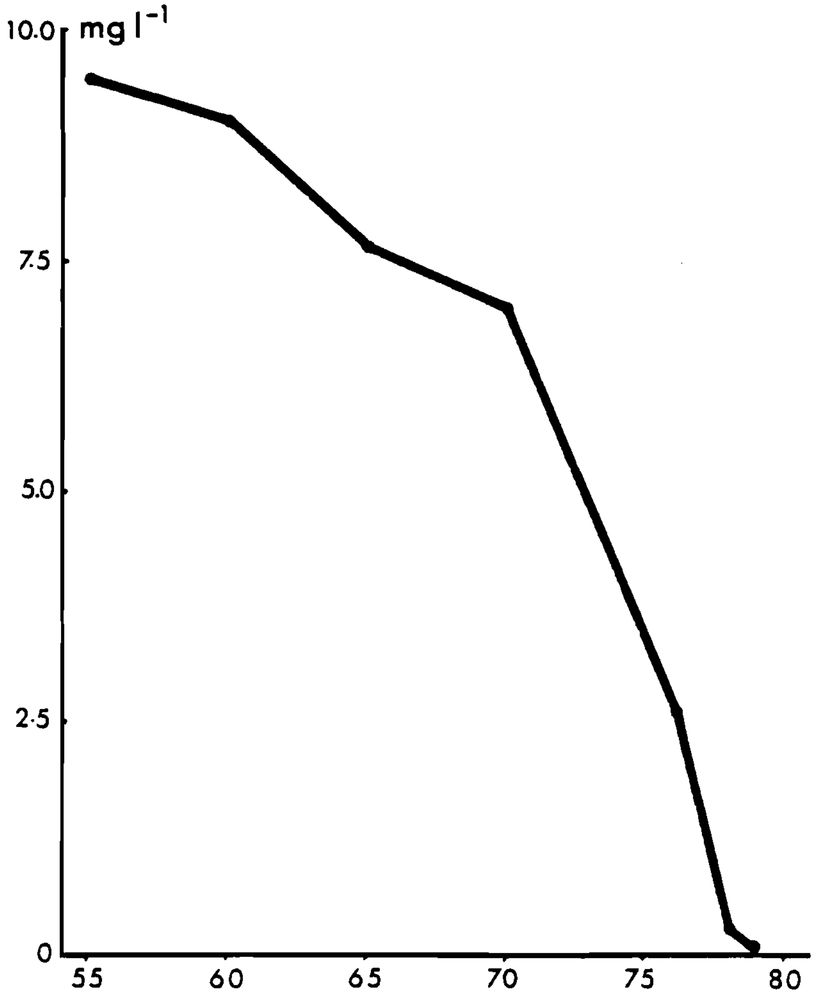


Figure 20: Historical development of the oxygen concentrations at the end of the summer stagnation in Lake Fuschl (after Haslauer, pers.comm). Note the sharp decline after 1970.

Similar to the measures taken in the other sub-catchments, a sewage diversion and -treatment system was designed as early as 1973 for the Fuschlsee, which only 1980 reached its completion (see below). Whether or not the diversion of the domestic pointsources alone will be sufficient for the recovery of the lake in the near future remains to be seen. This, however, will be an interesting test case for the value of model based predictions; the simulation of the lake's recovery will lead to real "forecasts", based on the analysis of the present situation only, as compared to many "a posteriori" predictions of historic developments.

Also, the Fuschlerache, originating at the outflow of Lake Fuschl, is the main source of nutrients for the Mondsee. Although the majority of the rivers nutrient load stems from the additional 88 km^2 catchment of the river below the lake outlet, the role of the lake itself and the impact of the sanitation measures taken on the downstream Mondsee, and subsequently on the Attersee, are of great interest. A rational evaluation of the benefits of any of the sanitation measures taken must always be made for the whole watershed system of the river Ager, if not for even larger hydrographic entities.

The Irrsee, or Zellersee, is the second of the two small uppermost lakes of the system. Being the smallest lake in terms of volume and depth, it is also the least studied one. Its catchment area of 24 km^2 is only covered by less than 30% of woodland, which is comparatively low for the area. Agricultural development as well as tourism create a situation quite similar to the Fuschlsee. According to its (eu)trophic state, the lake also shows and anoxic hypolimnion during summer stratification (Figure 21). To illustrate its role in the overall system, it is remarkable that the Zellerache, fed by the outflow of the Irrsee and draining an additional area of 11 km^2 contributes about 20% of the total loading of the Mondsee (1979 estimate from Moog, 1980). Its corresponding share of the area of the total catchment of the Mondsee is only about 17%.

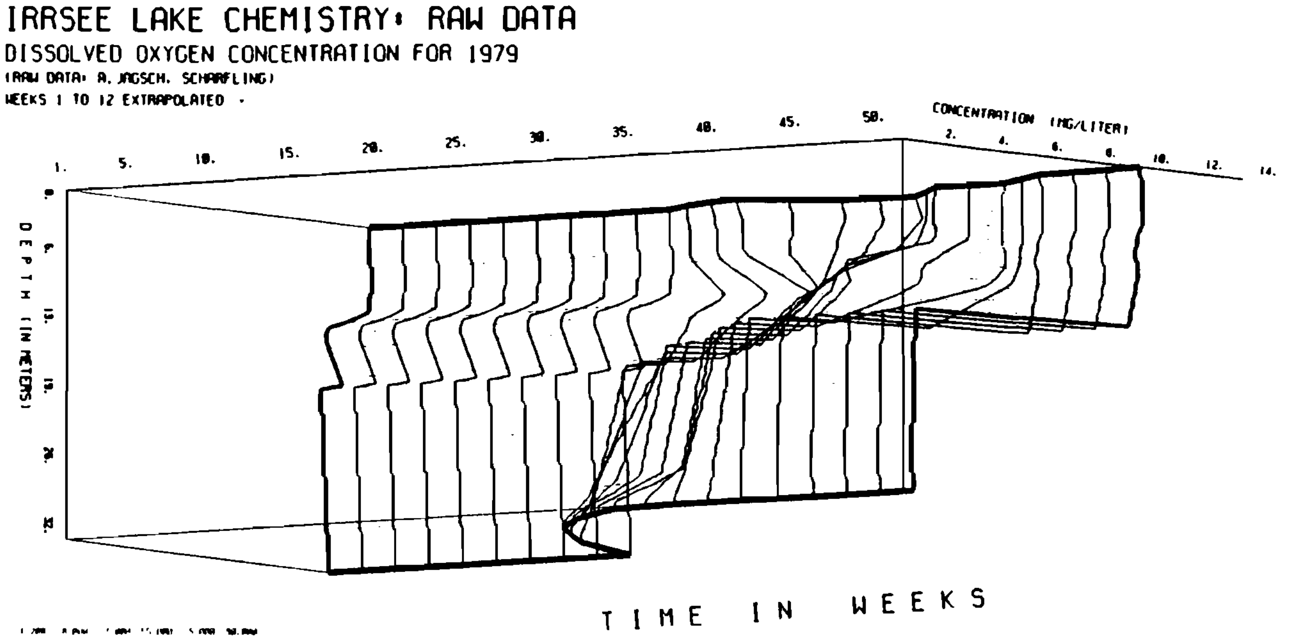


Figure 21: Oxygen concentration of the Irrse for 1979. Note the anoxic hypolimnion in the second half of the year (values for the first three months of the year have been extrapolated from April measurements). Raw data from A.Jagsch, 1980).

The Coupled System

The above described four major element of the Attersee-System are linked by flows of water and nutrients, connecting the lakes and their respecitive catchment areas. This constitutes a natural drainage (and sewer) system, which also acts as a nutrient retention system (in terms of phosphorus), and treatment system (e.g in terms of BOD). This basic natural system is now complemented by a technical system of sewage diversion and treatment, which complicates the picture. Although the technical system is comparatively small in terms of flows (the average flows in the Attersee diversions system amounts to about 0.5% of the lakes outflow), they are dominant in terms of nutrients. The technical system consists of three major elements, namely the diversion system for the Fuschlsee, connected to the treatment plant (tertiary treatment) in Thalgau, discharging into the Fuschler Ache; the diversion system for the northern part of the Mondsee and a treatment plant with tertiary treatment, discharging into the lake; and a diversion system for the Attersee, connected to a treatment plant in Lenzing, discharging into the river Ager (Figure 22).

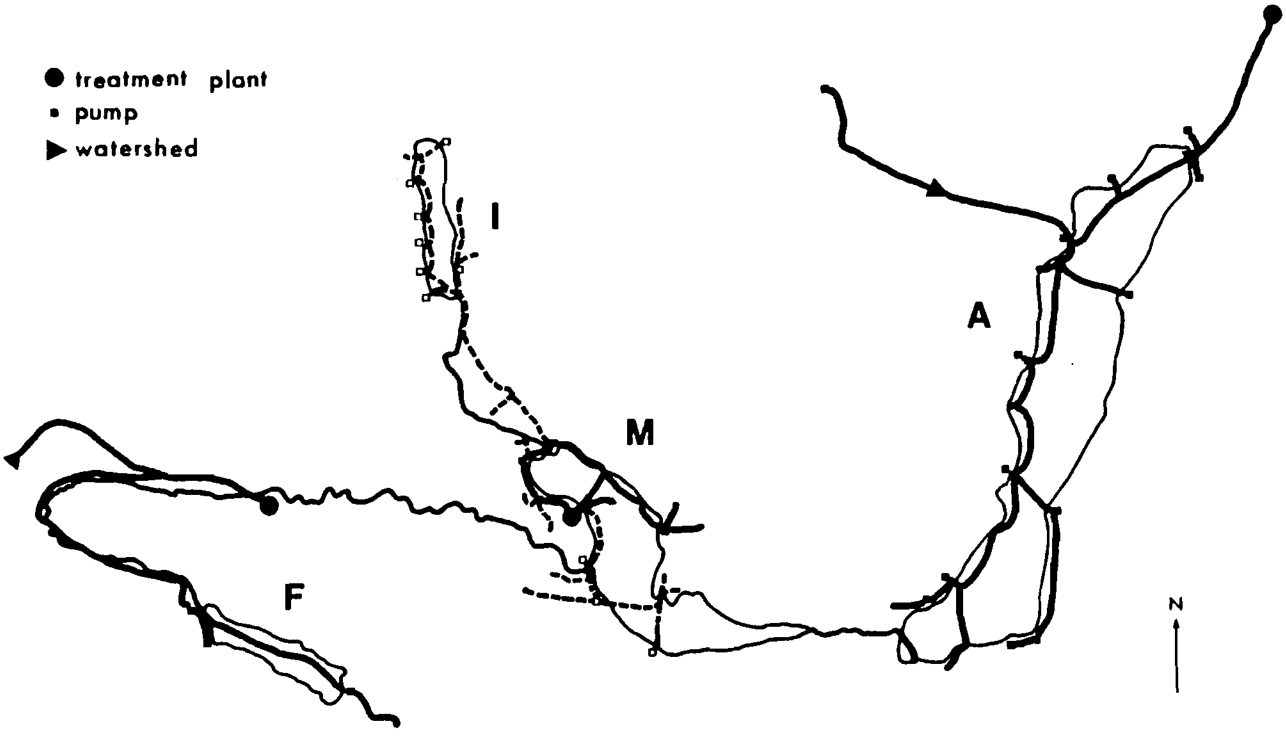


Figure 22: The nutrient diversion- and treatment systems in the Ager catchment basin. Lines indicate sewage pipelines, squares represent pumping stations, and large dots represent treatment plants; parts under construction are shown by broken lines and empty symbols.

According to the spatial distribution of the sources around the lakes, a diversion system collecting sewage from several communities and pumping it to a few centralized treatment plants was chosen as the most appropriate alternative (Flögl,1976). The connecting pipe system, which is fed from the sewer systems of the individual settlements, consists largely of plastic tubing, positioned on the lake bottom wherever feasible (see Figure 22). This was found to be the most economic alternative. The downstream treatment plant in Lenzing (mechanical/biological) is designed for 120,000 person-equivalents (current stage: 60,000). In 1979, average inflow to the sewagework corresponded to 43,000 person-equivalents in summer, and approximately 20,000 during wintertime. These figures, however, represent an interim situation. The overall system is still under construction. Construction started in 1973, and in 1976 first parts of the system were operational. At present, only certain parts of the shore communities are connected, ranging from 20% to 75%. The final stage of completion with 100% connections cannot be expected before 1983. Also, the settlements around the eastern basin of the Mondsee, which are also planned to be connected to the Attersee system, are not yet included.

At the Mondsee, the diversion system for the northern basin of the lake also includes the settlements around the Irrsee. In case of the Mondsee system, the wastewater is collected but not further diverted downstreams, but treated and discharged into the lake. This solution, which was planned already in 1964, was chosen because of the comparatively large costs of complete diversion. Complete diversion, involving pipelengths of up to 40 km (to the river Ager) or pumping over the watershed to the bordering catchments in the north over considerable altitudes, would have required mechanical and biological treatment anyway (Flögl 1976). Also, coordination with the Attersee system (which was initiated a few years later) would have caused further delay. A treatment plant with tertiary treatment was designed for 25,000 person-equivalents. This, in the mean time has been extended to 35,000 to include the Irrsee area. In 1974, the first stage with 12,000 person equivalents was operational, and in 1978 a removal of about 6 metric tons of Phosphorus was estimated. The system is still under construction for the connection of the Irrsee area, the completion of the sewer system around the Mondsee, and the extensions of the sewage work itself.

At the Fuschlsee, the sewage diversion system reached completion in early 1980. Constructions started in 1975, and already in 1976 the treatment plant in Thalgau (designed for 20,000 person-equivalents, and including tertiary treatment) was operational.

The legal and institutional structure for these three elements in the sewage diversion and treatment system for the Attersee region is given by federal laws as well as regulations on the provincial level. Summarizing from Ercman (1977), the Water Act of 1934, which underwent several significant amendments, makes the heads of the provincial and local administrations and the Minister of Agriculture and Forestry the authorities responsible for the control and management of waters and the execution of this Federal Act. The Federal Water Act of 1966 prohibits processes likely to cause pollution of waters, among them leaking of industrial and urban waste waters. Installations or constructions likely to produce effluents causing pollution are subject to prior authorization, and are required to maintain certain standards of purification. The owners are asked to take all suitable measures to prevent pollution. In case of failure, the local water authorities are empowered to take the necessary action at the cost of the liable party.

This federal legislation is complemented by a number of regulations, socalled "Verordnungen", from the Federal Minister of Agriculture and Forestry. To cite from one example, "The construction of sewage systems has to be such that a maximum proportion of pollutants will be affected; wastewaters shall be treated in addition to biological treatment with further methods, e.g. chemical ones. A joint wastewater treatment of neighboring communities should be attempted, if this is geographically and economically feasible." Accordingly, in all three cases mentioned above, the system built is a joint effort of several communities, which form a water association. These associations, after receiving the authorization from the provincial water authority, are subsidized with money from the federal as well as provincial government. For the Mondsee project, total costs are shared between the communities (21%), the provincial government (22%), and the federal government (57%).

For the model representation of the overall system of individual subwatersheds and nutrient sources, connecting river reaches and the lakes, these systems of sewage diversion and treatment have to be included. This is done by a wastewater diversion module, representing any kind of sewer system, and a treatment module, representing the sewageworks (Figure 23). The diversion module is linked to a certain proportion of the domestic and industrial sources of any subwatershed, and has certain maximum flow and retention characteristics. These technical specifications allow one to estimate the effects of different stormwater provisions, or the simulation of technical failure such as the failure of any of the pumps. The treatment modules, which are fed from the diversion module, simulate some of the operational characteristics of the respective plants, resulting in a certain reduction of total nutrients and changes in the proportions between particulate and soluble fractions. Again, the module allows one to simulate operational aspects, or the consequences of failures. Design alternatives, especially different sizes of stormwater retention facilities and maximum capacity can be included into the simulation. Also, since the costs for the sewer systems (the proportion of sources connected) and plant construction and operation are well known, the total cost of different alternatives can easily estimated. They can then be contrasted with the water quaility standards to be expected with each feasible alternative.

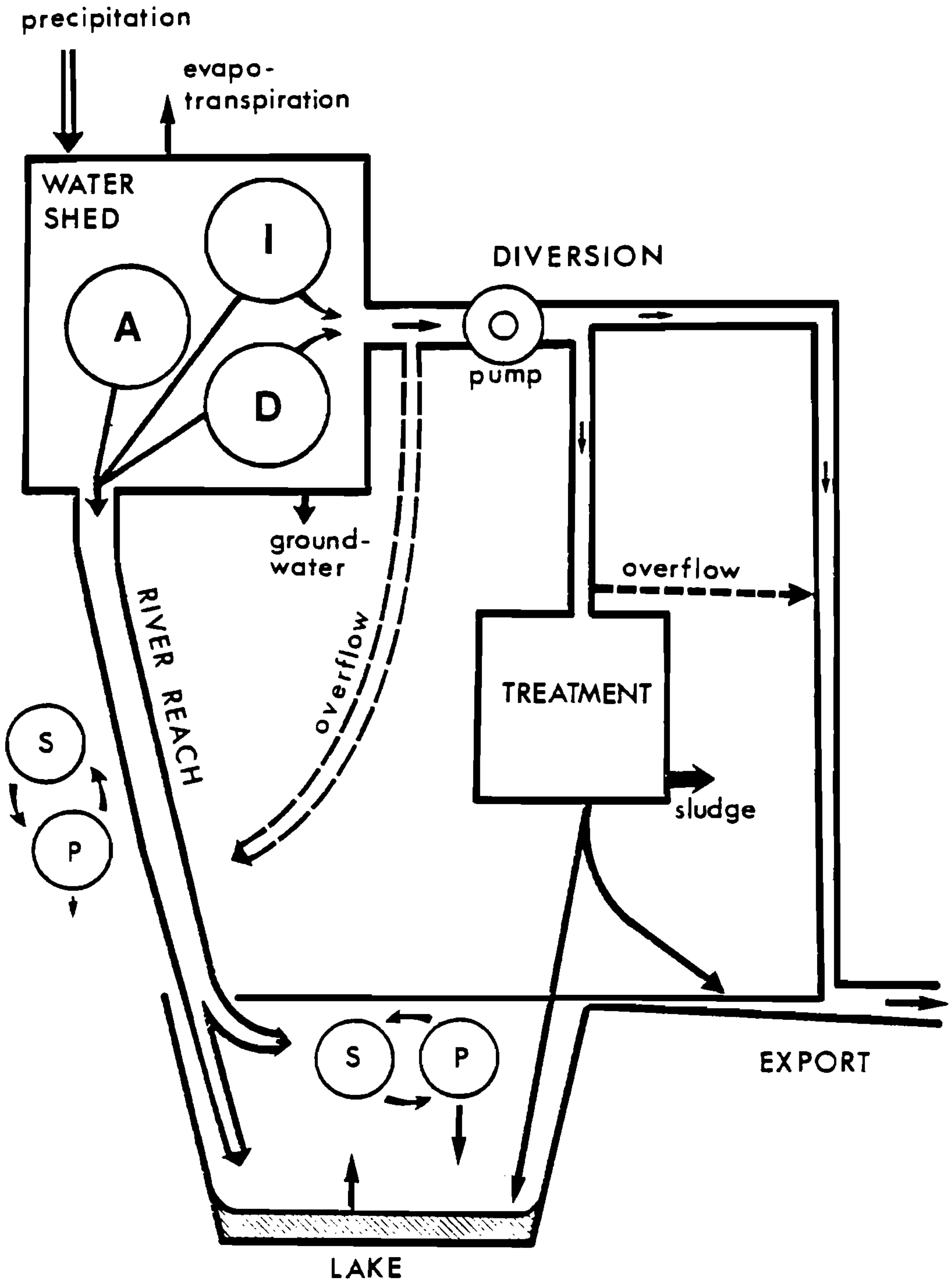


Figure 23: The basic structure of the individual simulation modules and their connections for the description of the Attersee-system.

Achievements, Problems, and Outlook

Similar to the achievements in the Neusiedlersee study, an up-to-date data base on the lakes themselves and data management system, including a variety of smaller utility programs for data handling, analysis, and display, could be established. Data for the watershed and the diversion and treatment modules are still uncomplete, but enough material is available to develop and test the individual simulation modules and their linkage.

The lake water quality models used sofar are based -- in their physical structure, using a variable-depth well mixed epilimnion and a multilayered hypolimnion, described by partial differential equations -- on the phosphorus model of Imboden and Gächter (1978); several versions however have been coded, including a version with oxygen as an additional state variable to estimate hypolimnetic oxygen depletion as an important water quality variable, and in order to estimate nutrient backflux from the sediments under anoxic conditions (compare Figure 18,19). Also, several different descriptions of primary production, and a more detailed description of the aquatic foodweb, including organic detritus and zooplankton, were built. This system of comparatively simple and general (stratified) lake water quality models ranges in complexity from the original Imboden and Gächter (1980) model structure with two state variables to a version with 8 state variables and much ecological detail; for a comparative analysis of model performances, the application of an appropriate version of the CLEANER model series (e.g. Park et al. 1974, Park et al., in press), capable of simulating up to 40 compartment with much biological detail, is planned in cooperation with the Rennselaer Polytechnic Institute, Troy, N.Y..

Vertical stratification of the lakes, and the vertical transport processes connecting the sediments, the hypolimnion, and the epilimnion with each other, are important features of the above models. To study the phenomena of vertical transport in more detail, and also to provide methods to link any detailed description of the hydrophysical processes responsible for the internal nutrient loading to the ecological processes, the coupling of an appropriate version of the MIT vertical stratification model (e.g. Octavio et al.1977) is planned in cooperation with the Ralph M.Parsons Laboratory of Hydrodynamics, MIT. For the test of the performance of such a model, a very detailed data set on vertical temperature distribution in the Attersee, together with the necessary meteorological observation, is currently established (Moog, pers. communication). The data collection system used consists of a series of 13 thermistor probes in the open lake, which continuously measure water temperature in depths of 0, 5, 7.5, 10, 12.5, 15, 17.5, 20, 22.5, 25, 30, 50, and 70 m. In parallel, at the shore air temperature, radiation, windspeed and direction, and relative humidity are measured continuously. The data collection is controlled by an 8K microcomputer, which also records the measurements at programmable intervals on cassetts. The computerized data collection system is complemented by the traditional paperchart recording devices for the standard meteorological variables, and an estimate of cloud cover three times a day. After a long and complicated phase of tests and improvements, the computerized data collection system is now operational since January.

In the second phase of the ALECS, the different modules will now be linked. For the first tests, extremely simple descriptions of the watershed runoff, the connecting river reaches, and the wastewatersystem will be used together with the more sophisticated lake models. Depending on the progress of the development or modification of these modules, they will subsequently be replaced by more sophisticated versions if necessary. This model system will be used for the simulation of the historic development of the last few years, based on the available records of hydrometeorological, limnological, and technical information about the overall system. Different scenarios with respect to the future development of the wastewater diversion- and treatment system will then be simulated, using synthetic timeseries of the driving climatic variables.

Emphasis on the methodological side will be on model linking and model simplification. The simulation and analysis of such a complex system as the overall watershed system described above, will require a rational method for simplification of the individual models. This is necessary to effectively link them, but also to be able to simulate the whole system with reasonable technical effort. Model simplification can be accomplished a priori, which is by building and running a simplified version of any model, or a posteriori. The latter approach would try to integrate the output from a detailed, complex model to obtain a sufficiently simple format for use within a system of linked models.

Also, it will be necessary to complement this system of linked models with several auxiliary programs for the analysis and interpretation of any of the runs. The very large amount of output such simulations can potentially produce is practically incomprehensible, if not condensed and analyzed by the machine itself. Although, as a consequence of the systems complexity, a very high number of questions can be studied with such a comprehensive model system. These are of course all the environmental management issues discussed above. Besides, a number of technical or methodological questions can be posed. Sensitivity analysis with such a complex system of models will certainly be challenging, though rewarding task. Questions of uncertainty and model reliability, which certainly should become more and more problematic with increasing model complexity and increasing number of arbitrary assumptions, will have to be studied. Answers such technical questions are prerequisits for the rational application of complex simulation models to realworld problems.

THE CARINTHIAN LAKE DISTRICT:
Case Histories of Lake Sanitation

The Carinthian lake district is one of the most important and also most traditional areas for tourism in Austria. The numerous lakes with their very high surface temperatures in the summer (up to almost 30° C) provide major attractions. Tourism experienced a continuous phase of growth over the last decades (Figure 24), represented in increasing numbers of visitor days and overnight stays, and in a conspicuous urbanization of the lake shore zones. As an example, overnight stays in the Wörthersee region increased from less than 500,00 in 1953 to more than 2,750,000 in 1977. Scientific investigations on these lakes are carried out since 1930 (Findenegg 1932, 1933, 1953, 1971), providing a most valuable set of historical observations. These observations are now continued by the Carinthian Institute for Lake Research (e.g. Kärntner Institut für Seenforschung, 1976, 1977, 1978, 1979). These observations have shown conspicuous indications of acute eutrophication in most of the Carinthian lakes, culminating in a series of algae blooms and severe oxygen depletion of the lakes in the early nineteenseventies.

This development, which led to severe consequences for tourism, has led to the installation of sewage diversion and treatment systems in the lake district. These measures, however, have a long lead time (Figure 24), and although initiated in certain cases as early as 1967, it is still difficult to demonstrate clear improvements in front of a background of high natural variability. Nevertheless, due to the comparatively long timeseries of observations, which span a period of water quality deterioration and consequent attempts at lake sanitation, the Carinthian lakes provide a set of excellent case histories for model testing. These data sets allow one to evaluate the performance of different kinds of water quality models in forecasting the longterm response of lake systems to dramatic changes in the loading.

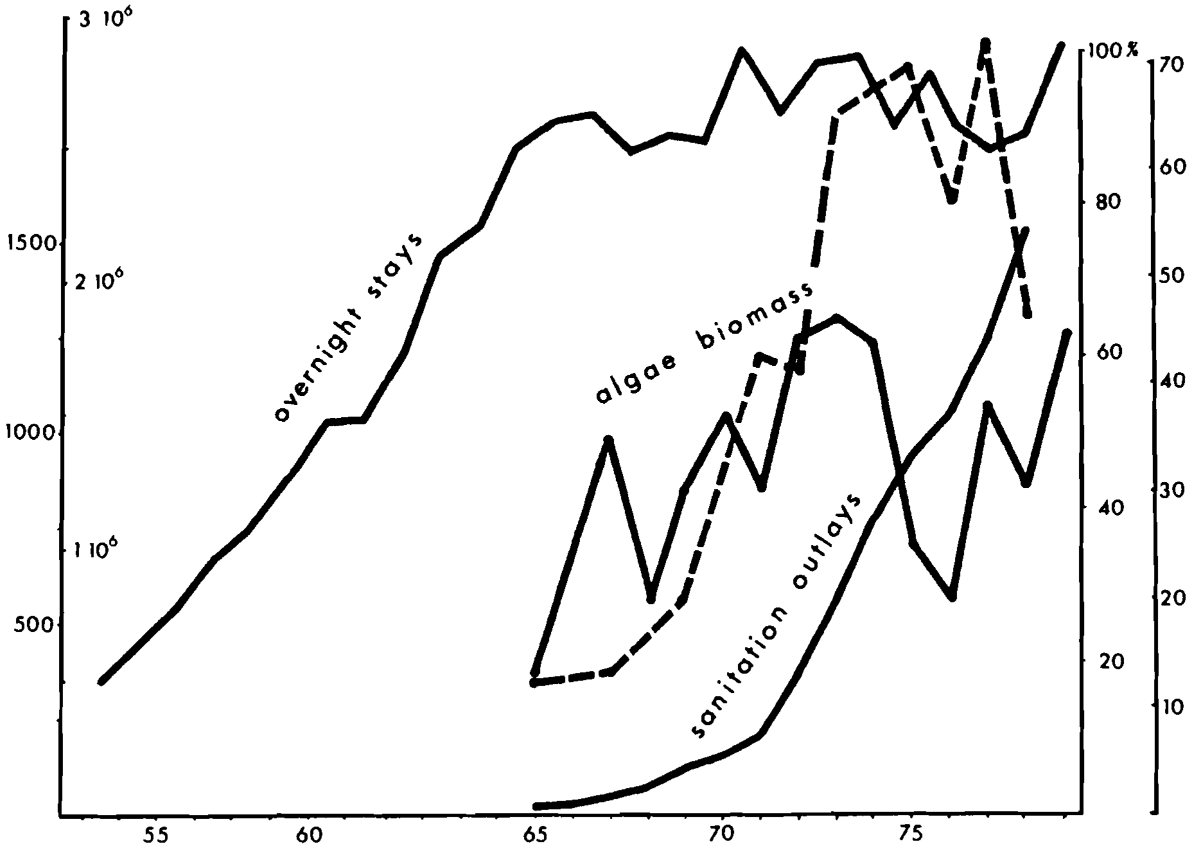


Figure 24: The development of tourism, water quality, and sanitation measures for the Wörthersee. Water quality in terms of epilimnic algae biomass (mg m^{-3}), broken line indicates depth integrated total algae biomass (g m^{-2}). sanitation outlays are given as percentage of total estimated project costs for the sewage diversion and treatment system (data from Sampl et al. (1979) and Thomaser (1979), and Kärntner Institut für Seenforschung, pers. comm.).

The three lakes chosen for a detailed study of their longterm response to the afore mentioned changes in their loading conditions are the Wörthersee, the Millstättersee, and the Ossiachersee. All three of them are not only subject to the routine measurement program of the Carinthian Institute for Lake Research, but are also studied within the UNESCO Man and Biosphere Program (Wörthersee, Millstättersee) and the Austrian Eutrophication Program (ÖEP, a national continuation of the former OECD program). These activities provide a most valuable background of empirical data.

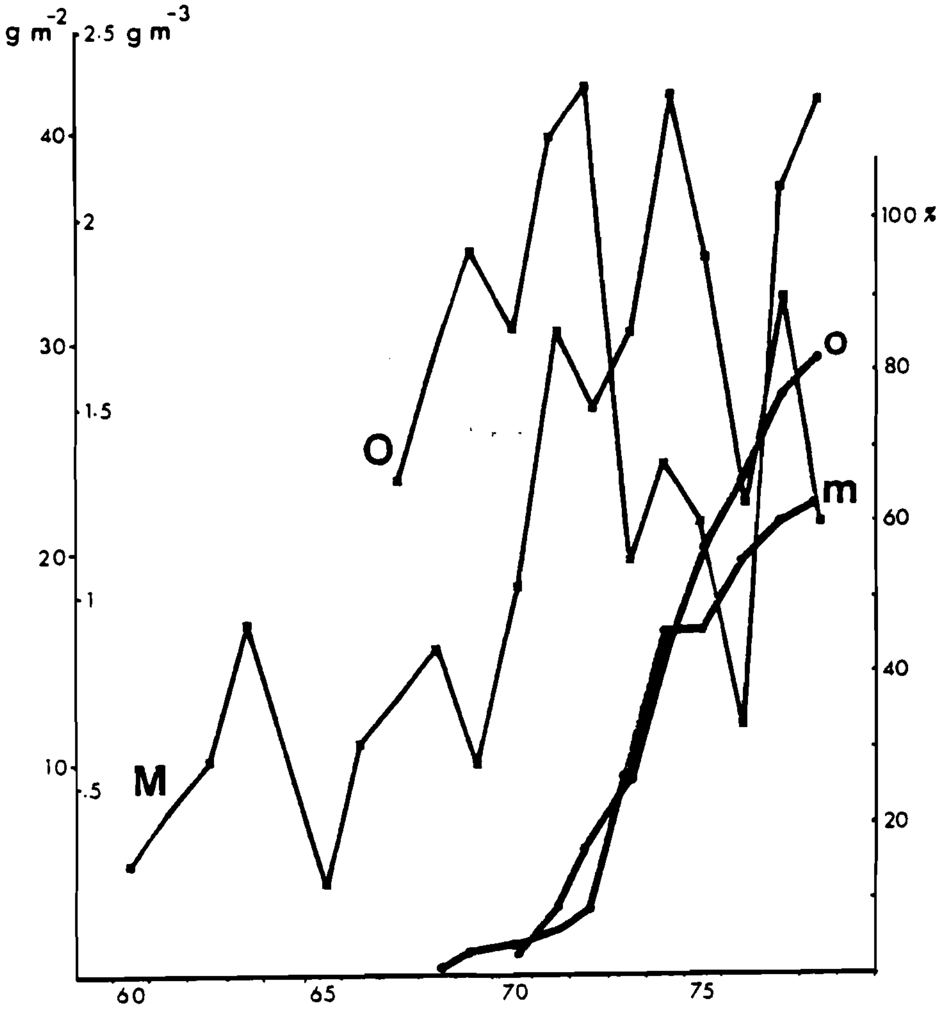


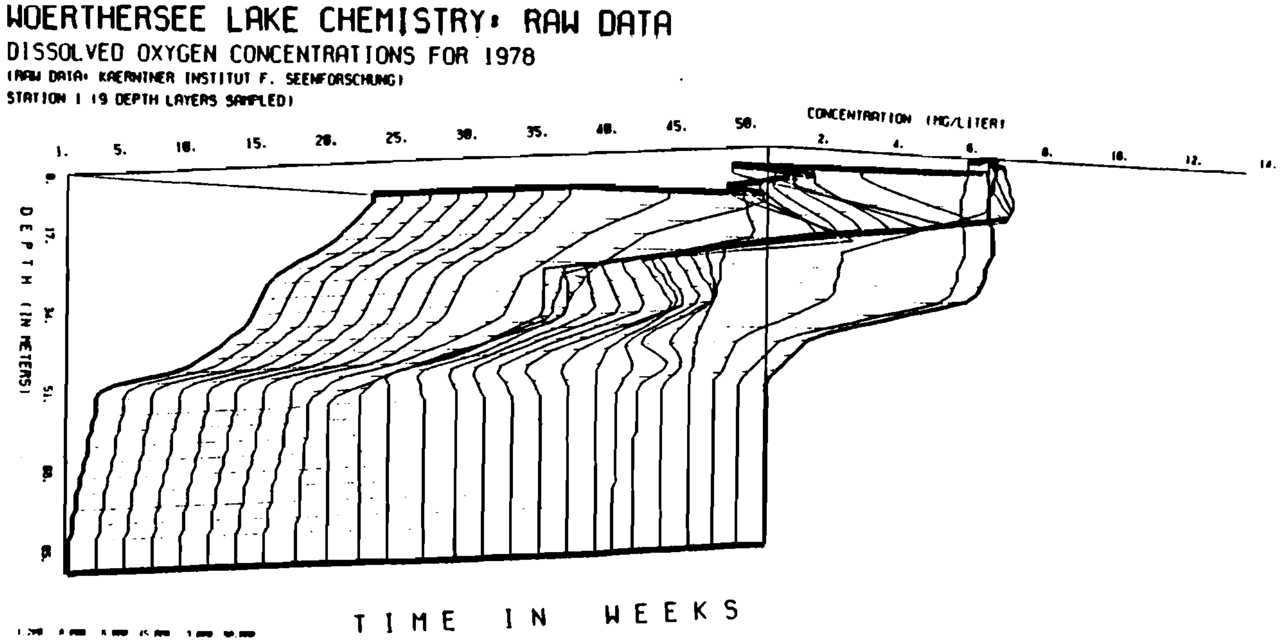
Figure 25: Water quality and sanitation effort. Average algae biomass (connected squares), and cumulative effort for sanitation (percentage of total estimated project costs spent) for the Millstättersee (m) and the Ossiachersee (o). Data from Thomaser (1979), Sampl et al. (1979) and Kärntner Institut für Seenforschung, (pers.comm.).

Also, the three lakes chosen represent two different types of deep, stratified lakes in terms of there mixing regime. The Ossiachersee is mixing twice a year completely, namely in the spring-overturn period following a winter stagnation, and in late fall, following summer stratification. In contrast, Wörthersee and Millstättersee a representing a meromictic regime. The waterbody of these lakes does not mix completely during the homothermal periods, but only down to a certain depth of about 50 m. Below is the generally anoxic and nutrient rich water of the socalled monimolimnion (compare Figures 26,27). This specific situation makes these lakes a good model for much larger lakes under similar (physical) conditions of complex vertical gradients, as for example Lake Baikal. Again, as in the case of the holomictic lakes of the Salzkammergut, the vertical transport and mixing phenomena of the lakes are important elements in the understanding of their behavior.

The Wörthersee

The Wörthersee, situated together with the Millstättersee (see below) in the Carinthian basin, is characterized by a low throughflow (average retention time about 10 years), and a sheltered position, resulting in a pronounced thermal stratification during the summer. The lake provides a perfect case history of eutrophication, which endangered tourism, and consequent sanitation efforts. Increased nutrient loading over the last decades resulted in increasing nutrient concentrations in the lake, high bioproduction, culminating in severe algae blooms, reduced visibility, and oxygen depletion of the lake. The Wörthersee is a typical meromictic lake, where the vertical mixing reaches down to about 45 to 50 m depth. The stagnant monimolimnion is very rich in nutrients, and oxygen free (Figure 26).

The lake is under detailed scientific study since 1931, and has also been studied within the frame of the International Biological Program from 1976 to 1973; it is currently, together with the Millstättersee, subject to a case study in the Man and Bioshphere project in Carinthia. The nutrient loading of the lake stems from .numerous smaller tributaries, and a very high proportion comes from urbanized areas along the shoreline without appropriate sewering. Sanitation measures have been initiated at the Wörthersee as early as 1964 (compare Figure 24). A sewage diversion system was installed for the western part of the lake. Wastewater is collected and, after mechanical treatment, diverted downstream of the lake to the river system draining the watershed. In 1968, construction of a diversion system all around the lake was started, collecting wastewater for mechanical/biological treatment and diverting it into the lakes outflow. These installations have led to a reduction in the total phosphorus loading to about 50% (estimate for the year 1976) as compared to the period before sanitation measures were taken (Sampl and Schulz, 1977). Improvements are also obvious in terms of visibility (measured as Secci-depth), which, after a low in 1972, is again increasing.



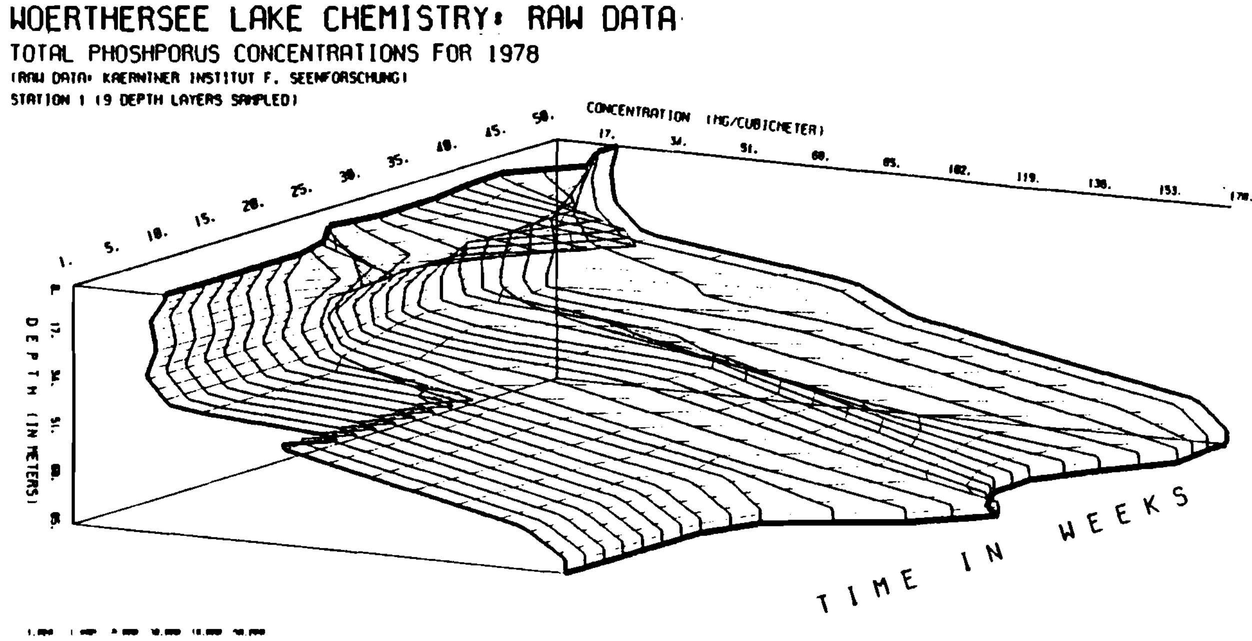


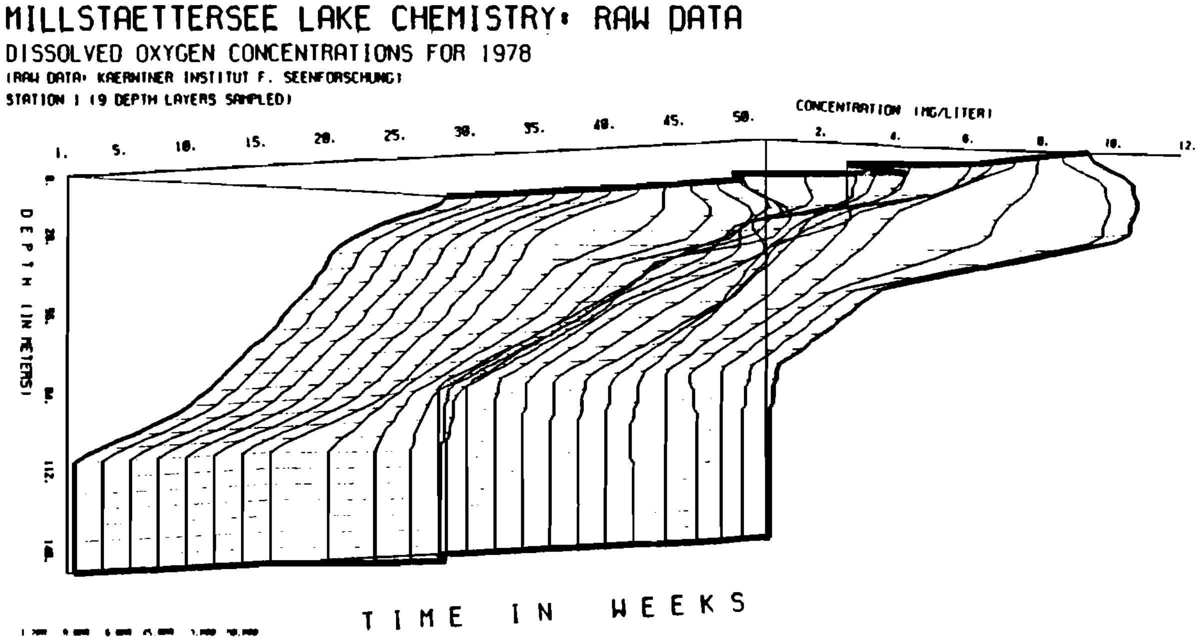
Figure 26: Oxygen and total phosphorus concentrations in the Wörthersee for the year 1978. Note the proportions of mixolimnion and monimolimnion.

The Millstättersee

The Millstättersee is the second large meromictic lake in the Carinthian basin. Although smaller in terms of surface area, it is deeper than the Wörthersee (140 m as compared to 85 m for the Wörthersee), and has a bigger volume. Average retention time, however, is only 8 years. The mixing regime is meromictic as in the case of the Wörthersee, with the same vertical distribution of nutrients and oxygen (Figure 27). The catchment of the lake totals 276 km^2. A major part of it, 208 km^2 in the east, are drained by one creek, contributing almost 90% of the surface inflows. Tourism in the catchment showed the same development as in the case of the Wörthersee, with a more than tenfold increase of overnightstays from 1953 to 1972, reaching almost 3,000,000.

Until 1968, there was no wastewatersystem for the area. Wastewater reached the lake directly or via several smaller tributaries. This lead to the formation of spectacular algae blooms. Sanitation measure were initiated in 1968. As a result of the sanitation effort, phosphorus loading decreased from an estimated 23,5 tons in 1967 to less than 6 tons in 1976 (Sampl and Schulz, 1977). Paralleling the development in the Wörthersee, visibility is increasing since a conspicuous low observed in 1972.

Although the general patterns for Wörthersee and Millstättersee are quite similar, there are some remarkable differences. First, the catchment of the Millstättersee is almost twice as big as the one of the Wörthersee; agricultural land use however, is only of importance in the Wörthersee catchment, whereas woodlands are dominating around the Millstättersee. Development of tourism, with increases in visitor days and increasing construction activities along the shores, are characteristic for both lakes. Also, industrial waste water with high alkalinity and a high load of solids from a large "Magnesit" plant polluted the Millstättersee until recently, when a change in operational practices, from wet to dry air filtering systems was made.



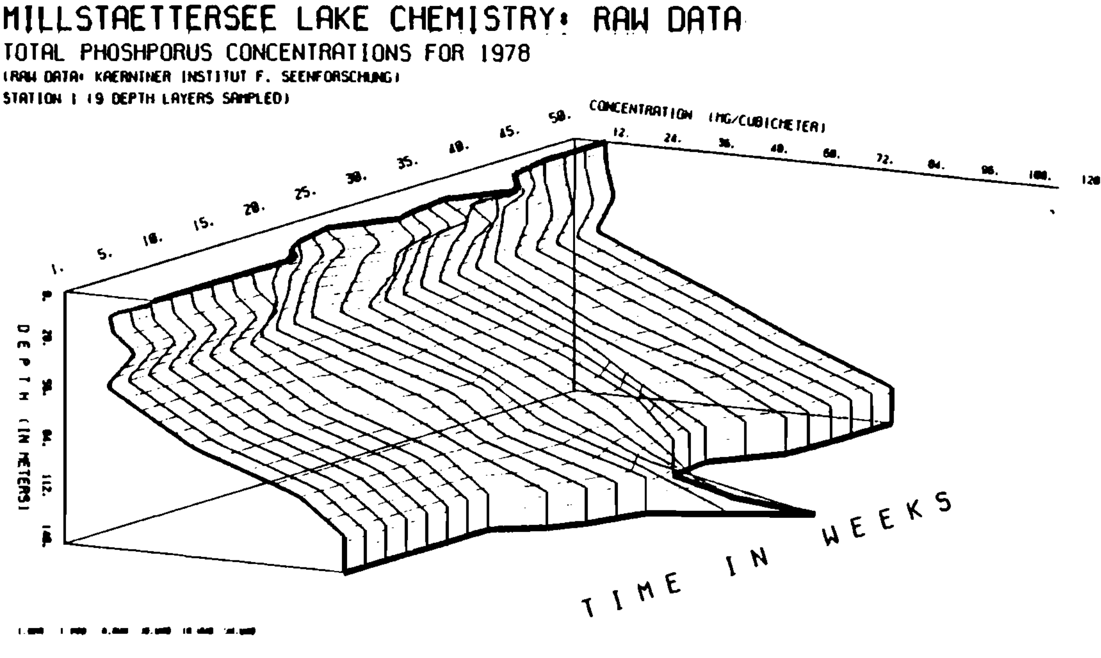


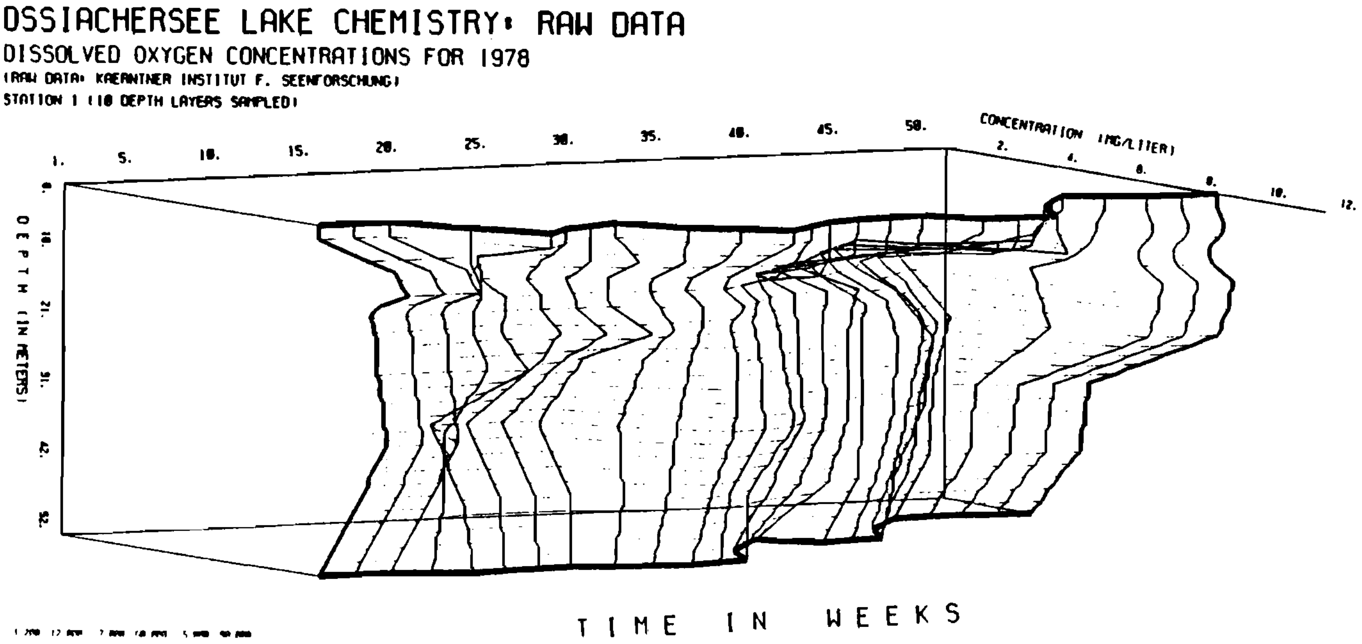
Figure 27: Oxygen and total phosphorus concentrations in the Millstättersee for the year 1978. Note the proportions of mixolimnion and monimolimnion.

The Ossiachersee

The development of the Ossiachersee in the last decades was essentially the same as for the other lakes discussed above: increasing domestic wastewater increasing number of visitors, and the more intensive use of mineral fertilizer in agriculture led to a rapid and severe eutrophication of the lake. Algae blooms and the formation of objectionable algae scums resulted, endangering tourism. Similar to the other lakes in Carinthia, the Ossiachersee is under more or less continuous observation since 1931. Again, this lake was studied in the International Biological Program, and is currently studied within the aforementioned OEP, the Austrian Lake Eutrophication Program.

In contrast to the above discussed lakes Wörthersee and Millstättersee, the Ossiachersee mixes completely, twice a year. The basic patterns of nutrients and oxygen in time and depth (Figure 28) are therefore quite similar to the Mondsee (compare p. nn), which is of comparable size and subject to the same holomictic regime.

As a result of the obvious water quality deterioration, observable since about 1965, a sewage diversion system around the lake, and a treatment plant for the major settlement in the catchment, which diverts its effluents out of the catchment, were built (e.g. Thomaser, 1977). Starting in 1970, constructions were underway during the most conspicuous algae development in the years 1972, and 1974/75. The algae dynamics (see Schulz and Schulz, 1977), however, are seemingly very much dependent on the climatic situation. Important controlling factors are the amount and duration of ice cover in the winter, the resulting circulation patterns, and finally stormrunoff in the spring (introducing large amounts of solids, which cause precipitation of nutrients). The obvious improvement of the year 1976 is largely due to such a high stormwater runoff in 1975 (Schulz and Schulz, 1977). An evaluation of the results of sanitation measures must consequently consider the role of natural variability, which potentially obscures any supposed trends. This is also reflected in the oxygen regime of the lake, although a certain trend of improvement since 1976 is obvious (Figure 29).



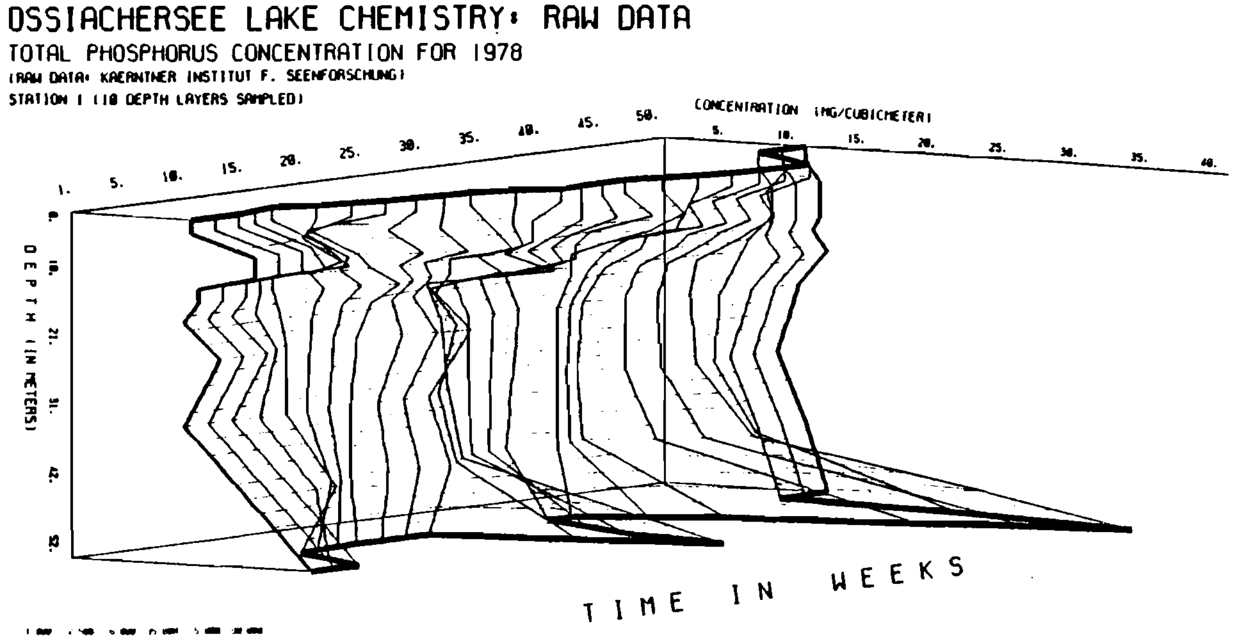
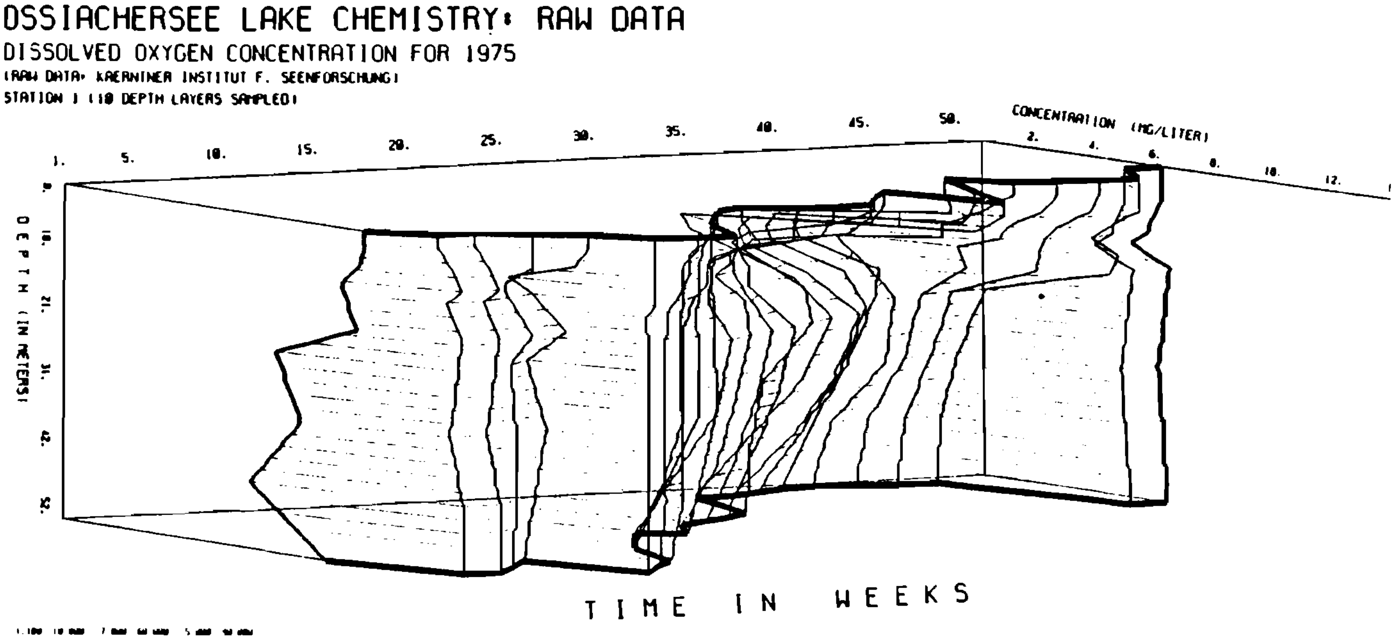


Figure 28: Oxygen and total phosphorus concentrations for the Ossiachersee for the year 1978. Note the similarity of the patterns with the situation of the Mondsee (Figures 17,18).



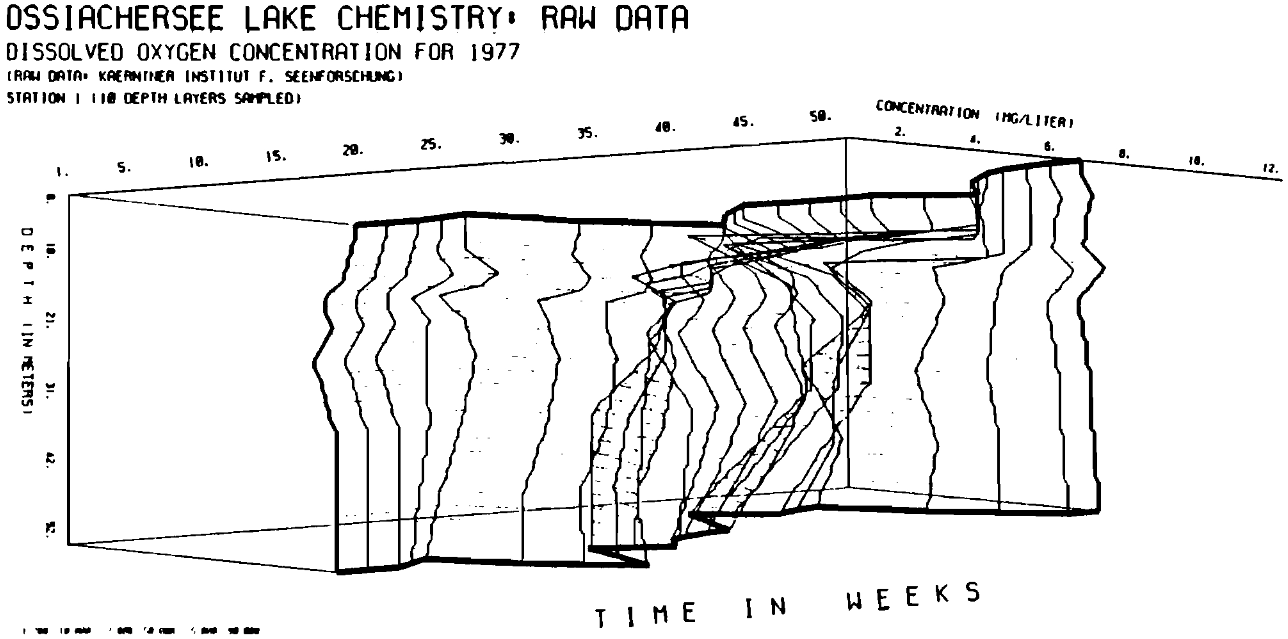


Figure 29: Oxygen distribution for the Ossiachersee, contrasting the year 1975 with the obviously improved situation of the year 1977.

Achievements, Problems, and Outlook

The basic goal in the study of the Carinthian lake system is to simulate the longterm behavior of these lake systems under considerable changes of their nutrient loading. Emphasis was therefore on the establishment of the appropriate data base. According to the lakes structure, the same data management system as developed for the lakes of the Salzkmmergut, could be used. Also, the basic simulation model is derived from a generalization of the stratified lake nutrient- and oxygen model used for the Salzkammergut study. The model has to be modified with respect to the difference in the mixing regime. In a first rough approximation, a forced vertical profile of eddy diffusivity will be used for the description of the meromictic regime; this vertical profile is calibrated, using the available depth profile of the chemical parameters. The description of algae growth and decay will have to be more detailed to simulate the observed rapid formation of blooms. Also, in order to include the effects of stormwater with high turbidity, precipitation of nutrients will have to be built into the model. Similar to the nutrients, algae and primary productivity show a complex vertical structure as well (Schulz and Schulz, 1977). The simulation of these patterns will require the inclusion of biological detail like adaptation in process descriptions and model structures, to represent the changing composition of algae communities functional response, without introducing numerous additional state variables or compartments into the simulation models.

Emphasis will be on the in-lake processes, namely the biological processes and the complex physical regime of the lakes. As opposed to the approach in the Salzkammergutstudy, the nutrient loadings will be considered as known forcings. Together with the available weather records, they will be used for longterm simulations of lake response of more than 10 years. Also, the relation of the state variables to factors relevant in environmental perception, such as visibility and scum formation, will be attempted.

One rather principal problem, which can very well be studied using the example of the Carinthian lakes, is the relative role of man-made changes (nutrient increases as well as the later sanitation measures) versus natural variability in the driving conditions. High variability in the yearly patterns of radiation, temperature, and precipitation affects the behavior of the lake systems to a considerable degree. This obscures any underlying trends due to human impacts. Together with the relatively high data uncertainty in the observation of large and complex environmental systems, this phenomenon makes it difficult to identify any quality deterioration in time, but alo to demonstrate the improvements due to sanitation measures. Obviously, rather long observation times would be needed for a reliable diagnostic. Considering the lead time of any potential management action, and the considerable inertia forces of large systems, these time spans are generally not available. Also, as some damages might well be more or less irreversible, planning ahead on the basis of insufficient and uncertain information seems to be the only alternative to a purely reactive, but belated strategy.

An analysis of these relationships, where the basic elements are natural variability versus man-made trends in the controlling forces affecting an environmental system, and time lagged systems response to changes versus project lead times, seems to be of more general interest for environmental management and planning.

SOME MORE LAKE SYSTEMS

In addition to the lake systems above, one example of a more untypical body of surface waters is also studied within the frame of the Austrian Lake Ecosystems Case Study. In cooperation with a UNESCO Project, carried out on behalf of the City of Vienna by the Experimental- and Research Institute of the City of Vienna (Versuchs- und Forschungsanstalt der Stadt Wien, MA 39), a surfacewater system in the "Untere Lobau" in Vienna, is studied. These water body as situated on the Northern bank of the river Danube, in the easternmost part of Vienna (Figure 30).

The waterbodies of the Untere Lobau are formed by a series of connected old branches of the river Danube, disconnected from the main river, without point sources of nutrients, but a strong apparent coupling to the (ground) water system of the Danube. This coupling is most obvious during occasional flooding, when water from the main stream enters the systems from its downstream end. Average depth of the old riverarms is 1.5 meters, with a potential maximum of 6 m. The total area of the three connected arms considered is 3.2 ha, corresponding to roughly 50,000 m^3 of water under average water level conditions.

The area is situated in the approximately 2000 ha of Nature Reserve of the Lobau in Vienna. At the same time groundwater resources for potable water supply for the City of Vienna are extracted from several wells in the area. Agricultural landuse, concentrated in the north of the old river arms, and recreational use, including sport fishing, are the dominant forms of landuse.

These shallow old river arms with considerable fluctuations in their water levels pose an interesting example of surface water quality problems in a rather complex, specific setting.

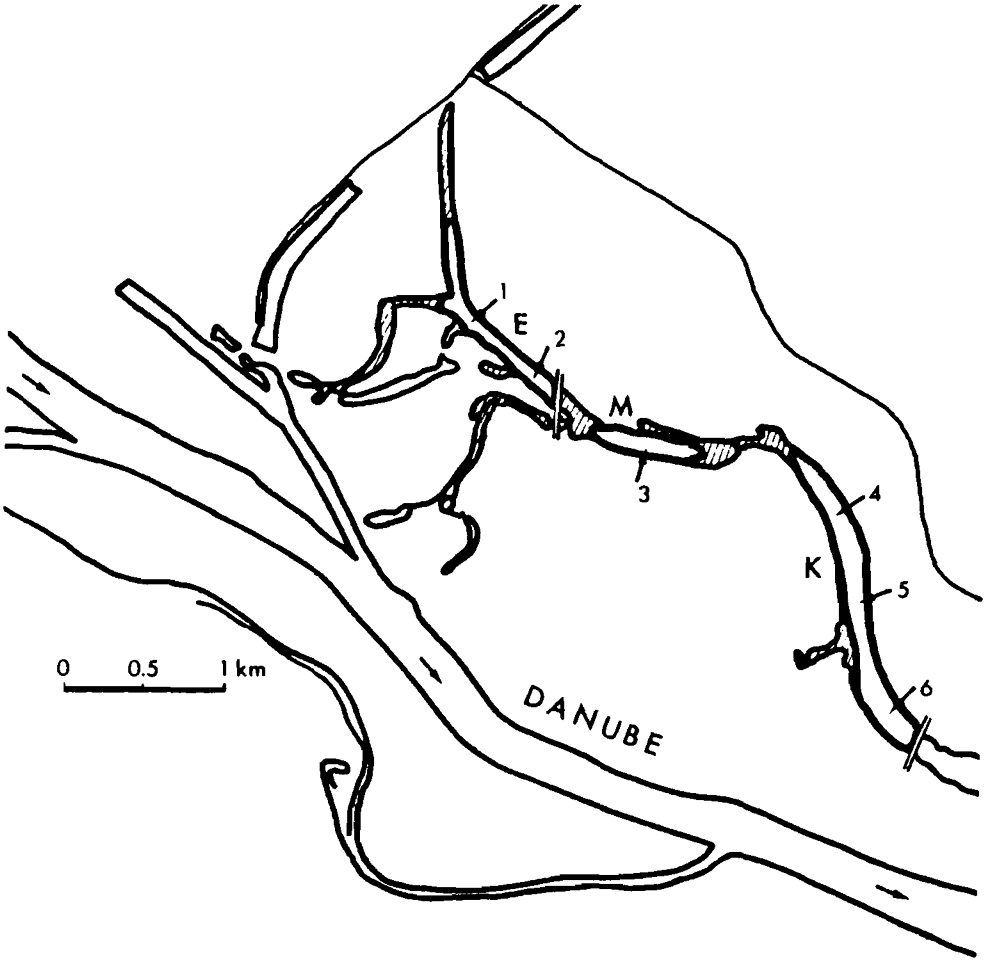


Figure 30: The surfacewater systems of the Untere Lobau. From left to right: Eberschüttwasser (0.6 ha); Mittelwasser (0.4 ha); and Kühwörtherwasser (2.2 ha). Dots mark sampling stations 1 to 6. Shaded areas indicate reed communities.

Under normal water level conditions, the three water bodies are subject to a low throughflow from west to east, paralleling the flow direction of the Danube. They are separated by shallows, which are covered with reed communities. The soft mud bottom of the three trenches is, in its shallow and intermediate depth, covered with dense macrophyte communities.

The analysis of this system aims at an understanding of their nutrient budget and dynamics (Figure 31), and the influence of the hydrographic regime on the water quality of the system. Dramatic changes in the water level trough natural or man-induced flooding of the system will certainly affect its overall balances. Changes in waterlevel, and the introduction of low-quality water from the Danube might well lead to anoxic layers under stagnant conditions. The model built for these shallow waterbody includes therefore a detailed description of the oxygen cycle and the sediment water interactions. Macrophyte dynamics, and nutrient accumulation in the sediments are important features in the description of this system.

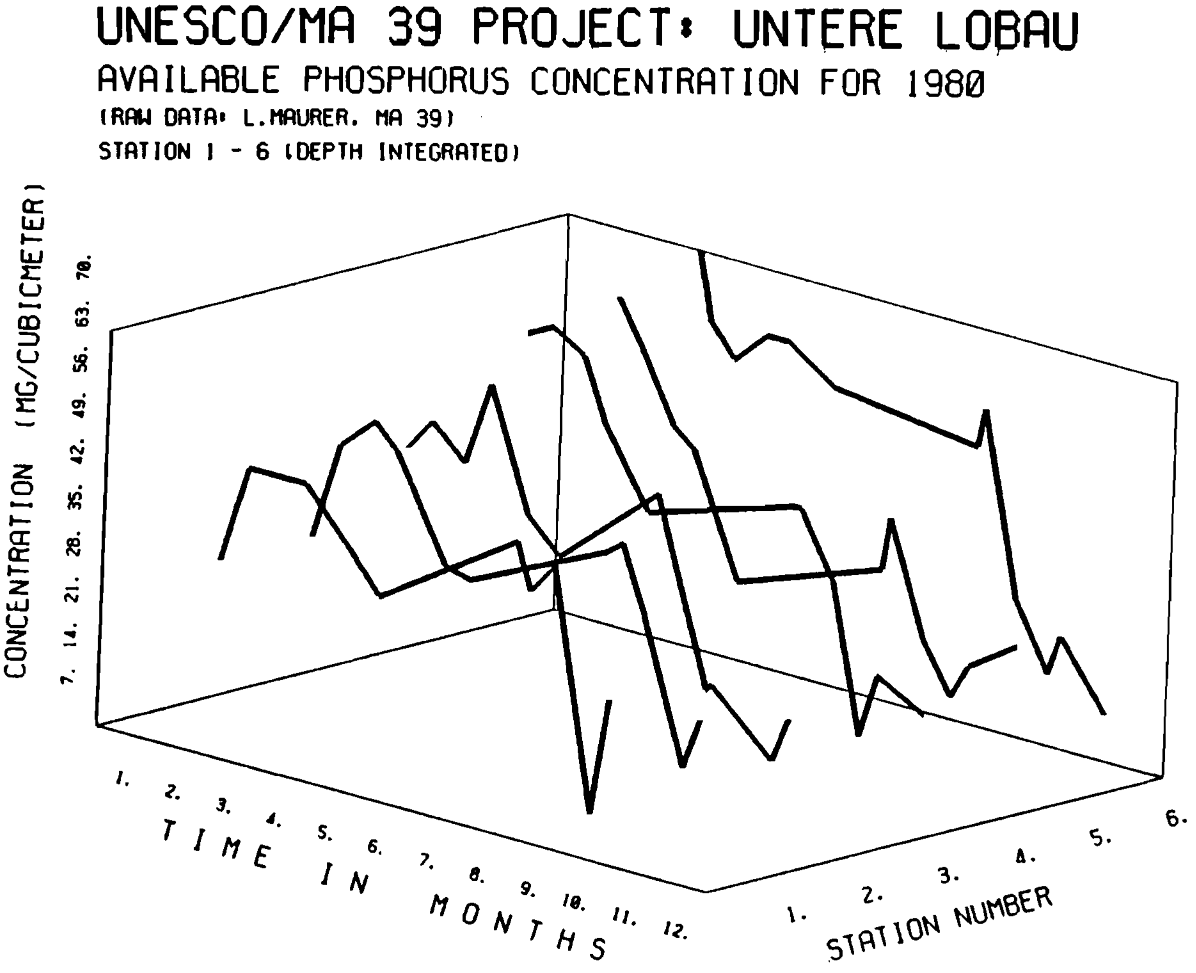


Figure 31: Nutrient dynamics of the Untere Lobau system for 1980. Phosphate P-PO$_4$ for the six stations shown in Figure 30. Note the high variability between sampling stations.

To complement the above set of case studies, some examples of successful restoration (as opposed to sanitation) are provided by a number of smaller lakes in Tyrol (e.g. Pechlaner 1978). They are examples for hypolimnic discharge of water with high nutrient concentrations and low oxygen concentrations. Discharging hypolimnic water from stratified lakes to improve their trophic state was used as an additional management option after diverting major sources of nutrients. These lakes and their limnological development after nutrient diversion and hypolimnic discharge could serve as ideal test cases for the models developed for the stratified lakes described above. For these lakes the interaction between the productive upper layer and the nutrient richer hypolimnion are important elements of their functioning. A model capable of describing the behavior of these lakes should therefore also be able to simulate the response of a lake to the discharge of nutrient rich bottom water. This discharge of bottom water, which not only is characterized by low oxygen concentrations but also by low temperature, will also affect the heat budget of a lake. This will consequently lead to changes in vertical stratification and the mixing processes, which again influence the internal nutrient cycle and ambient water quality.

Although the examples listed above are only a minute subset out of the 9,000 lakes in Austria, they cover a wide range of lake types and eutrophication problems. Based on these case studies, it should be possible to generalize some of the approaches and solutions, and to develop a sufficiently general and flexible set of tools for the quantitative analysis of lake ecosystems.

METHODOLOGICAL RESEARCH

To study the problems discussed above, a certain set of tools, techniques, and methods has to be used. Many of these tools are standard methods of what is rather pragmatically labeled "applied systems analysis". Environmental systems however, and in particular their ecological components, pose specific problems. They are peculiar in many aspects of their structure and behavior. Compared to physics or chemistry, or more applied fields like the engineering sciences, ecology has a rather weak theoretical background as a formal science. Quantitative numerical methods are not always directly applicable to living systems, since they have been developed for qualitatively different systems. Quantitative methods, and numerical models in particular, are in need of a critical re-evaluation when their application to environmental systems is attempted. As a contribution to this critical re-evaluation of methods, and in an attempt to develop and modify a set of more appropriate tools for the study of environmental systems, three major topics for methodological developments were chosen. They are mutually related to a considerable degree, and the research on these topics is always intimately linked with the above described study of the environmental issues of the selected lake systems. Since the methodological developments should improve the usefulness and practical applicability of a quantitative approach to environmental problems, this coupling is most necessary.

The three major topics for methodological research are the following:

-the inclusion of systems properties and control mechanisms of high hierarchical level such as adaptation and selforganization in process descriptions and model structure, to improve the predictive power of ecological models, which form the core of environmental models;

-the development of concepts and methods for the quantification of model uncertainty and prediction accuracy, related to data availability and quality, and systems variability. This leads to the development of techniques for the use of fuzzy data sets and the probabilistic interpretation of model simulations, with special emphasis on the role of model application in environmental management;

-the development of rational methods for model simplification, and the linking of model systems of a wide range of complexity and resolution, again in an attempt to make models practical and useful tools for the analysis of large, complex environmental system.

ECOLOGICAL COMPLEXITY

Adaptation and Self-Organization

Ecological systems -- which form the core of the more comprehensive class of environmental systems -- are characterized by a large number of component elements and interrelations, by richness and variety. This complexity and diversity poses principle problems in a deterministic mathematical representation of such ecological system. On the other hand, ecological systems are also characterized by numerous self-organizing and stabilizing mechanisms, which allow their persistence in a rather hostile -- from a thermodynamic point of view -- physical environment. These self-organizing capabilities are reflected in an often simple and easy to predict input response behavior of ecological systems, at least within a specific range of input fluctuations.

Mathematical models of ecological systems are mainly descriptive and basically empirical -- especially when they are designed for practical application in the analysis, control, and management of the environment. Although there has been a rapidly progressing development in the field of mathematical modeling, the outcome of most ecosystems models is rarely satisfying. It is either trivial or quite unrealistic compared to real-world observations. Considering the structure of mathematical representations of biological processes within the frame of ecosystems models, we have to admit that these representations are mainly extrapolations of basic physical, chemical, and physiological processes. They are applied, however, to compartments which include a large variety of functionally dissimilar components. Without doubt we need more realistic descriptions of the processes determining the behavior of the compartments in ecosystems models if we want to obtain reliable predictions. This is particularly important when considering drastic changes in the input conditions.

The traditional approach to any refinement of mathematical models would be an increase in the level of detail; more variables, more parameters, splitting up compartments into their component elements. However, such a reductionistic approach is not only illusive from the technical point of view -- considering data requirements and computer capacities -- but also has to be questioned from a conceptual point of view. Describing and modeling ecological systems by using as many elements as possible is the same as describing the state of a volume of gas by attempting to solve Newton's equations for all the component molecules. Not only would one have to know the initial state of all the component molecules, but it is also necessary to consider whether the information obtainable, at least in theory, is what we really want to know about the system. Generally we are looking for relevant macro-properties such as the temperature in the gas example. However, ecological systems are much more complex than an ideal gas, and a basic lesson from systems science tells us that the systems behavior is not simply the sum of the behaviors of the component elements. This requires the identification of appropriate holistic features of ecological systems for description and modeling. Such features can often be found when looking at ecological systems within a more comprehensive environmental, and finally socio-economic framework. Criteria for environmental quaility perception may well be appropriate candidates for relevant holistic features in a praxis oriented approach.

It is ill-conceived to attempt a description of a diverse community or trophic level -- the standard biological compartment in an ecosystem model -- in terms of the chemical or physiological properties of a single organism, using the respective time invariant parameters. Standard parameters used in ecological models such as maximum growth rates or uptake rates, half saturation constants or other rate constants for biological processes have, in fact, to be considered as time varying, related to various state and input variables of a system.

One of the basic mechanisms in the change of a compartments properties is the mechanism of adaptation of biotic compartments or systems to input variations. Within a certain range of input or state changes, adaptation will result in the stabilization and persistence of certain features of the compartment or the system as a whole. And one of the basic strategies of adaptational response to input changes can be found in a strategy of environmental tracking. In other words, this represents the continuous adjustment of certain properties according to the pattern of environmental changes in space and time.

To give a definition, the term adaptation can be used to subsum any deviation counteracting mechanisms, which allow any biotic system to damp its output or stabilize a given property under a certain range of input fluctuations. Adaptation in thus the major mechanism of persistence in a variable and uncertain environment. However, with regard to the adaptational mechanisms involved, a distinct relation to the predictability or the probability of certain input changes (environmental uncertainty) and the energetics of the response mechanism can be noted. Returning to the above definition of adaptation, it might be convenient to consider two major aspects, namely a physiological and an ecological one. Although it can be shown that both aspects can be described and modeled in the same terms, with the same underlying rules, a distinction might be necessary to avoid the criticism of a "super-organism" concept for ecosystems. The basic difference in ecosystems is the lack of heredity; of course there is something like the accumulation of information in terms of structure in at least some ecosystems. This, however, can only roughly be compared to genetic information transmission.

Physiological adaptation can be used to describe input dependent changes in the physiology of an organism -- if it fulfills the requirements of the above definition -- which basically involves biochemical and behavioral mechanisms. Ecological adaptation is used to designate corresponding responses on the community or ecosystems level, basically involving species and organisms interactions. Of course both mechanisms, physiological as well as ecological, will inseparably contribute in an ecosystems behavior.

The effect of community adaptation is reflected, for example in the varying composition of the spring, summer, and winter-plankton in most temperate aquatic ecosystems. Another example might be species succession under conditions of increasing eutrophication, or the transition from phosphorus to nitrogen limitation for primary production. All these examples are relevant for the lake systems described above. In all examples, competitive species interactions play a dominant role. The problem of model representation can be handled in two ways. The mechanistic approach would be to treat at least the major component species separately, so that changes in the community structure can be explicitly represented. However, a sufficient amount of physiological information must be available on all of the component species, which is rarely the case in most situations. The alternative would be to allow for adaptational adjustment of the parameter values describing the total community. These parameters have to be made time-variable, and related to the course and pattern of determining state and input variables with a certain time lag.

Community adaptation simultaneously reacts to all relevant environmental properties such as light, temperature, nutrients, etc.. This simultaneous influence of numerous variables together with the stochastic variability of these variables are important conditions for the maintenance of diversity in natural communities. From the modeling point of view, the problem lies in the determination of parameters and the description of their dependencies. One possible way is to empirically relate them to certain environmental variables on the basis of statistical data analysis (Straskraba, 1976).

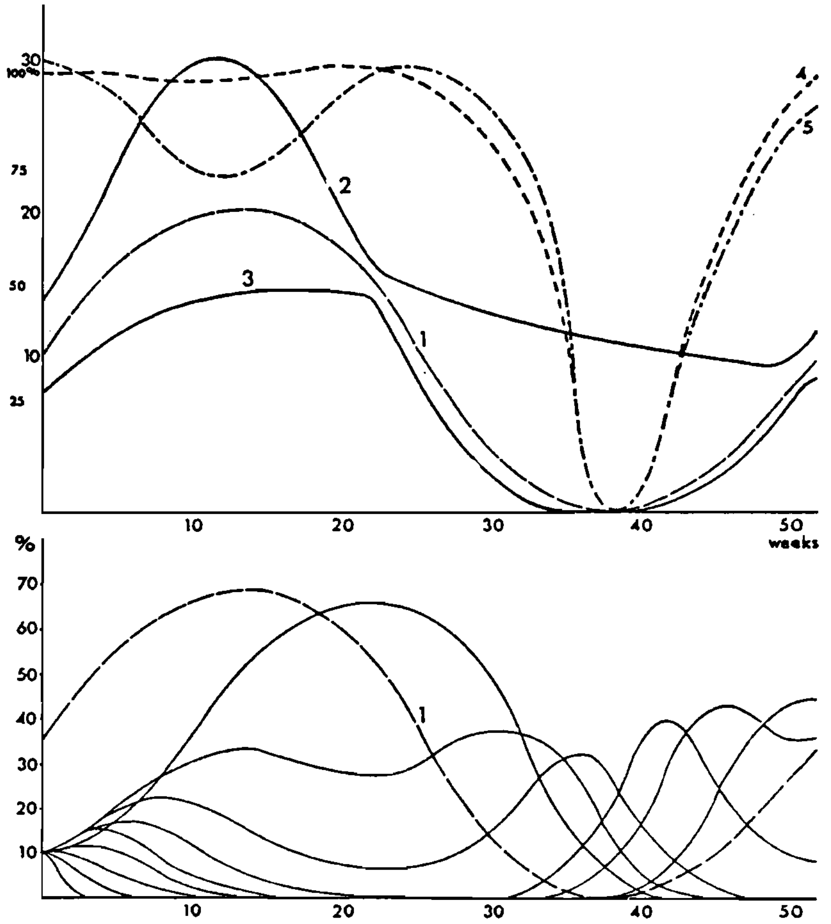


Figure 32: Community adaptation model output (from Fedra, 1979). Curve 1: light input, arbitrary units; Curves 2 and 3: upper (light limited) and lower (light inhibited) value of community light optimum, arbitrary units. Curves 4 and 5: Community productivity (percent of maximum value) for the adapting community(4) versus a constant value (corresponding to the yearly light average). Lower graph: component species percentages.

An alternative approach, based on a posteriory model aggregation, was used to study the above relations (Fedra 1979). A traditional representation of the photosynthesis light response in a hypothetical phytoplankton community was used for first test. It is planned, however, to incorporate an operational adaptation module in the lake models described above. This would be especially valuable in the case of Lake Neusiedl, where the algae communities are subject to extreme fluctuations in the driving conditions.

In the example shown in Figure 32, a ten species algae community, where the component species differ only in their light optimum, is simulated under a simple light pattern. This light pattern was also complicated by superimposing random fluctuations. As a result from numerous runs, the community light optimum as determined from the integration of the component species was found to be time-variable, tracking the light input with a certain time lag of several days. Time lag and accuracy of tracking were depending on the arbitrary initial conditions. With a constant value for the community light optimum, productivity can be underestimated for up to 20%. With this extremely simple model, it was possible to successfully demonstrate the functioning of environmental tracking based on a simple mechanistic explanation.

A second attempt to study community adaptation and self-organization was based on the work of Radtke and Straskraba (1978). Using their model for Szlapy reservoir (Checoslovakia), the above approach of a posteriori model aggregation was used. In this study, which was largely performed by Rodriguez (1980), a multi-sizeclass phytoplankton community with size dependent rate constants of the biological processes was simulated. Using a Monte Carlo method, a parameter set which would allow the model to meet certain constraint conditions of its behavior was sought. A preliminary report on this work is given in Rodriguez, 1980.

ISSUES OF UNCERTAINTY

Hypothesis Testing

Ecosystems are diverse, complex (e.g.Pielou 1975), mostly large-scale systems. They are characterized by a rich behavioral repertoire, are variable in time and highly structured in space (e.g Steele 1978), they are driven by (generally unpredictable) fluctuating external conditions, and exhibit complex feed-back and control mechanisms (e.g. Conrad 1976, Straskraba 1979) such as adaptation and self-organization. Most functional relationships in such systems are non-linear and time-variable, and even the boundaries of the system have to be defined quite arbitrarily in many cases. Summarizing, ecosystems seem to be the least desirable objects for deterministic mathematical modeling.

All the above features are well reflected in the theoretical background of systems ecology. There is no well established, unifying theory in systems ecology. At best, one can find a mosaic of unrelated concepts and approaches (e.g. Halfon 1978). Quite often, ecological theories (or rather hypotheses) are contradictory. The processes governing ecological systems are generally poorly understood, especially on a high "systems level" of organization or rather abstraction -- the level used in systems modeling. This is at least in part due to the fact that much of the available information stems from micro-scale laboratory experimentation. Usually, in such physiologically oriented experiments, all but one (or a few) variables are kept constant, and the response of the system (usually an individual organism or a mono-culture) to changes in one external condition is observed. Such experiments are difficult to interpret on the "ecosystems level", where nothing is constant, everything affects (almost) everything else, and the "unit" of concern is a functionally heterogeneous, diverse, adapting, multi-species, multi-age and size-class, more or less arbitrarily lumped aggregate. Generally, the empirical basis or the data available are singular measurements, so that their reliability in terms of the spatial or functional macro-level used in the model cannot be estimated. Consequently, ruling out or rejecting any hypothesis put forward is rather difficult, and in fact, examples of more than one contradictory hypothetical construct, "possible" in terms of the data to be described, are known (Bierman et al 1979, Nihoul 1978). However, as the a priori knowledge about a system is essential for model building, the lack of reliable and unambiguous knowledge adds considerable uncertainty to the problem.

All the above features are -- again -- reflected in the data available on environmental systems. Not only do spatial and temporal variability make data collection under logistic constraints an art rather than a scientific method, but in many cases, it is simply impossible to sample or measure what is described (conceptualized) in a model. Most state variables used in model descriptions are more easily represented in a flow diagram than measured, as the level of abstraction in the model representation is completely inaccessible for direct measurement. Consequently, ecological data are scarce, scattered, sampling error-corrupted, and usually do exist on the "wrong" variables in light of the objective of any numerical analysis. Monitoring programs, as a rule designed independent of subsequent evaluation and analysis, traditionally tend to concentrate on what other monitoring programs have included. And as only the theory can tell the observer or experimenter what to measure (an only seemingly trivial truth ascribed to A.Einstein), the "wrong" variables are measured. Also, different variables tend to get measured at different places and at different times. Even the most ambitious, money-consuming attempts at data collection like the IFYGL do not result in the smooth, unambiguous curves one would (probably rather naively) like to find (cf Scavia 1980).

Considering the above constraints, the direct use of the raw data available on any ecosystem seems to be rather difficult for the testing of complex and highly aggregated dynamic hypotheses. Consequently, we have to derive from the available data a description of the system and the processes we want to study at an appropriate level of abstraction and aggregation. This description, which already has to be formulated in the terms of the hypothesis to be tested, should take advantage of all the available information, and at the same time provide an estimate of the reliability of this information on the required level of abstraction.

The very high number of interactions between the numerous elements of ecological systems requires conceptual simplifications, aggregation, and abstraction of the systems under study, to make the theories one can formulate about the structural properties and the function of a system traceable.

Universal statements, describing those properties of a system which are invariant in space and time, may be called models, whether they are of an informal verbal or mental, or a formalized mathematical structure. Such models, viewed as scientific theories, have to be testable, that is to say, when one puts a set of specific singular statements (the initial conditions, which, in the case of a mathematical model also include the model parameters in a general sense, cf. Fedra et al.1980, Fedra, in press a) into the model, it must be possible to deduce or predict testable singular statements (observations or experimental results). Disagreement between the prediction deduced from the hypothesis or model and the available observations would then require to reject the given hypothesis, to modify and improve it, or to look for alternative hypotheses, to be subjected to the same procedure. This method, which would basically represent the strategy of scientific research proposed by Popper (e.g. 1959), however, has a major drawback when applied to complex simulation models or dynamic hypotheses describing ecological systems, in that the socalled initial conditions to be used with the basic structure of the theory to deduce the testable predictions, are not exactly known. This certainly could be seen as the results of two basic shortcomings, one in the measurement techniques available, another one in the formulation of the models themselves: if the models require unknowns as inputs, they are not well formulated. The latter is certainly a generic shortcoming of ecological models, or ecological theory in general.

The same line of argument can be followed with regard to the observations used for model-output comparison in hypothesis testing. The degree of abstraction and aggregation is quite different in the measurements and in the model conceptualization, so that the measurements can only serve as samples of the properties of the units conceptualized. As these units are generally heterogeneous (in terms of their measurable properties), and are generally characterized by a high degree of variability, that is to say, that the repeatable part of observations is only a certain range, further uncertainty has to be dealt with in the hypothesis testing procedure. For a more detailed discussion of issues of uncertainty in ecosystems modeling see Fedra et al.1980 and Fedra, in press a,b.

But whatever the objective for a formal approach to the analysis of a complex, dynamic environmental system may be, the testability of the models involved is an essential criterion to make them a useful scientific tool.

As an illustration to these principles, a series of hypotheses on the structural relations and the dynamic function of a generalized pelagic aquatic food web was formulated in terms of numerical models (Figure 33). Hypotheses of various degrees of aggregation and abstraction were tested by comparing singular statements (predictions) deduced from the proposed hypotheses (the models) with the observations. For the comparative testing of these alternative hypotheses (or models, in more familiar terminology) a data set from the German Bight, Southern Sea, was used (Fedra, in press). The model, however, are general aquatic ecosystems model, which basically could be used for freshwater ecosystems as well.

The basic processes of primary production, consumption, and remineralization, driven by light, temperature, and advection-diffusion, are described in systems models ranging in complexity from two compartments to many compartments and species groups. With each of the proposed models, a yearly cycle of the systems behavior is simulated. The comparative analysis of the response of each of the models allows conclusions to be drawn on the adequacy of the alternative hypotheses. This analysis also allows one to reject inadequate constructs, and provides some guidance on how to improve a certain hypothesis, even in the presence of a high degree of uncertainty.

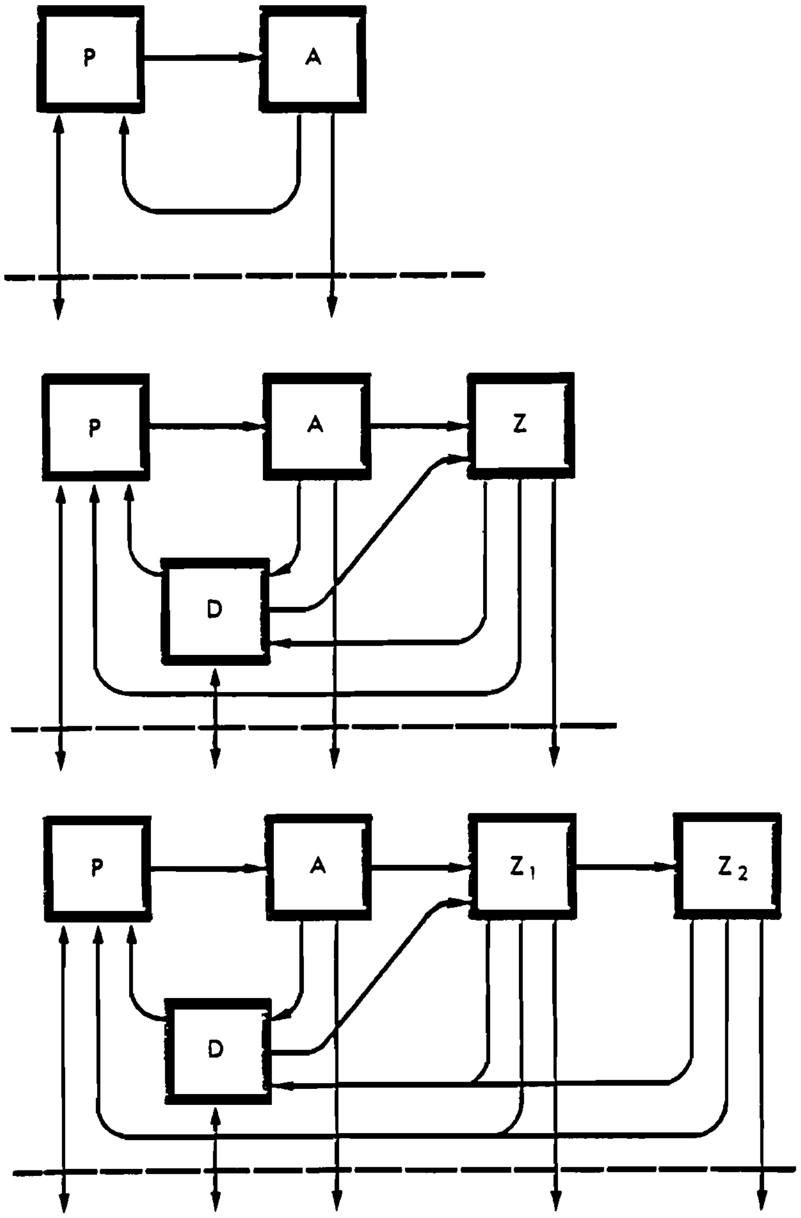


Figure 33: Alternative model structures of increasing complexity for the description of a pelagic aquatic food web (from Fedra, in press). The compartments are: primary producers, algae (A), nutrients, phosphorus (P), organic detritus (D), herbivore zooplankton (Z_1), carnivorous zooplankton (Z_2).

To summarize the experiences from the comparative investigation of such a family of models, applied to one and the same set of data, it was most striking that none of the versions could fulfill all the behavior constraint conditions formulated. Each of the models was able of reproducing certain subsets of the required behavior (Figure 34). Although the number of trials may not have been sufficient, the introduction of a rigid quantitative errors criterion as opposed to a qualitative concept of a gradual "goodness of fit" resulted in the rejection of all the comparatively simple model versions. As has been demonstrated, subsets of the required behavior could easily be reproduced. This however, goes parallel with unrealistic behavior in other parts of the system. A complex hypothesis or model, however, can only be accepted as a valuable working tool with explanatory value and predictive capabilities, if it fulfills all the constraints one formulates as defining the observed systems behavior. Violation of one single condition necessitates the rejection of such a model, which should be just one step in an iterative process of analysis.

One basic idea of the approach is to use the available information according to its relevance on the models' (this is the theory's) level of abstraction. Obviously, the description of the states of a system can be done much more easily on the appropriate level than the description of process rates and controls (just think in terms of phytoplankton biomass versus production rate). Consequently, we turn the argument of the hypothesis testing process around: instead of putting the "known" initial conditions (the rates, among others) into the model structure and deriving the response for comparison, we use the allowable response as a constraint to identify possible initial conditions. This is to say, we map a given region in the response-hyperspace of a model back into the input-hyperspace.

The test is then as follows: whether or not this region in the input space exists within the specified possible or plausible bounds. In addition, several other features of the inputspace can be used as a basis for either rejecting or corroborating a given hypothesis, for example, the uniqueness of the inputspace region, whether it is closed or not, and its structure, which is determined by the interdependencies of the individual input values. In addition, all these features, including the relationship or correlation of input- and outputspace, allow us to learn something on the way the proposed systems' structure functions. The method facilitates an understanding of the systems behavior on the appropriate level of abstraction, which is the input and output of the model, and it also provides diagnostic information for hypothesis generation.

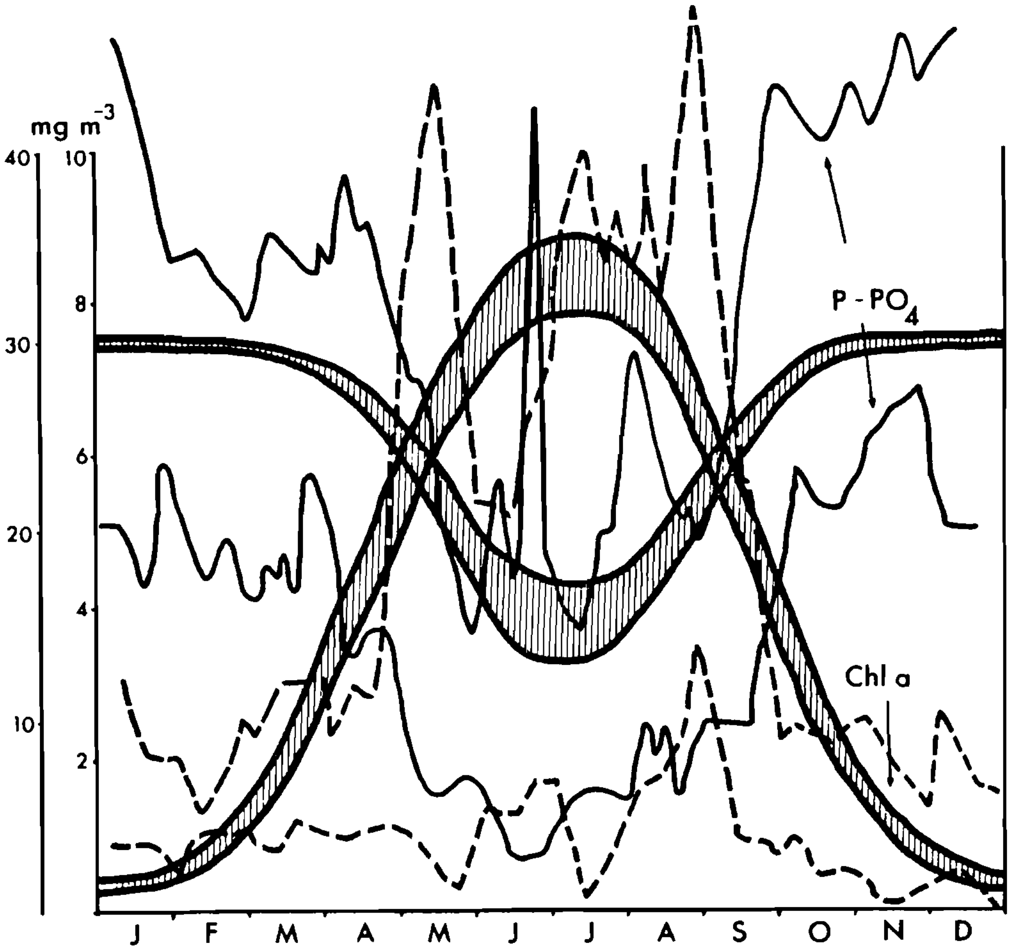


Figure 34: Model output from model version 1 (compare Figure 33). Envelope over 31 runs (for the state variables "algae" and "nutrients"), contrasted with the envelopes over the field data set used. The runs shown fulfill all behavior requirements but the condition of two peaks of algae biomass during the productive season.

And above all, the approach emphasizes testability. Any rigorous scientific approach to the study and analysis of complex, hard to handle systems which are no longer easily understandable and traceable, requires that all the individual elements of the systems' conceptualization, all the assumptions that are necessary, are made explicit - and thus testable.

Parameter Uncertainty and Prediction Accuracy

The following discussion on the relationship between estimation and prediction under uncertainty summarizes a series of papers (Fedra 1979, Fedra 1980, Fedra et al.1980, Fedra, in press) which all address various aspects of modeling uncertainty.

Forecasting the water quality of a given aquatic ecosystem by means of a mathematical simulation model is subject to various sources of uncertainty. The ecosystem to be modelled is generally a diverse, large-scale system, with a rich behavioral repertoire, a considerable degree of variability in the driving environmental factors and in its structure, and with complex feed-back and internal control mechanisms. The understanding of the governing processes in such systems on the level of abstraction, aggregation, and simplification, characteristic of formal models, is poor, and a unifying ecological theory is lacking. The data available about environmental systems are usually scarce, scattered and typically connected with a considerable level of measurement and sampling errors (Figure 35). Finally, models of ecosystems are by necessity gross simplifications and require numerous arbitrary assumptions in their construction. Estimating model structure and parameters under the above constraints is therefore subject to uncertainty, and this uncertainty should also be reflected in model based predictions.

Using a concept of allowable ranges to constrain the model response in the estimation procedure, uncertainty is explicitly accounted for. This results in an ensemble of parameter sets, characterized by a certain variability and correlation structure. Forecasting by means of such an ensemble allows for an interpretation of the model response-ensembles generated in terms of probabilities, and reflects the initial uncertainty in the information available for the modeling exercise.

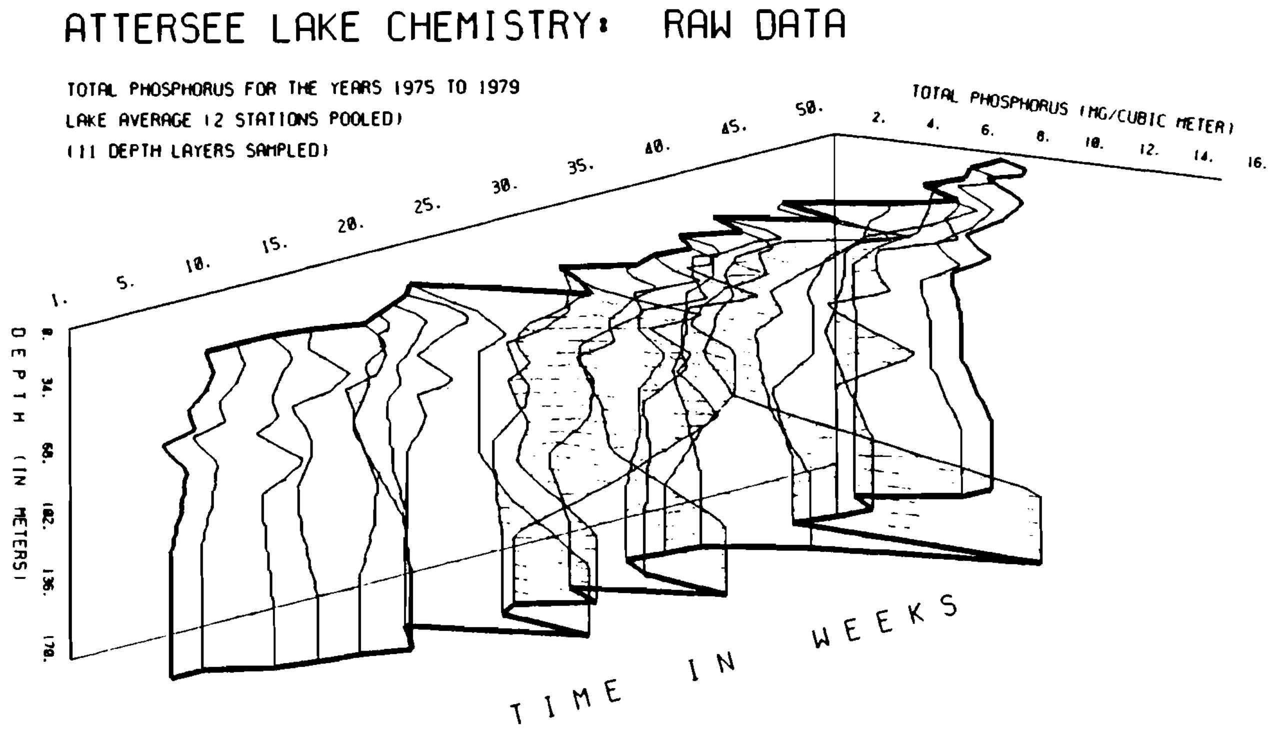


Figure 35: Total phosphorus in the Attersee, average yearly pattern of the depth distribution. Since total phosphorus is essentially conservative in the hypolimnion of such a large lake, the observed data variability represents sampling errors due to patchiness (Raw data: F.Neuhuber).

Mathematical models of ecosystems are considerable simplifications of reality, and the data upon which they are based are usually scarce and uncertain. Calibration of large, complex models depends upon arbitrary assumptions and choices, and frequently calibration procedures do not deal adequately with the uncertainty in the data describing the system under study. Since much of the uncertainty and arbitrariness in ecological modeling is inevitable, because of both practical as well as theoretical limitations, model-based predictions should at least reveal their dependence on, and sensitivity to uncertainty and arbitrary assumptions. The paper proposes a method that explicitly takes into account the uncertainty associated with data for modeling. By reference to a partly qualitative and somewhat vague definition of system behavior in terms of allowable ranges, an ensemble of acceptable parameter vectors for the model may be identified. This contrasts directly with a more conventional approach to model calibration, in which a quantitative (squared-error) criterion is minimized and through which a supposedly "unique" and "best" set of parameters can be derived. The ensemble of parameter vectors is then used for the simulation of a multitude of future systems behavior patterns, so that the uncertainty in the initial data and assumptions is preserved, and the thus predicted future systems response can be interpreted in a probabilistic manner.

Recently, formalized parameter calibration routines have begun to be applied in the field of modeling complex aquatic ecosystems, e.g. Lewis and Nir (1978), Jorgensen et al. (1978), Di Toro and van Straten (1979) and Benson (1979). In these methods a loss function is defined, usually in a squared-error form, and, subsequently, a parameter vector is sought that minimizes this loss function. This procedure thus avoids the analyst's subjective perception of which parameter ought to be adjusted to improve the fit, inherent in the more commonly applied trial-and-error calibration procedure. Also, the equally subjective judgement of agreement between simulation and observation is replaced by a more formal quantitative notion. However, although frequently called "objective function", this does not imply that the criterion chosen is free from subjective elements. For example, in problems with state variables having different physical dimensions some (subjective) form of weighting is required in the formulation of a single-valued loss function. Furthermore, it is not easy to account for uncertainty in the field data, although methods to do this have been attempted (Beck and Young, 1976; Beck, 1979; Lewis and Nir, 1978; Di Toro and van Straten, 1979; Jolankai and Szollosi-Nagy, 1978; Fedra, 1979; Fedra, in press a,b). Finally, however, it has to be recognized that the assumption that a single 'best' parameter vector exists is at least questionable, especially if data uncertainty is considered, and in any case experience shows that this is extremely difficult to find such a unique vector if the number of parameters to be estimated is larger than, say, six to ten.

This discussion proposes a method that explicitly takes into account the uncertainty associated with data for modeling, including initial conditions and forcing functions; the method proposed also circumvents the problem of assuming parameter uniqueness. Basically, instead of assuming the existence of a "best, unique" parameter vector, which may be found found through minimization of a loss function, the method allows a set of vectors to be identified by reference to a more "vague" definition of systems behavior. The uncertainty in the available information is expressed in this "vague" definition through the specification of bounds between which "acceptable" model simulations should fall. Clearly, given these ranges, more than one vector exists that fulfills the requirements of being "acceptable". This part of the work owes much to the recently reported study of Spear and Hornberger(1980), although the emphasis and focus are different.

Once it is recognized that the uncertainty of the field data suggests the specification of bounds on acceptable system behavior, -- and nothing more precise -- it ought also to be recognized that those parameter vectors that are found to give the defined behavior are all equally good in view of the data uncertainty. Any sample parameter-vector that is found to simulate the defined system behavior can -- since it has passed the "test" of "calibration" -- be applied in principle to generate future systems responses under changed conditions (represented by a change in any of the vector elements). Hence a multitude of simulated future system behavior patterns can be generated from the set of acceptable parameter vectors.

The method is illustrated with an application to a specific problem relating to the Attersee model described above (compare Figure 16).

Let us suppose that a given structure for the model is assumed -- this is, we admit, an unavoidable (arbitrary) assumption that will subsequently affect the predictions obtained. Further, let us represent this model by a vector-function f with domain $\mathcal{D}(f)$ and range $\mathcal{R}(f)$. If RD is a subset of $\mathcal{R}$, then the inverse image of RD under f is the subset of $\mathcal{D}(f)$ given by

$$f^{-1}(RD) = \{ x : f(x) \in RD \}$$

which we will call CM (see fig.1). To identify CM -- which in our terminology is the set of all <u>character vectors</u> (for a definition see below) resulting in the defined realistic model response (RD), we proceed as follows.

For the first step in the approach the system behavior is defined in terms of the model to be used by a series of constraint conditions. From the field data typical features of the system's behavior are derived. We consider it significant that the behavior definition, i.e. the constraint conditions, includes both dynamic and aggregate features. The latter, for example yearly primary production, are usually more reliable than individual data at any single instant in time, thus they allow for a definition of the system's behavior in which one intuitively would place more confidence. The set of m ranges of behavior describing measures defines an m-dimensional box in the range-space of the model, or a set RD of plausible, acceptable model responses.

From empirical evidence and from previously quoted values for model coefficients, it is possible to specify ranges of inputs, forcings, initial conditions, and model coefficients required by the particular model structure. A vector of numerical values taken from these ranges fully characterizes the response of the model. In order to make a distinction from the usual term parameter-vector, we shall call any sample combination from these ranges a <u>character vector</u>. The ranges of n character vector elements define a region CD (the set of all allowable character vectors) in the n-dimensional domain space of the model.

Third, this character vector region CD is now randomly sampled N times by a Monte Carlo technique. Each sample character vector CS_i (i=1,...,N) is then used for a simulation run, and the resulting set RS of model responses RS_i(i=1,...,N) is classified according to the behavior definition RD:

behavior:

$$RS' = \{RS_i \mid (RS_i \in RD)\} \qquad n(RS') = M$$

not-behavior:

$$RS'' = \{RS_i \mid (RS_i \notin RD)\} \qquad n(RS'') = N-M$$

The set CS of sample character vectors is separated correspondingly into two complementary subsets CS' and CS'', with M and N-M elements respectively. In other words, by this "calibration" procedure we are looking for a separation of the sample of character vectors into a behavior-giving subset (CS') and a not-behavior-giving subset (CS''). The total sample of M plausible behavior-generating character vectors is then analyzed to give some insight into possible relations and interdependencies or the character space configuration.

The character vectors CS_i' giving rise to a response RS_i' completely within the behavior defining boundaries are considered as random samples from a character space region CM corresponding to the defined behavior region RD of the model:

$$CS' \subset CM$$
$$CM = f^{-1}(RD)$$

as illustrated in Figure 36. It should be noted that CM may not be fully included in CD, so that there are character vectors some of whose elements are outside the specified ranges, that give rise to the defined behavior.

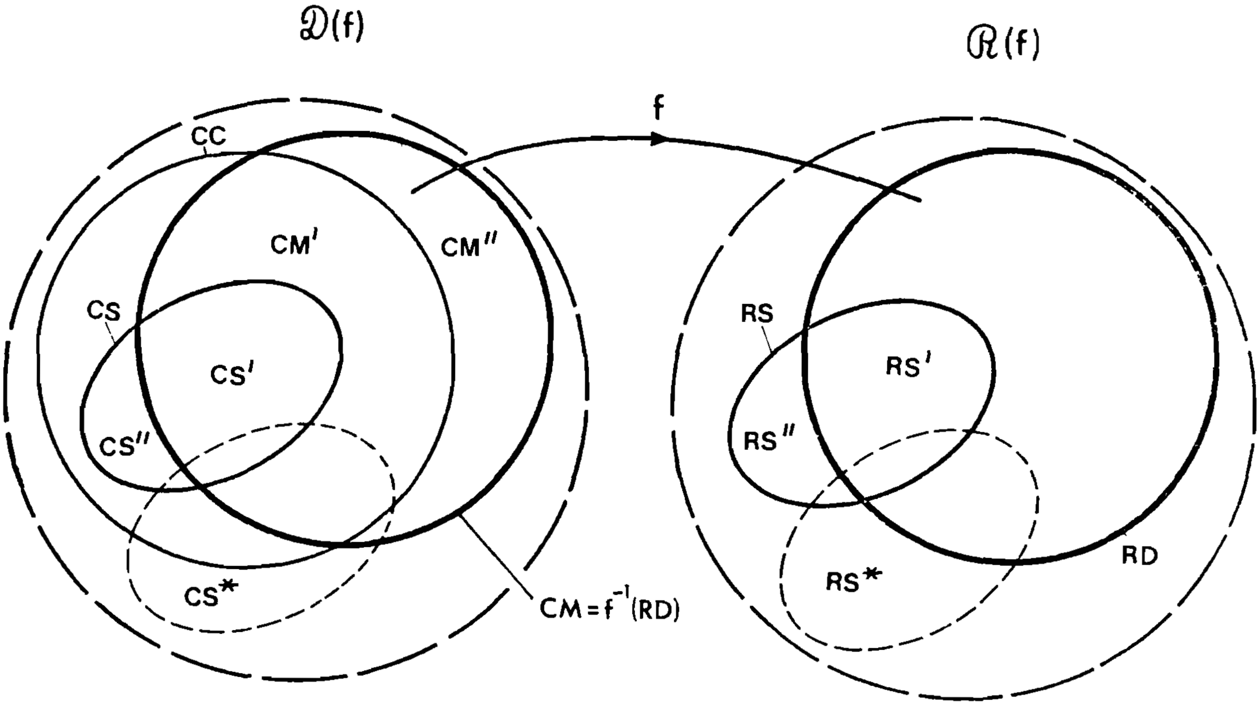


Figure 36: Set diagram of the relationships between input (character)- and output (response)-space of a simulation model. 𝒟(f): set of all possible character vectors (domain of f); ℛ(f) set of all possible model responses (range of f); f: model (vector function), CD: defined set of plausible character vectors; RD: defined realistic response region; CM: inverse image of RD; CS: character vectors sampled in Monte Carlo procedure; RS: direct image of CS; CS': subset of CS, generating plausible, realistic response RS'; CS'': subset of CS resulting in unrealistic response RS''; CS*: modifief CS' used for predictions, resulting in RS*. (from Fedra et al, in press).

Finally, the set CS' of M sample character vectors CS'_i, being identified as 'acceptable' character vectors, is then used for computations of model responses under changed conditions. That is to say, one or more elements of the M character vectors are changed according to the extent of the assumed alteration, and the set of M modified vectors is used to generate probability distributions of model responses. This procedure can be repeated to represent different conditions, and in fact the modification of the vector elements may be done systematically to investigate a range of possible future changes and their significance in terms of response probability distributions.

The concept of allowable ranges

Reconsidering the meaning of field data in terms of the systems elements and properties conjectured in the model, we obviously have only some rather uncertain estimates of the values we are looking for, namely the numerical values describing the input conditions, the model parameters, and finally the expected ("observed" in the field) behavior of the model. Clearly, forcing the model output trajectories through the measurement points by means of a highly sophisticated calibration scheme might produce quite meaningless answers, especially as the data for the input conditions will have to be assumed as being known exactly. Rather, one might try to deduce, from the available information, plausible ranges within which each of the numbers we have to specify has to be. The specification of these allowable ranges can of course take advantage of data from the literature, and certainly all the available data might be appropriately lumped or pooled. Being aware of the fact that ecosystems might have a rather large behavioral repertoire, it is very important, for the explicit purpose of prediction, to capture all of that repertoire in estimating the model parameters. Since we cannot exclude the possibility of any of the systems behavioral features occurring in the future, we have to account for them in the way we predict.

Allowable ranges are specified for the model parameters as well as for the input describing data, which together form the model input data (the set of numbers one has to put into the model to run it). The more data there are available, the narrower the ranges can be - if there are almost no data available, one can at least define some limits of physical or biological plausibility (e.g. an extinction coefficient cannot be smaller than that of clear water, or a daily growth rate for phytoplankton should hardly exceed a value of ten). Generally, the wider a range is specified, the more likely the true value (whatever that may be) will lie within it, but the less useful this information will be. One obviously has to compromise between arbitrariness and meaninglessness in many cases, which should throw some light on the usefulness of a formal model or analysis in such a case.

The concept of response-space

The kind of information one needs for the specification of the input data (parameters and input conditions) is largely determined by the structure of the model. The comparison of model output with the observations on the system behavior are much more flexible. Again ranges are used, but these ranges can be defined for various measures of different kinds: besides the more straightforward range within a given variable has to be at a given point in the period simulated, relational and integrated measures might be used as well. Total yearly primary production, or the minimum relative increase of phytoplankton biomass, the maximum allowable peak value, average trophic efficiency of a biological compartment and many more similar conditions can be specified in terms of ranges. Generally, not only state values but also process rates and flows as well as their sums or integrals over certain periods and various relations between such measures can be used to define the expected model response; the selection of appropriate measures depends largely on the kind of information available about the system. Considering each of these measures as one dimension of a hyperspace, the model response clearly has to be within the region defined by the ranges (Figure 37). The description of the systems behavior is thus conceptualized as a region in n-dimensional hyperspace, where -- given a high number of observations on the systems behavior over a comparatively long period of time -- probability density might be an additional dimension.

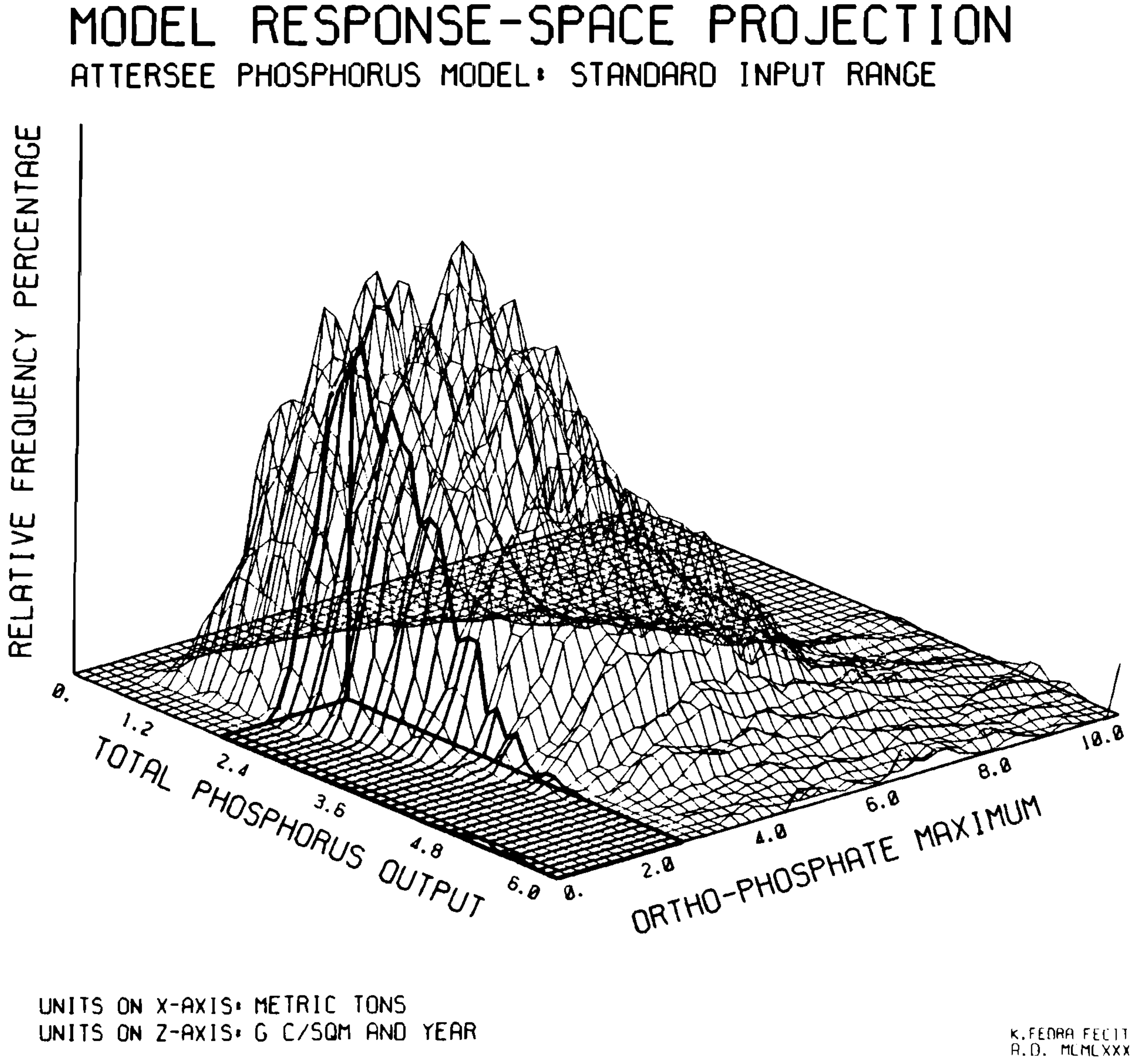


Figure 37: Projections from the model response hyperspace on planes of two behavior constraining response variables. Attersee phosphorus model, projections based on 100,000 individual model runs. (From Fedra, in press.)

Ecological systems, most pronounced in temperate zones, perform periodic fluctuations within a seasonal cycle. For many systems, cyclic stability with regard to certain features can therefore be an important condition to meet, unless an obvious trend was observed. In the absence of such a trend, however, the input conditions can be assumed to be of a cyclic stable nature, and pooled to derive the estimates for the above ensemble. Consequently, observations on systems properties in comparable periods of different years can also be pooled, and the resulting behavior definition envelops the systems behavior in a certain period. This envelope includes not only the variability due to measurement or sampling errors, but also the variability of the system including the input conditions in this period, as the assumed cyclic stability is of course no perfect one. Again, if the resulting definition is broad to the extent of meaninglessness, this would suggest that an important determining element which was not constant or cyclically stable during the period of observations failed to be recognized, or simply, that the available data are insufficient to describe the system precisely enough for a formal analysis.

The concept of probabilistic behavior

Given the allowable ranges for the input data (again a region in a hyperspace) and the behavior definition, the ensemble of input data combinations or models (model structure plus input data) is sought, which produces the expected response in accordance with the behavior definition. The numerical method to do so is a straightforward application of Monte Carlo techniques. A random sample from the input data space is taken, used for a run of the simulation model, and the resulting model response is then classified according to the behavior definitions. If all the definition constraints are fulfilled, the input data set is saved, and the process repeated until a sufficient number of data sets has been found. This can, for example, be tested by some appropriate statistics of the data sets themselves, and the search is stopped, whenever the distributions and correlation structure of the behavior giving data sets are more or less unchanged by additional data sets.

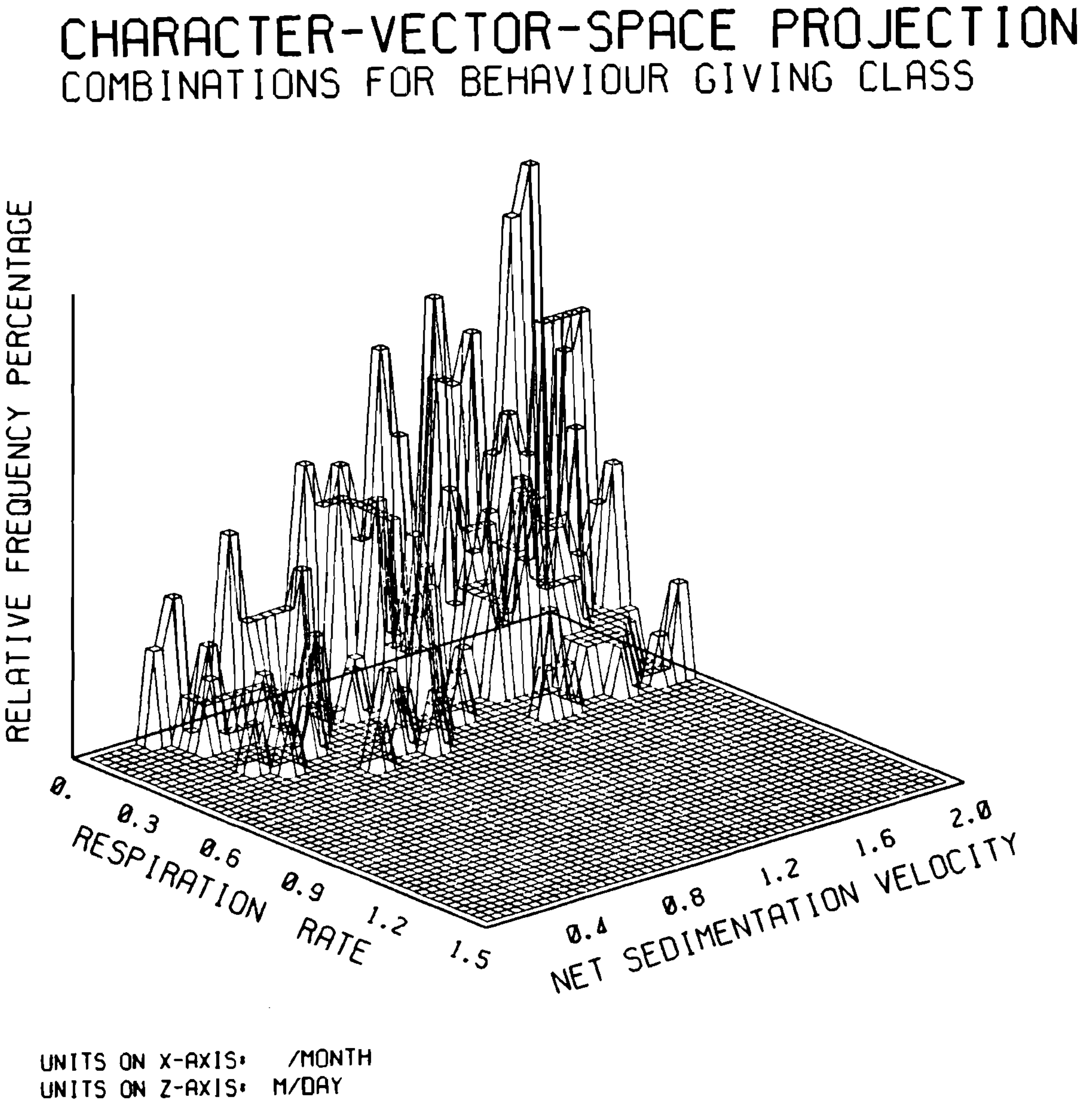
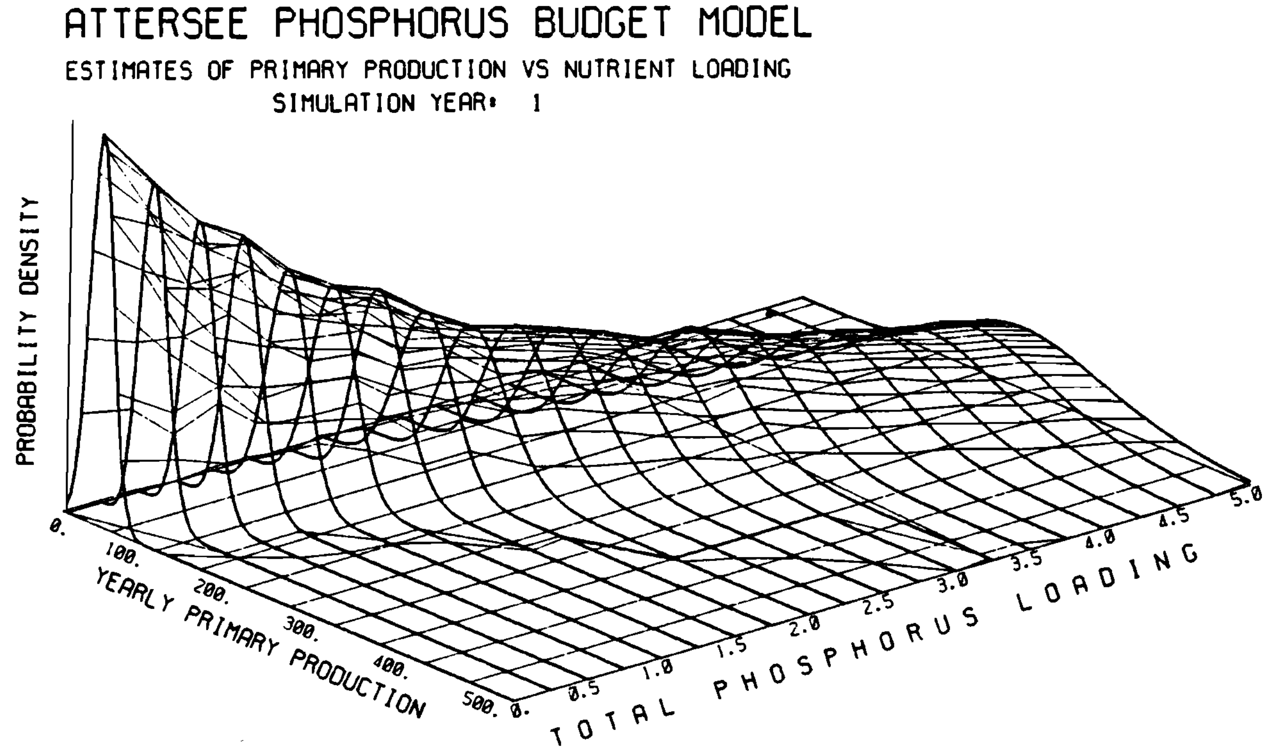


Figure 38: Character vector space projection for a behavior giving set of character vectors. Projection from the 22 dimensional charactervector space on a plane of two model parameters; extension of the individual axes indicates the range used for sampling.



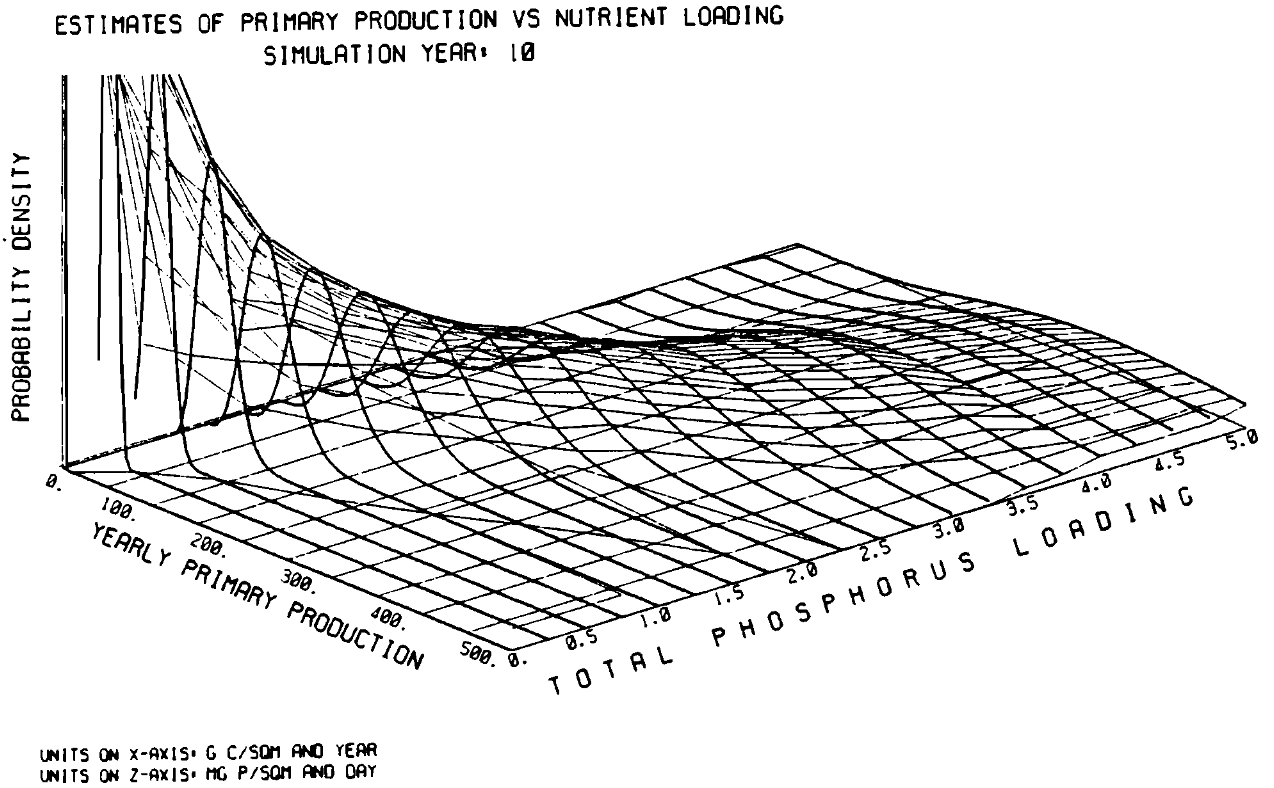


Figure 39: Probability distributions for model output variable "Yearly Primary Production", for different total phosphorus loading values. Top: first year of lake response, initial state represents the empirical range of lake behavior. Bottom: lake response after ten years of changed phosphorus loading. Note the extremely flat distribution in the high loading classes.

The resulting ensemble of data sets and model responses represents (for a given system in a certain period, conceptualized in a given model, described by a given data set, and all the additional a priori information one might have) the "best available knowledge". Each of the single "answers to the calibration problem" is an equally valid description of the system. The variability in the ensemble of data sets (Figure 38) and model responses reflects the uncertainty associated with the conceptualization, the observations, and finally the variability of the system itself. As stated above, too large a variability should make one cautious to proceed with a formal analysis; rather, more information about the system should be sought.

The available information, however, is of a statistic or probabilistic nature (although in a rather subjective sense). Each of the model responses in the behavior class might be understood as a sample from the overall response space of the model, which is taken to represent the behavior space of the system. From the frequency distributions of the variables considered, some conclusion on the probability density distribution of the behavior space could be drawn. The behavior space is characterized by the probability distributions along the individual axes as well as by the cross-correlation structure. The concept of the behavior space is readily extendable for the predictions. Changing any of the input data to represent some change in external or internal conditions, will result in an ensemble of predictions which could be interpreted in the same probabilistic way. The probability density of the predicted response will again allow an estimation of the relative accuracy of the forecasts, especially if they are extended for a long time relative to the observation period (Figure 39). Trivial projections in terms of the questions posed might mainly be taken as a warning that the limits of predictability (on the basis of the information utilized) are reached.

From 22-dimensional regions in input-data space (each defined by a set of ranges) altogether 23000 samples were drawn and used for model runs. The model response space corresponding to the gross (unstructured, disregarding any correlations between the input-data) input-data space was plotted on planes of two response variables used in the behavior definition (see Figure 38). The independent selection of input values from ranges with an assumed rectangular probability density function, resulted in only a small percentage of "successful" behavior-runs (between 0.5% to about 10%, depending on the definitions used). As expected, the set of input-data for the behavior group shows a marked correlation structure. Rather than the individual absolute value for a single coefficient, the combination of values determined the model behavior. Extreme values for a given coefficient can well be balanced by smaller changes in several other coefficients to result in the same response-region. These findings should throw some light on attempts at rigid deterministic calibrations with reference data and input conditions assumed to be certain. A sample output of the analysis programs, used to compact the information resulting from the Monte Carlo approach, is given in Table 3.

TABLE 3: sample output from the Monte Carlo analysis programs, showing parameter ranges and distributions, constraint condition violations, and parameter and output correlation matrix.

```
Automatic Parameter Space Analysation Program

  Behaviour definition applied:

  Minimum primary production  gc/m2 and year          50.00
  Maximum primary production  gC/m2 and year         150.00
  Time range for biomass peak value:  day  60. to day 210.
  Upper limit for biomass peak  mg P/m3               15.00
  Minimum relative increase of biomass max/min         2.00
  Orthophsophate maximum in mixed period  mg/m3        2.50
  Total phosphorus output range:
  Upper limit   metric tons per year                   8.00
  Lower limit   metric tons per year                   2.00
  Maximum ratio of total P relative change             0.50



  automatic analysation results:

  number of simulation runs evaluated:     10000

  number of well behaving runs:              293

  number of non-behaviour runs:             9707  including   26 aborted runs


  constraint conditions violated by BAD class:

Primary Production too low:                849 cases
Primary Production too high:               937 cases
Biomass peak too early:                   4991 cases
Biomass peak too late:                    1480 cases
Biomass peak too high:                       4 cases
Relative Biomass increase too low:           0 cases
Orthophosphate level too high:            7517 cases
Phosphorus output too low:                2089 cases
Phosphorus output too high:                  1 cases
Relative change in P-content too high:    2250 cases
```

TABLE 3, continued.

```
Constraint violations  %-coincidence matrix:

 condition:      1        2        3        4        5        6        7        8        9       10

       1    100.00     0.00    74.79     3.53     0.00     0.00    54.30    55.01     0.00    26.74
       2      0.00   100.00    13.02    39.27     0.43     0.00   100.00     0.00     0.11     9.39
       3     12.72     2.44   100.00     0.00     0.00     0.00    65.02    31.48     0.00    36.59
       4      2.03    24.86     0.00   100.00     0.27     0.00    93.11     6.22     0.07    14.26
       5      0.00   100.00     0.00   100.00   100.00     0.00   100.00     0.00     0.00    50.00
       6      0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00     0.00
       7      6.13    12.47    43.17    18.33     0.05     0.00   100.00    10.02     0.01    13.70
       8     22.36     0.00    75.20     4.40     0.00     0.00    36.05   100.00     0.00    43.03
       9      0.00   100.00     0.00   100.00     0.00     0.00   100.00     0.00   100.00     0.00
      10     10.09     3.91    81.16     9.38     0.09     0.00    45.78    39.96     0.00   100.00
```

```
Automatic Parameter  Space Analysation Program
correlation analysis for well behaving runs:


runs to be evaluated:        293


                                                                 mean     stand.dev.    minimum      maximum
 1 michaelis constant                            mg/m3          1.0042      0.5135      0.2041      1.9930
 2 resp./mineralization epilimnion               day-1          0.1134      0.0526      0.0219      0.2000
 3 resp./mineralization hypolimnion              day-1          0.0141      0.0034      0.0100      0.0244
 4 net sedimentation velocity epilimnion       m*day-1          0.2571      0.1604      0.0119      0.7438
 5 net sedimentation velocity hypolimnion      m*day-1          1.4196      0.4241      0.3231      1.9983
 6 minimum production rate                       day-1          0.3770      0.0734      0.2505      0.4994
 7 maximum production rate                       day-1          6.3429      2.2301      1.1798      9.9996
 8 time lag of productivity maximum                day        218.4715     25.4016    180.0387    269.8400
 9 diffusion coefficient hypolimnion        cm2*sec-1          0.2788      0.1396      0.0200      0.4986
10 diffusion coefficient thermocline        cm2*sec-1          0.1318      0.0685      0.0100      0.2498
11 extinction coefficient                          m-1          0.2885      0.0562      0.2003      0.3979
12 self shading coefficient                   m2*mg-1          0.0150      0.0030      0.0101      0.0200
13 initial thermocline depth                         m          4.4748      0.8464      3.0053      5.9889
14 final thermocline depth                           m         17.6395      1.4145     15.0251     19.9728
15 begin of stratified period                      day        155.3691     16.8105    120.9221    179.8988
16 end of stratified period                        day        302.5700     14.8651    280.0211    329.7845
17 thickness of thermocline                          m          7.5441      1.4705      5.0062      9.9848
18 orthophosphate input                 mg*m-2*day-1          0.1067      0.0509      0.0116      0.1989
19 particulate phosphorus input         mg*m-2*day-1          0.9294      0.3339      0.2604      1.4997
20 hydraulic loading                           m*day-1          0.0422      0.0050      0.0301      0.0500
21 initial orthophosphate mixed period          mg*m-3          1.0648      0.4933      0.2000      1.9893
22 initial particulate phosphorus mixed p.      mg*m-3          3.4447      0.7131      2.5156      6.1065
 model output data:
 1 primary production                     gc*m-2*year-1         80.6641     15.9106     50.3616    128.9642
 2 op maximum  mixed period                     mg*m-3          2.1760      0.2434      1.3256      2.4989
 3 pp epilimnion  minimum                       mg*m-3          0.4115      0.1971      0.0714      1.1612
 4 pp epilimnion  maximum                       mg*m-3          4.4593      0.8348      3.0174      8.2083
 5 day of epilimnic pp maximum                     day        135.4863     31.8503     61.0000    185.0943
 6 total phosphorus input                 tons*year-1         17.1331      5.6574      5.7596     27.7315
 7 net phosphorus loading                 tons*year-1         14.6376      5.5953      3.4143     25.1839
 8 total phosphorus output                tons*year-1          2.4955      0.3823      2.0007      3.8662
 9 lake content total p  time=start              tons         17.7356      3.3204     11.6538     29.3214
10 lake content total p  time=end                tons         12.6229      1.6847      8.4954     17.5518
11 sedimentation total p                  tons*year-1         19.6748      5.8205      5.8417     34.4694
```

```
      Data-Input & Response  Correlation Matrix

     1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22   1   2   3   4   5   6   7   8   9  10
 2 0.1
 3-0.1 0.1
 4 0.1 0.1 0.1
 5 0.1-0.1 0.1-0.2
 6 0.1 0.1 0.1 0.0 0.1
 7 0.2-0.0 0.2-0.1 0.0-0.1
 8 0.0-0.0-0.0-0.3 0.2 0.0-0.1
 9-0.1-0.0 0.0-0.0 0.0 0.0-0.0 0.0
10 0.0 0.1-0.0-0.0-0.0-0.0-0.0-0.0 0.0
11-0.1 0.1-0.1 0.1 0.1 0.0 0.0-0.0-0.1-0.1
12-0.0 0.1 0.0-0.0 0.1-0.0 0.0 0.1-0.0 0.1 0.1
13 0.1-0.0-0.1-0.0 0.0 0.1-0.1-0.0-0.0-0.0 0.0 0.0
14-0.0-0.1-0.1 0.0 0.0 0.0 0.0 0.1 0.1-0.0 0.1-0.0-0.0
15 0.1-0.0 0.1 0.1-0.1 0.0-0.0 0.1-0.0 0.0 0.0 0.1-0.0 0.0
16-0.1-0.1-0.1 0.0 0.1-0.0-0.1 0.0 0.0-0.1 0.1-0.0 0.0 0.1 0.2
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18 0.0 0.0-0.1 0.1 0.0-0.0 0.0-0.1 0.0 0.0-0.0-0.0 0.1-0.1 0.1 0.1 0.1
19 0.0-0.1-0.2 0.5 0.2-0.1 0.0-0.1-0.1 0.2 0.0 0.1-0.0 0.0 0.1 0.0 0.0 0.1
20-0.0 0.1 0.2 0.2-0.2 0.1-0.1-0.1 0.0 0.0-0.1-0.0 0.0-0.0 0.0 0.1-0.1-0.0-0.2
21 0.1-0.0-0.1 0.3-0.0 0.0-0.1-0.1-0.0-0.0 0.1 0.0 0.1 0.1 0.1 0.1 0.1-0.0 0.1-0.1
22-0.1-0.0-0.3-0.1 0.2-0.1 0.0-0.1-0.0-0.1 0.1 0.0-0.0-0.0-0.1 0.1 0.0 0.0-0.0-0.2-0.1
 1-0.1 0.4 0.3-0.2 0.1 0.0 0.3 0.2-0.0 0.0-0.1 0.1-0.1 0.0 0.2-0.2 0.1 0.1 0.1-0.3 0.1 0.2
 2-0.0 0.1 0.2 0.0-0.2-0.1-0.1-0.1-0.1 0.0 0.1 0.0-0.1-0.1-0.1 0.2 0.1 0.0 0.0-0.2 0.2 0.2 0.3
 3-0.1-0.0-0.5 0.5-0.5-0.1-0.0-0.2-0.0 0.3-0.0 0.0-0.0 0.0 0.2-0.1 0.1 0.2 0.6-0.1 0.1-0.1-0.1 0.1
 4-0.1-0.2-0.4-0.5 0.4-0.2 0.1 0.0-0.0 0.0 0.0 0.1-0.0 0.0-0.0 0.1 0.0 0.0 0.1-0.4 0.2 0.7 0.4 0.2-0.1
 5 0.1-0.0 0.0-0.5 0.3 0.0-0.2 0.6 0.0 0.1 0.1 0.1-0.0 0.0 0.3 0.0-0.0-0.0-0.1-0.1-0.2-0.2 0.1-0.0-0.2 0.1
 6 0.0-0.1-0.3 0.5 0.2-0.1 0.0-0.1-0.1 0.2 0.0 0.1-0.0 0.0 0.2 0.0 0.0 0.2 1.0-0.2 0.1-0.0 0.1 0.0 0.6 0.1-0.1
 7 0.0-0.1-0.2 0.5 0.2-0.1 0.0-0.1-0.1 0.2 0.0 0.1-0.0 0.0 0.1 0.0 0.0 0.2 1.0-0.2 0.1-0.0 0.1 0.0 0.6 0.1-0.1 1.0
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 9-0.0-0.0-0.3 0.1 0.1-0.1-0.0-0.2-0.0-0.1 0.1 0.0-0.0 0.0-0.0 0.1 0.1-0.0 0.0-0.2 0.5 0.8 0.2 0.3 0.0 0.7-0.3 0.3 0.0 0.4
10-0.1-0.1-0.3-0.1-0.1-0.2-0.0-0.1-0.1 0.2-0.0 0.1-0.1 0.0 0.0-0.0 0.1 0.2 0.6-0.3 0.0 0.1 0.4 0.6 0.5 0.5 0.1 0.6 0.5 0.4 0.1
11 0.0-0.1-0.3 0.6 0.3-0.1 0.0-0.2-0.0 0.1 0.1 0.1-0.0 0.0 0.1 0.1 0.1 0.2 0.8-0.2 0.4 0.4 0.1 0.0 0.5 0.3-0.3 0.8 0.8 0.2 0.5 0.3
```

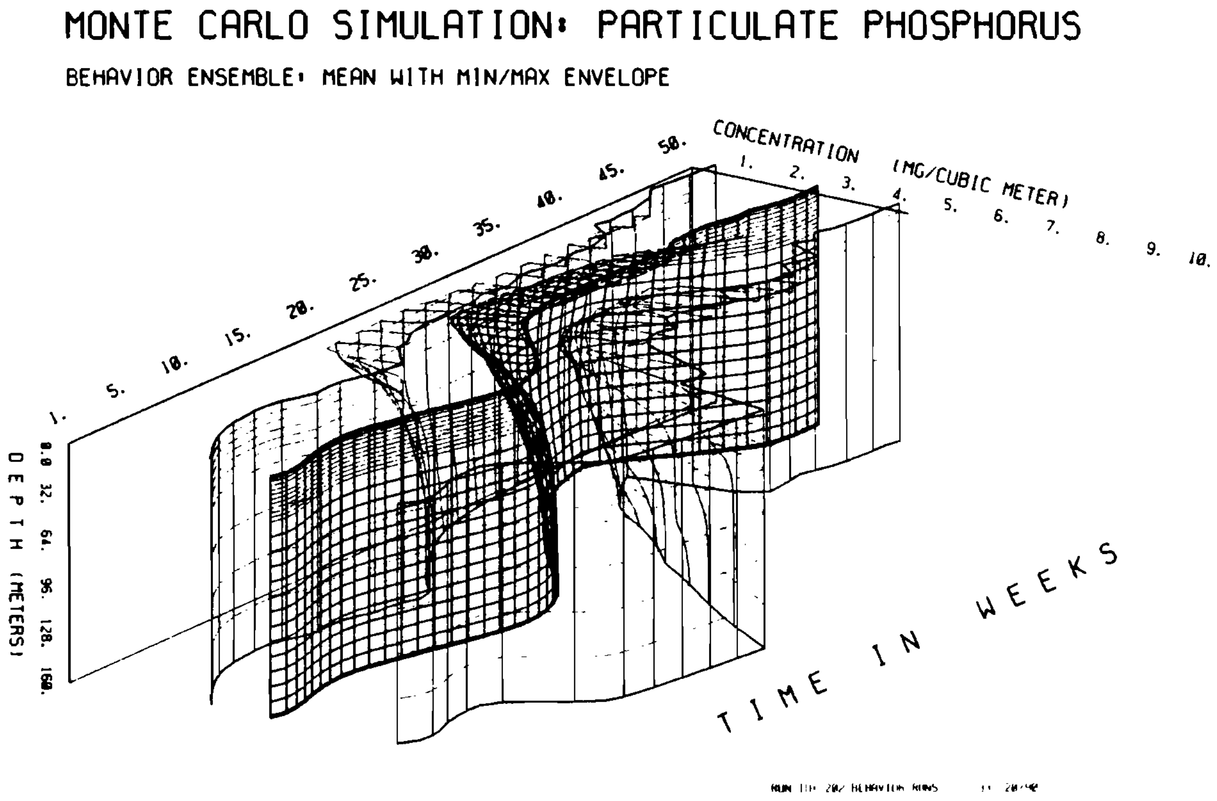
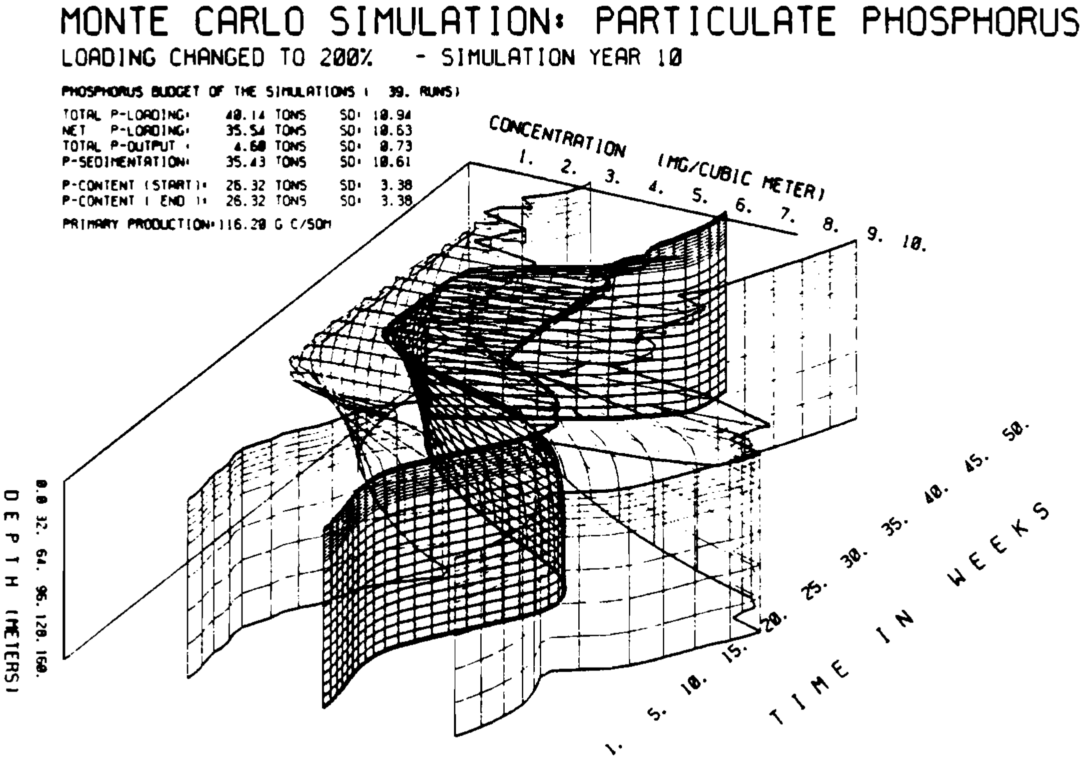


Figure 40: ensemble of behavior-runs for the Attersee model. Mean of 39 runs with minimum/maximum envelope.

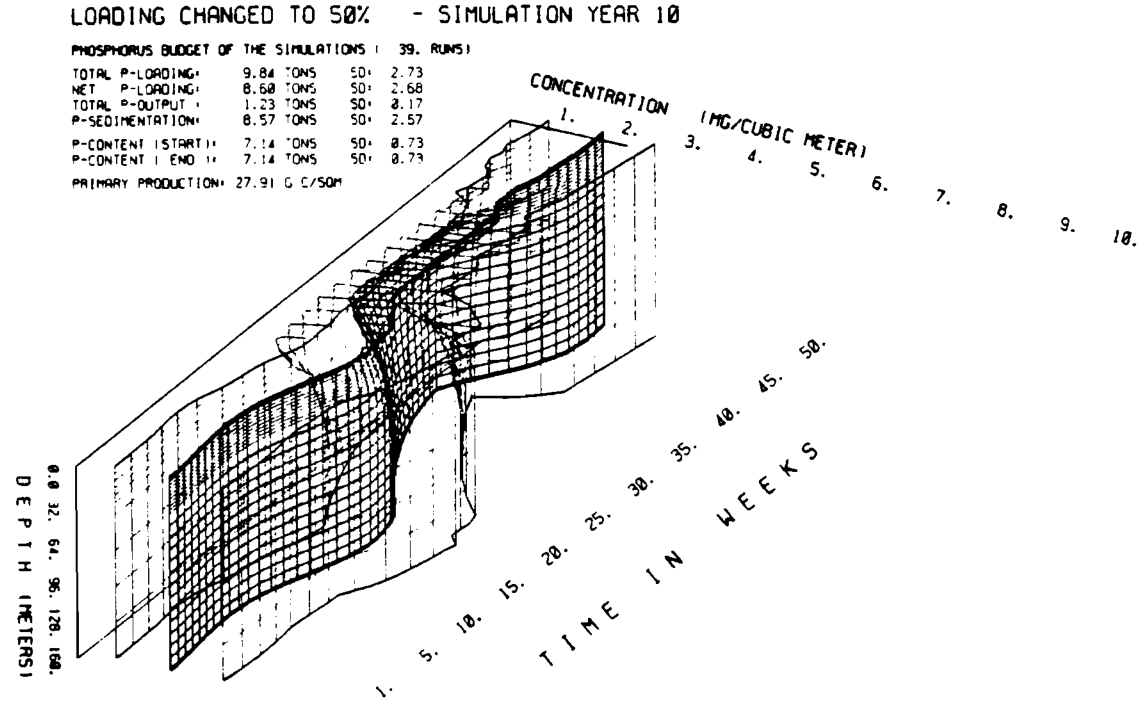
Figure 40 shows an ensemble of behavior-runs ("stochastic mean" with a minimum/maximum envelope) resulting from the standard definition set; the plots for the state variables particulate phosphorus and phosphate are found to envelope the comparable 5-year data set from the lake. However, it should be stressed again that the comparison of field data with the model output is somewhat dubious: "particulate phosphorus" in the model includes only living algae's phosphorus (actually assuming a constant proportion of phosphorus in the photosynthesizing biomass).



PHOSPHORUS BUDGET OF THE SIMULATIONS (39. RUNS)

TOTAL P-LOADING:	40.14 TONS	SD:	10.94
NET P-LOADING:	35.54 TONS	SD:	10.63
TOTAL P-OUTPUT :	4.60 TONS	SD:	0.73
P-SEDIMENTATION:	35.43 TONS	SD:	10.61
P-CONTENT (START):	26.32 TONS	SD:	3.38
P-CONTENT (END):	26.32 TONS	SD:	3.38

PRIMARY PRODUCTION:116.20 G C/SQM



PHOSPHORUS BUDGET OF THE SIMULATIONS (39. RUNS)

TOTAL P-LOADING:	9.84 TONS	SD:	2.73
NET P-LOADING:	8.60 TONS	SD:	2.68
TOTAL P-OUTPUT :	1.23 TONS	SD:	0.17
P-SEDIMENTATION:	8.57 TONS	SD:	2.57
P-CONTENT (START):	7.14 TONS	SD:	0.73
P-CONTENT (END):	7.14 TONS	SD:	0.73

PRIMARY PRODUCTION: 27.91 G C/SQM

Figure 41: Prediction with ensembles. Model response in terms of mean and minimum/maximum envelopes of the Attersee model for changes in the phosphorus loading. Graphs show model response after ten years of simulation, representing a dynamic equilibrium of lake response and loading.

The field measurements, however, do not discriminate living algae and everything else containing phosphorus that would be retained on the filters used in the chemical analysis (e.g. zooplankton and all kind of organic detritus). The same is true for the "phosphate", which in terms of the model represents all "directly utilizable for photosynthesis" phosphorus, which is clearly neither $P\text{-}PO_4$ nor soluble phosphorus.

Predictions of future systems response to changes in the phosphorus loading conditions were made by subsets of the behavior-giving input-data ensemble, where the loading determining coefficients were changed by a certain factor. This "relative" change not only accounts for the uncertainty in the inputs, but also preserves the correlation structure of the behavior generating ensemble of input-data sets. Input changes representing increases of 50% and 100% (to simulate the effect of no control actions but increasing nutrient release in the catchment area) and reductions to 75%, 50% and 25% of the current (1975-1978) empirical range of loading were simulated for a ten year period. Some examples of these scenarios, again showing the stochastic mean with a minimum/maximum envelope are given in Figure 41.

To estimate prediction accuracy as related to the changes in the phosphorus loading (the degree of extrapolation in input space), and as related to simulation time (the extrapolation in time), the coefficient of variation vs extrapolation was plotted. Figure 42 shows one example for the model output variable yearly primary production. The plot shows an increase of prediction uncertainty with time, stabilizing when a new equilibrium is reached after a transient period following the change in the phosphorus loading. The plot also indicates an increase of uncertainty with the amount of change in the input conditions, showing a minimum of the coefficient of variation in the empirical range. Summarizing, prediction uncertainty (measured as the coefficient of variation of the Monte Carlo ensembles) increases with the extrapolation in time as well as in input space. Being related to the initial variability in the descriptive empirical case, there is an obvious (and intuitively to be expected) relation of prediction reliability or non-triviality to these three magnitudes: input variability (incorporating data uncertainty and systems variability in time), degree of extrapolation in the controlling inputs, and the degree of extrapolation in time. Obviously, the more precise the original knowledge about the system is, the larger the extrapolation in the controlling conditions and in time can be, before the limits of predictability are reached; or, the larger a change is to be simulated, the better the knowledge about the system has to be.

A different representation of prediction accuracy was shown in Figure 39 (where prediction refers to the mean estimate, and accuracy is measured in terms of confidence intervals). The probability distributions fitted for the response variable frequency distributions can be read in the above terms. These probability distributions are not primarily to be understood as the probabilities of certain systems states in the future -- they are rather representations of prediction uncertainty, or the propagation of the initial uncertainty and variability in the available information. However, being aware that the predictions are biased by the (unrepresented) model-error (e.g. O'Neill and Gardner 1979), the probability distributions for future states might also be interpreted in the usual way.

The above analysis and the generalizing conclusions to be drawn are certainly biased with regard to the model used and, to a lesser extent, with regard to the data set used. The arbitrary selection of any model for a given system seems to be unavoidable in light of the meager data available; the model order and structure cannot be derived from the available data, and one has to use a priori information about the system to be described. However, the thus conjectured model might well turn out to be inadequate, and changes in the model structure will become necessary. One indication of inadequate model structure -- in terms of the above approach -- would be, if no behavior-giving combinations of input-data can be found in the specified region; or if the distributions of the single input data within the ranges sampled suggest a high number of possible solutions outside the specified "plausible" bounds. If a combination of unrealistic inputs still results in a realistic behavior of the model, one might also question the validity of the model structure. This of course requires that the expected behavior is defined in a sufficiently detailed way.

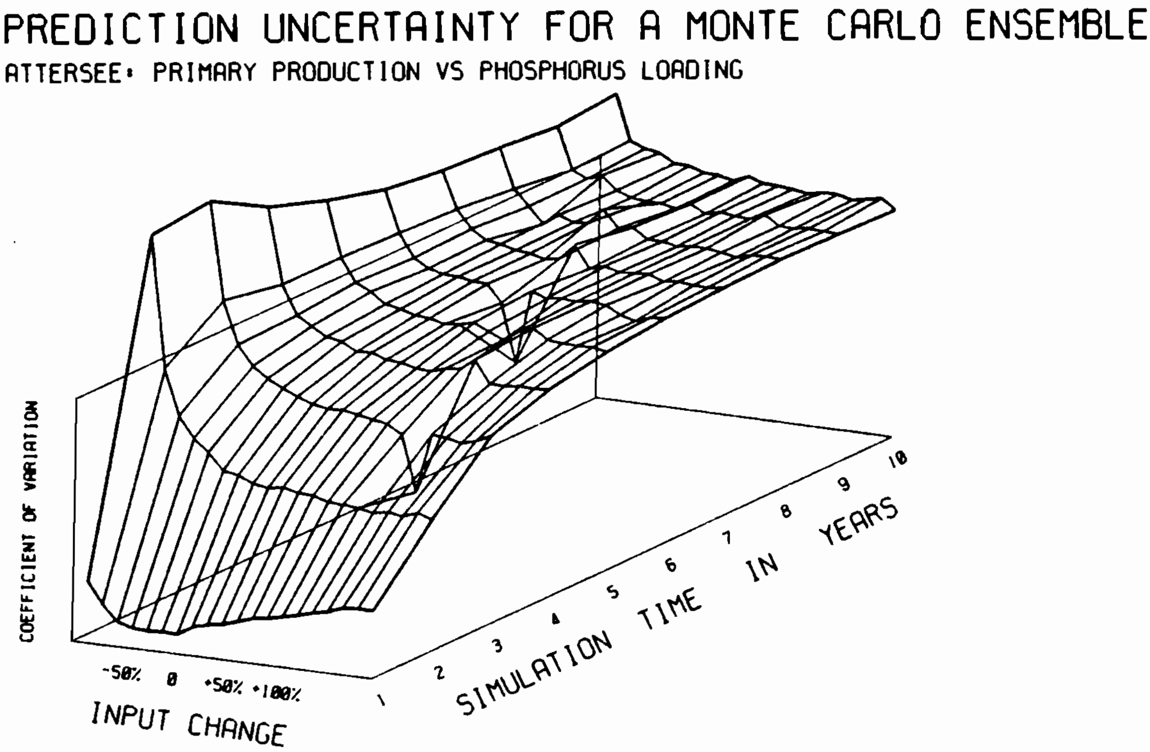


Figure 42: A representation of prediction uncertainty (coefficient of variation for an ensemble of plausible model runs) versus input change (extrapolation) and time (from Fedra, in press).

The variability in the prediction results directly from the variability in the ensemble of input-data used. And the variability of the input-data stems from two basic sources, both reflected in the ranges used for the initial input-data space to be sampled, and in the ranges describing the empirical systems behavior: data (measurement) uncertainty and systems variability. By including systems variability (through the use of several year's data), future variability in the conditions driving and controlling the system are somewhat accounted for (under the assumption that a representative part of the systems behavioral repertoire has been captured in the observation period). This should also account for another basic problem of the "naive extrapolation" approach: systems containing biotic elements are known to adapt to changes in their driving conditions, their structure and parameters (in terms of a model description) are state- and input- dependent (cf. Fedra 1979a, Straskraba 1976, 1979).

The above analysis indicated, that for a model with 22 input-data (which, at least for ecological models is a rather low figure) or "degrees of freedom" in the estimation procedure, behavior-giving values can be found all over the ranges (independently) sampled (compare Figure 38). On the other hand, only a small percentage of the possible combinations resulted in a satisfactory model response. As a consequence, the ranges for the search should be constrained as much as possible, for reasons of efficiency as well as to avoid "unrealistic" input-data combinations (where the unrealistic value in any of the parameters or inputs will be "balanced" by some changes in all the other values) in the behavior ensemble. This of course requires, that all the parameters used in the model are physically interpretable and can be measured or at least estimated from field measurements or experiments. The same holds true for the state variables of the model and measures derived: only if they are measured (or are at least measurable), can their allowable values be reasonably constrained in the definition of the systems' behavior. Including unmeasured (and unconstrained) state variables will result in behavior runs (in terms of the constrained measures), where the uncertainty is all transferred to this unconstrained "leak" in the behavior definition. The ability of even a simple model to balance its (constrained) response in terms of some variables by (unconstrained) changes in others, requires that all model behavior (and, of course, output), should be interpretable in physical (measurable in the field) terms. Also, the above approach raises some doubt whether models by including more and more detail (requiring more and more state variables and parameters, and consequently more data for the "calibration") become more realistic (see above discussion on hypothesis testing). Obviously, increasing model complexity without increasing the available data for constraining input-data ranges as well as allowable response ranges, just adds degrees of freedom for the calibration or estimation procedure. Undoubtedly such models can be very useful, especially in more qualitative "hypothesis testing" approaches. But their value for prediction might well be questioned.

Uncertainty in ecological modeling seems to be an inevitable element in the method as well as in the object of study, which is most obvious when one tries to predict the future. The analysis of model uncertainty and its "inverse", prediction accuracy, is certainly at an early stage of development (cf. O'Neill and Gardner 1979). However, being aware of model, and especially prediction uncertainty and the thus obvious limits of predictability, might well help to avoid a naive trust in numerical models. Analysis of the various sources of model uncertainty and their relations and interdependencies will be necessary to improve model applicability. And the least impact from model error analysis on model application should be a critical reevaluation of the questions that can reasonably be answered by means of numerical models.

OPEN PROBLEMS AND FUTURE DIRECTIONS

The problems encountered in the analysis of environmental systems are numerous; one of the most obvious ones is the lack of appropriate information. Although much information might be available on a given system in principle, this information will rarely be coherent and relevant for the analysis. Data collection is often a goal in itself, when part of a routine monitoring program. Little effort seems to be put in sound, statistically based data collection strategies, and the pilot programs necessary to design them. The same is true for the way data are usually stored and eventually aggregated and analyzed. Consequently, one of the most time consuming tasks in environmental systems analysis is the establishment of an appropriate data base. This entails the collection of original data, which often enough is complicated by institutional or personal problems. Potentially relevant information tends to be decentralized and hard to trace. Besides, many of the elements in the analyst's conceptualization of a given system might never have been looked at. Consequently, numerous guesses and extrapolations will be the basis of further quantitative analysis.

Admittedly, there is no generally valid data collection strategy for yet undefined problems. Each problem would require a specific kind of data collection strategy, which eventually may exclude each other at least in practical terms. However, designing data collection strategies anew on the basis of pilot studies and their analysis, and conducting data collection and systems analysis in parallel, is not always feasible. Often enough there may be little time available, so that no additional information can be collected for a specific analysis.

This inevitable lack of appropriate information must therefor be taken as a challenge rather than a staggering limitation for the analyst. Wherever possible, data collection can profit from a parallel on-line analysis. In general however, the analyst has to cope with insufficient information and methods to do so are therefor most valuable in light of the realworld constraints.

Besides data availability and relevance, the management of environmental data poses special problems. Environmental data are extremely diverse, and -- in part due to the often unsystematic way they have been collected -- difficult to handle. In some instances, like for example in the case of meteorological or hydrological observations, format and structure of the information will be standardized and easily yield to computer storage and analysis. In the majority of cases however, we will have to cope with numerous singular observations of high complexity. Such information may be extremely important and valuable, as for example the observation of extreme situations like an algae bloom or a storm runoff. But their incorporation into one general data management system is extremely difficult.

As a compromise, in the current study an attempt is made to use several approaches to data management, according to the respective structure of the individual data sets, in order to obtain flexibility and easy handling. Although this system requires some additional record keeping and documentation, it was found more practical than one comprehensive data management program. Taking full advantage of the file structure of the IIASA computers' operating system, most raw data are stored in a hierarchical system of directories or on tape. A multitude of smaller programs has been developed to sort and merge, filter, and extract data for analysis or display. These programs, together with the structure of the raw data files, are under continuous modification, attempting further generalization of the system.

One major principle problem was encountered in the difficulties of communication of modeling results. This however is a basic prerequisit for their practical implementation. On the one hand, a quantitative numerical analysis requires a high degree of sophistication and detail; on the other hand, the final result has to be as simple as possible to be understood by a non-technical audience as an aid to decision making. This rather general problem has numerous aspects. One of those is tackled by the hierarchical, modularized approach proposed. However, it seems extremely difficult to develop formal methods for model simplification or the aggregation of information, satisfying the scientist as well as the policy maker or the general public. A formal approach is certainly required, since every arbitrary step, based on subjective judgement alone in the analysis and the interpretation and communication of results should be avoided, wherever possible. A basic requirement of an analysis that purports to be objective is the testability of all assumptions, and the replicability of each single step in the process. Since applied systems analysis attempts to link "hard science" with more soft policy-oriented domains, this is a most difficult, but also rewarding thing to do.

One example of how to approach these problems can be demonstrated using the notion of "water quality." Water quality is certainly an important variable in environmental systems analysis and management. However, it has to be defined in each specific context. One way to define it is related to the use of a given waterbody, and the resulting set of desirable properties of the water. A simple example may be drinking water quality standards, related to public health. Looking at such standards makes immediately obvious that they are in no way absolute, but rather related to the specific situation. Nevertheless, clear standards can usually be defined for water quality requirements for domestic, agricultural, and industrial use. Technical or public health criteria are as a rule well understood. The problem becomes more complex, where aesthetic criteria are included in the definition of water quality. Aesthetic criteria however play a dominant role in water quality for recreation; and recreational use of water is probably the most quality demanding use of water in industrialized countries. This at least is implied by recent estimates of benefits from water quality improvements (Feenberg and Mills, 1980). In their recent book these authors estimate almost 90% of obtainable benefits from pollution abatement, this is to say water quality protection or improvement, to be allocatable to recreational use of water in the US.

A definition of water quality for recreational use of waterbodies has to be based on the perception of water quality. This is certainly the most direct link between water quality (as a physical notion) and the socioeconomic domain. The implications are twofold. First, is becomes necessary to relate the physical, multi-dimensional concept of water quality to a one-dimensional, arbitrary, biased appraisal of water quality by its consumers. And second, it becomes necessary to incorporate the variability in subjective human judgements into the formulation of such a relation. This relation may be quite complex, and is in no way general but site-specific. Certainly, to use examples from the lake systems discussed above, turbidity or visibility will be differently valued in a shallow lake like the Neusiedlersee, and a deep lake like the Attersee. The latter will be expected to be crystal clear -- reduced transparency will certainly influence its water quality; in the case of the Neusiedlersee, visibility might be completely irrelevant for the visitor. Many elements in the perception of water quality relate to taste and odor, which are the most easily detectable characteristics besides the above mentioned turbidity and temperature. These variables are all intimately coupled to the trophic state of a waterbody, and thus with its eutrophication. However, to make the result of a systems simulation relevant to a "decision maker", "no detectable taste and odor, high visibility" may be a more informative statement than "less than 50 mg m^{-3} algae biomass measured as Chlorophyll a, 100 % oxygen saturation, P-PO_4 below 2 mg m^{-3}, etc".

Certainly, there are dimensions of water quality which cannot be perceived immediately, but are nevertheless most relevant. Examples may be fecal bacteria, toxic substances, or radioactivity. In general however, the obvious and perceivable dimensions will be of greater interest. The inclusion of environmental perception as a major link between the physical and the socioeconomic aspects in water quality studies should be an important step in any comprehensive approach and certainly warrants further research.

Inherent in the problems of environmental perception and, more general, the problems of values, is the problem of treating them quantitatively. Human perception and judgement as well as human value systems are highly arbitrary, adaptive, and variable over a broad range. They are, however, a determining element in the socioeconomic domain. In fact, they are also inevitable elements in the scientific domain, as was attempted to demonstrate above (p 91 ff). Subjective values are certainly non-unique, and may span a wide range within a given population relevant for any analysis. Relating these values to objective, measurable criteria is therefore not straightforward. Specific methods to include the range and variability of subjective values into a formal quantitative analysis have to be sought. Probabilistic approaches, and the use of more fuzzy concepts of goal functions might be needed. Also, if the result of any analysis should be relevant in light of the uncertainty in the socioeconomic domain, the robustness of any solution advocated has to be demonstrated. Only if a solution is robust in terms of the arbitrary variability in the way to judge it, it will be relevant in political terms.

All the above issues indicate the direction future research might have to take. Together with the problems addressed in more detail in the previous sections of this report, they represent some of the most rewarding objects for study in the field of environmental systems analysis and management. Comprehensive approaches must not only include the relevant physical and ecological processes governing the behavior of environmental systems, they must also include appropriate links to the human systems of values, which finally determine which of the infinite number of aspects of an environmental system are considered relevant. Some of these requirements are easy to achieve from a technical point of view. Once the functional relations are formulated, the inclusion of additional "output variables" is no technical problem. The formulation of the relationships between dimensions of environmental quality, its perception, and the values attributed, and the interelationships between all these factors, is the major problem.

Besides the problems in the linking of "hard science" with the socioeconomic and policy domain, the physical background of environmental systems analysis poses problems as well. Quite obviously, our understanding of major processes supposedly governing the behavior of ecosystems is insufficient. This often seems to result from singledisciplinary conceptualizations, which tend to ignore important aspects. Such examples were discussed above, emphasizing the role of coupled physical and biochemical processes. In case of the shallow Neusiedlersee, we have a two-dimensional transport problem as well as a vertical problem with regard to the sediments and turbidity. In case of the deep lakes the problem is essentially vertical. The physical processes and the biological processes however, are generally seen to operate on quite different scales in time and space, so that their coupling in a model description is not straightforward. Methods to link models of quite different dimensions have to be developed. The increased complexity of systems of coupled models for the description of environmental systems is certainly not only constrained by time and manpower restrictions for a given task, it is also constrained by data availability. And finally, more detail in the analysis poses more problems in its interpretation, as was and communication, as was discussed above.

The general line of development is thus determined by a number of goals, which seem to be mutually exclusive. This certainly calls for a (systemic) compromise. In general terms, it is the problem of a formal approach to truely interdisciplinary research and communication, linking basic natural sciences, engineering sciences, and the life sciences, with economics and policy. To do so, requires innovative approaches. One aspect might be the full and more rational utilization of computer power, ranging from microprocessor controlled data collection and storage to numerical systems simulation on large mainframes.

New ways of man-machine interaction have to be developed to provide computer assistance to a larger group of people without formal training in computer use. Letting the computer do the nasty part of the work, like data organization, basic analysis, and the number crunching, should provide more time for the analyst to think and learn along those dimensions the machine cannot handle.

APPENDIX:

(A) Collaborating institutions and individuals

The following list compiles institutions (and key-individuals from such institutions) with which the Austrian Lake Ecosystems Case Study could establish cooperation.

Amt der Burgenländischen Landesregierung, Raumplanungsstelle, Eisenstadt
(Dipl.Ing. Grosina).

Amt der Oberösterreichischen Landesregierung, Gewaseraufsicht, Linz
(Dr.Müller)

Arbeitsgemeinschaft Gesamtkonzept Neusiedlersee, Eisenstadt.

Biologische Anstalt Helgoland, F.R.G.
(Dr.Wulf Greve)

Biologisches Institut Neusiedlersee, Illmitz, Bgld.

Biologische Sation Lunz der Österreichischen Akademie der Wissenchaften, Lunz
(Dr.G.Bretschko)

Bundesinstitut für Gesundheitswesen und Umweltschutz, Wien.
(Dr.W.Katzmann, Dr.W.Pillmann).

Bundesinstitut für Gewässerforschung und Fischereiwesen, Scharfling, Mondsee;
(Dr.A.Jagsch).

Bundesministerium für Land- und Forstwirtschaft, Hydrographisches Zentralbüro, Wien
(MR Dr.Wiederstein).

Center for Ecological Modeling, Rensselaer Polytechnics Institute, Troy, New York
(Prof. R.A. Park)

Hydrobiological Laboratory, CSSR Academy of Sciences, Praha
(Dr.M.Straskraba)

Institut für Limnologie und Gewässerschutz der Österreichischen Akademie der Wissenschaften, Wien

Institut für Wasserwirtschaft, Berlin

Kärntner Institut für Seenforschung, Klagenfurt, Carinthia.

Massachusets Institute for Technology, Ralph M.Parson Laboratory for Water Resources Management and Hydrodynamics, Boston
(Prof.D.R.F. Harleman)

Österreichisches Eutrophie Programm, Projekt Salzkammergutseen, Weyregg, Upper Austria.

Universität Hamburg, Institut für Meereskunde,
(Dr.H.-G. Ramming)

Universtät Göttingen, Institut für Paläontologie und Geologie,
(Prof.J.Schneider)

Versuchs- und Forschungsanstalt der Stadt Wien, MA39
(Dr.Maurer)

Zentralanstalt für Meteorologie und Geodynamik, Wien Hohe Warte 38
(Dr.Neuwirth)

Zoologisches Institut der Universität Wien, Lehrkanzel für Limnologie, Wien.

(B) Publications and publication projects

This section compiles all contributions to the Austrian Lake Ecosystems Case Study published so far, including their abstracts, as well as a listing of publication projects which are under work and can be foreseen to be completed during the run time of the project. The list also includes contributions which originated during the preparatory stage of the project.

Already published:

Fedra,K. 1979 Angewandte Systemanalyse im Rahmen des Österreichischen Eutrophie- Programmes, Projekt Salzkammergutseen. In: Arbeiten aus dem Labor Weyregg, 3/79, Jahresbericht 1978, 121-130.

ABSTRACT:

A stochastic approach to the dynamic modeling of the Attersee is introduced. Using Imboden's phosphorus model SEEMOD 2 (Imboden and Gächter 1978), the influence of the phosphorus loading from the Mondsee discharge on the trophic state of the Attersee, defined as primary production per unit lake area, is studied. According to the typically high uncertainty in the data base and consequently also in the model parameters resulting from standard calibration techniques, a stochastic approach is chosen. A semiquantitative definition of the problem-defining "typical systems behavior" is given, incorporating data uncertainty and the stochastic variability in almost five years of field observations. The parameter space, defined by the ranges of the parameters for the simulation model, were based on Attersee field data as well as on literature values, is then explored by Monte Carlo techniques. Referring to the problem-defining systems behavior, a behavioral classification of different regions of the parameter space is made. The analysis of the parameter space is a kind oof sensitivity analysis, where emphasis is put on parameter combinations and their interdependencies. The conclusions from the analysis should allow one to judge model adequacy, further data requirements, and thus possible improvements in the field research strategies. It could also possibly lead to careful and critical predictions on the lake's response to changes in the Mondsee discharge.

Fedra,K. 1979 Modeling Biological Processes in the Aquatic Environment; with special reference to adaptation. WP-79-20, 56 pp, International Institute for Applied Systems Analysis, Laxenburg, Austria.

ABSTRACT:

Based on some of the most recent contributions to the field of biological modeling within the frame of ecosystems analysis, some aspects of modeling eco-physiological processes in the aquatic environment are discussed. First, a few rather general comments are made on the predictive capabilities of complex ecosystems models, and the related need to use more realistic and causal descriptions for various complex biological processes. Following this, some ideas and formulation, guided by the above priciples, are compiled and discussed. The use of more realistic representations of biological processes, including time-variable parameters, is advocated, and several approaches are compared. Key factors such as temperature, light or nutrients are considered with regard to the basic biological control mechanism of adaptation. The inclusion of adaptation phenomena in the representation of, for example, effects of temperature, light dependency of primary production, or nutrient uptake kinetics, is described on different levels of mechanistic detail and complexity, and as a holistic feature. This is also an attempt to reduce dimensionality in complex models by increasing the realism in the description of functionally heterogeneous lumped compartments and thus avoiding separate detailed description of their major component elements. In addition to the adaptation in single-species populations, the problem of community adaptation in multi-species populations, represented in most ecosystem models by lumped variables and averaged parameters, is considered in relation to environmental fluctuations and environmental uncertainty. A concept of environmental tracking is proposed, represented by the relation of parameter values to their governing input variable and state variables, as a major adaptive strategy for biotic systems.

Fedra,K. 1979 A Stochastic Approach to Model Uncertainty: a lake modeling example. WP-79-63 46pp, International Institute for Applied Systems Analysis, Laxenburg, Austria.

ABSTRACT:

A stochastic approach for modeling uncertain and incompletely known ecosystems, using a lake modeling example, is proposed. In order to estimate the reliability and precision of model predictions based on uncertain data from ecological systems, the explicit inclusion of the uncertainty in the numerical modeling approach is advocated. Starting with a fuzzy definition of of systems behavior in terms of a behavior space region, the corresponding region in the data space of a given model is explored by Monte Carlo techniques. A set of data vectors -- random samples from the data space region corresponding to the empirical range of systems behavior -- is then used to generate independent estimates of states or outputs for selected deterministic inputs. These estimates have to be understood as random samples from a probabilistic behavior space, which reflects the initial uncertainty in the data space delimitation. The estimates are used to establish probability distributions for systems states or outputs (cross-sections of the probabilistic behavior space) for given input conditions. These probability distributions replace the deterministic point-estimates of a traditional approach, and reflect the incomplete knowledge about the system as well as the stochastic variability of ecosystems. The approach is extended for long-term simulations of systems

behavior under changed input conditions, and estimates of prediction accuracy in time are obtained.

Fedra,K.,van Straten,G. and Beck,M.B. 1980 Uncertainty and arbitrariness in ecosystems modeling: a lake modeling example. WP-80-87, International Institute for Applied Systems Analysis, Laxenburg, Austria; 39pp.

ABSTRACT:

Mathematical models of ecosystems are considerable simplifications of reality, and the data upon which they are based are usually scarce and uncertain. Calibration of large, complex models depends upon arbitrary assumptions and choices, and frequently calibration procedures do not deal adequately with the uncertainty in the data describing the system under study. Since much of the uncertainty and arbitrariness in ecological modeling is inevitable, because of both practical as well as theoretical limitations, model-based predictions should at least reveal their dependence on, and sensitivity to uncertainty and arbitrary assumptions. The paper proposes a method that explicitly takes into account the uncertainty associated with data for modeling. By reference to a partly qualitative and somewhat vague definition of system behavior in terms of allowable ranges, an ensemble of acceptable parameter vectors for the model may be identified. This contrasts directly with a more conventional approach to model calibration, in which a quantitative (squared-error) criterion is minimized and through which a supposedly "unique" and "best" set of parameters can be derived. The ensemble of parameter vectors is then used for the simulation of a multitude of future systems behavior patterns, so that the uncertainty in the initial data and assumptions is preserved, and the thus predicted future systems response can be interpreted in a probabilistic manner.

Fedra,K. 1980 Numerische Simulation der Wasserqualität: ein Phosphor-Szenarium für den Attersee. In: Attersee Jahresbericht 1979, Arbeiten aus dem Labor Weyregg 4/1980, 194-212.

ABSTRACT:

Based on a simple simulation model of lake phosphorus dynamics, an analysis was made of the relationship between phosphorus loading and trophic state of the Attersee. Taking the uncertainty of the available data explicitly into account in the numerical analysis and simulation, the long-term response of the lake to relative changes in its nutrient loading was simulated. The influence of changed phosphorus loading and time on measures of water quality such as total primary production, algae peak biomass, or ortho-phosphate maximum as well as on the phosphorus budget of the lake, were estimated in terms of probability distributions.

<u>In press</u>:

Fedra,K. Estimating Model Prediction Accuracy: a stochastic approach to ecosystem modeling. Proc of the 2nd State of the Art Conference in Ecological Modeling, Liege, Belgium, 1980

ABSTRACT:

Ecosystems are, as a rule, characterized by a large behavioral repertoire showing a high degree of structural variability and complex control mechanisms such as adaptation and self-organisation. Our quantitative understanding of ecosystems behavior is generally poor, and field data are notoriously scarce, scattered, and noisy. This is most pronounced on a high level of aggregation where considerable sampling errors are involved. Also, no well established and generally accepted ecological theory exists, so that an operational ecosystem model consists of many more arbitrary, simplifying assumptions (more often than not implicitly hidden in process descriptions) than properties measurable in the field. Consequently, predictions of future systems behavior under changed conditions -- a most desirable tool for environmental management -- cannot be precise and unique in a deterministic sense. Rather, it is essential to estimate the levels of model reliability and the effects of various sources of uncertainty on model prediction accuracy. A concept of allowable ranges for model data-input and expected model response, explicitly including uncertainty in the numerical methods, is proposed. Straightforward Monte Carlo simulation techniques are used, and the approach is exemplified on a lake ecosystem eutrophication problem. The method attempts to predict future systems states in terms of probability distributions, and explores the relations of prediction accuracy to data uncertainty and systems variability, the time horizon of the prediction, and finally the degree of extrapolation in state- and input-space relative to the empirical range of systems behavior. The analysis of almost 100,000 model runs also allows some conclusions on model sensitivity, and some desirable model properties in light of prediction accuracy are identified.

Fedra,K. Pelagic food web analysis: hypothesis testing by simulation. (presented for the 15th EMBS, Kiel, 1980) Kieler Meeresforschung

ABSTRACT:

Energy flow and material cycling in aquatic environments can be conceptualized in terms of food webs, linking various taxonomic or functional biological compartments and their physical environment. Interpretation of empirical data and finally a functional understanding of the systems studied, requires a high degree of abstraction and aggregation. The complexity and variability of environmental systems, the scarcity of appropriate observations and experiments, and the lack of a well established theoretical background make it difficult to test any possible conceptualization, or hypothesis, describing a given system. A formal approach to hypothesis testing, based on numerical simulation, which explicitly considers the above constraints, is proposed.

Based on a data set from the North Sea, a series of hypotheses on the structural relations and the dynamic function of the pelagic food web is formulated in terms of numerical models. Hypotheses of various degrees of aggregation and abstraction are tested by comparing singular statements (predictions) deduced from the proposed hypotheses (the models) with the observations. The basic processes of primary production, consumption, and remineralization, driven by light, temperature, and advection/diffusion, are described in systems models ranging in complexity from two compartments to many compartments and species groups. With each of the proposed models, a yearly cycle of the systems behavior is simulated. The comparative analysis of the response of each of the models allows conclusions to be drawn on the adequacy of the alternative hypotheses. This analysis also allows one to reject inadequate constructs, and provides some guidance on how to improve a certain hypothesis, even in the presence of a high degree of uncertainty.

Fedra,K. Mathematical Modeling -- a management tool for aquatic ecosystems? Helgoländer wiss.Meeresuntersuchungen 34/4 (1980)

ABSTRACT:

Mathematical modeling may serve as a rational and powerful tool in the management of complex ecosystems. However, ecosystems models are drastic simplifications of the real world. As a rule they are based ona rather incomplete and scattered knowledge of the system in question. Furthermore, ecological systems and in particular marine systems are characterized by a high degree of complexity, spatial and functional heterogeneity, complex behavioral features such as adaptation and self-organisation, and a considerable stochastic element. Nevertheless, if management is to be based on predictions from mathematical models--and it has to be based on some kind of "model" in at least a broad sense--we need an estimate of prediction accuracy in terms of the management variables and constraints. One possible approach to model uncertainty is a probabilistic interpretation of model predictions, generated by use of Monte-Carlo techniques. Fuzzy data sets and ranges are used. The resulting model respose allows the derivation of measures for model credibility. Probability distributions can be computed for certain system states under (un)certain input conditions, representing the effects of insufficient data and structural uncertainty on model-based predictions. Such analysis indicates that prediction uncertainty increases, not only with the uncertainty in the data, but alo with increasing "distance" from the empirical conditions, and with time. Present ecosystem models can be a tool for qualitative discrimination between different management alternatives, rather than a credible means for detailed quantitative predictions of system response to a wide range of input conditions.

Fedra,K. Nährstoffhaushalt und Wasserqualität: Systemanalyse und numerische Simulation (presented at the 6th Neusiedlerseetagung, Illmitz, Bgld.)

ABSTRACT:

Die vorliegende Arbeit beschreibt ein aus mehreren gekoppel-

ten numerischen Simulationsmodellen aufgebautes System zur Beschreibung und Analyse des Problemkreises der Wasserqualität in Abhängikeit vom Nährstoffhaushalt für den Neusiedler See unter Einbezug des Schilfgürtels. Die Koppelung von hydrodynamischen Transportprozessen und biologisch-chemischen Umsetzungsprozessen soll eine umfassende Analyse der Funktion des Gesamtsystems erlauben. Das Modellsystem wird in erster Linie von meteorologischen Grössen gesteuert, und berücksichtigt die Möglichkeit von Schilfschnitt und -export als Kontrollmassnahme. Zahlreiche punktuelle wie diffuse Närstoffeinfuhren können individuell beschrieben werden, um einen Vergleich realistischer Szenarien von Kontrollmassnahmen zu ermöglichen. Die Probleme der Datenerfordernisse, Modellungenauigkeiten, und der Interpretation von numerischen Simulationsergebnissen werden diskutiert.

Accepted for publication:

Fedra, K. A Monte Carlo approach to estimation and prediction. Proceedings of the IIASA workshop on Model Uncertainty and Forecasting. IIASA Conference Paper (M.B.Beck, G.van Straten eds.)

ABSTRACT:

Forecasting the water quality of a given aquatic ecosystem by means of a mathematical simulation model is subject to various sources of uncertainty. The ecosystem to be modeled is generally a diverse, large-scale system, with a rich behavioral repertoire, a considerable degree of variability in the driving environmental factors and in its structure, and with complex feed-back and internal control mechanisms. The understanding of the governing processes in such systems on the level of abstraction, aggregation, and simplification, characteristic of formal models, is poor, and a unifying ecological theory is lacking. The data available about environmental systems are usually scarce, scattered and typically connected with a considerable level of measurement and sampling errors. Finally, models of ecosystems are by necessity gross simplifications and require numerous arbitrary assumptions in their construction.

Estimating model structure and parameters under the above constraints is therefore subject to uncertainty, and this uncertainty should also be reflected in model based predictions. The paper discusses the relationship between estimation and prediction under uncertainty for a Monte Carlo approach to lake water quality simulation. Using a concept of allowable ranges to constrain the model response in the estimation procedure, uncertainty is explicitly accounted for. This results in an ensemble of parameter sets, characterized by a certain variability and correlation structure. Forecasting by means of such an ensemble allows for an interpretation of the model response-ensembles generated in terms of probabilities, and reflects the initial uncertainty in the information available for the modeling exercise.

** Monte Carlo Simulation. In: Parameter Estimation in Ecological Modeling, S.E.Jorgensen ed. (invited chapter contribution to the above book).

Under work:

** A Phosphorus Budget for an Oligotrophic Lake (Attersee, Austria): estimating errors and probabilities. ?? in prep. (together with A.Jagsch, O.Moog, G.Mueller and F.Neuhuber) IIASA CP

ABSTRACT:

A phosphorus budget was established for a deep (Z_{max}: 171 m), oligotrophic lake of 3934 10^6 m^3 volume, a surface area of 46 km^2, and an average hydraulic loading of 17.5 $m^3 sec^{-1}$ (Attersee, Austria). To arrive at an estimate of accuracy of the phosphorus budget, established from measurements on imports/exports, some detailed analysis of the field data (covering the years 1975 to 1979) was carried out. Several empirical black-box steady-state models were used to summarize these calculations. In parallel, taking advantage of the available time series of lake-phosphorus concentrations and algae biomass data, a dynamic numerical compartment model was used to simulate the phosphorus balance of the lake. Uncertainty in the data input was explictly included in the numerical simulation, using a concept of fuzzy data and behavior of the model. A set of estimates for the variables of the simplified yearly steady-state balance equation

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was thus derived from (a) the analysis of field data and direct observations; (b) comparative application of several black-box steady-state models; and (c) the integration of a dynamic simulation model. Including the uncertainy in data and models explictly into the analysis, allowed for a probabilistic interpretation of the respective magnitudes, providing an estimate of their reliability. The models were also used for estimates of a phosphorus budget under changed loading conditions. Field data analysis and the results of the parallel model applications are discussed in light of eutrophication control and environmental management.

Fedra,K. and Moog,O. Lake Water Quality in a Watershed Framework: the Attersee-region (Salzkammergut, Austria). IIASA CP

ABSTRACT:

Lake water quality in its interdependency with the physical as well as socio-economic aspects of the surrounding watershed is discussed, using the example of the catchment area of the river Ager (Salzkammergut, Austria). This catchment basin of about 460 km^2 contains four major lakes. The area is a traditional tourist resort, and various and partly conflicting forms of land- and wateruse can be identified. Based on a spatial disaggregation of the area in sub-watersheds and unit-land areas, a major factor influencing lake water quality -- namely nutrient runoff -- is estimated in close coupling to the water

budget of the area. Estimating nutrient runoff takes into account for each of the sub-regions considered the point sources identified (i.e. domestic sewage and industrial runoff) as well as the non-point sources of surface runoff and interflow from forests and agricultural areas. Including waste-water treatment and sewage diversion, and coupling the individual areas, a dynamic accounting is made for the nutrient loadings of the individual lakes. These loading estimates are then used with models of lake water quality and in-lake nutrient transformation, which again, by the lake's outflow, feed back into the system and the overall nutrient budget. This dynamic nutrient budget -- which can be formulated in terms of functional as well as spatial units -- allows a comparative estimate of the relative contributions from major sources, and their effect on the overall water quality situation, and finally to study the relative impacts of various possible (or already implemented) control measures, taking into account costs and benefits of alternative planning and management options.

Projects pending:

?? Modeling Lake Eutrophication Control: simulation of sanitation and restauration and the long-term prediction of lake response (together with N.Schulz and L.Schulz) IIASA CP

?? Nutrient Budgets of Coupled Lake Systems: Fuschlsee-Mondsee-Attersee (Salzkammergut, Austria). IIASA CP together with a group of Austrian limnologists.

?? Phosphorus and Oxygen dynamics of a stratified, eutrophic lake: Mondsee, Salzkammergut. (together with A.Jagsch)

?? Water Quality Modeling: a case study of Austrian lake ecosystems. Study (to be prepared for the OECD workshop on lake management)

?? Modeling Ecosystems Dynamics: on the estimation of time-variable process rates (to be prepared for the 16th EMBS in Texel)

?? Model systems and systems of models: a case study of lakes and watersheds (to be prepared for the 3rd ISEM meeting, Fort Collins, Collorado, May 1982.

?? Dynamics of stratified lakes: coupling of physical and ecological processes [Salzkammergut, ev. Kärnten] (joint project with Prof.D.R.F.Harleman)

?? Modeling the water quality of old river branches: a contribution to the UNESCO/MaB project "Untere Lobau" IIASA CP

?? Background data report for lake modeling: Neusiedlersee (Austria) IIASA CP (together with A.Herzig)

?? Background data report for lake modeling: Attersee, Mondsee, Fuschlsee Irrsee (Salzkammergut, Austria). IIASA CP

?? Zum Wasserhaushalt des Neusiedlersee-Gebietes: flächenhafte Abschätzung der Grundwasserneubildung. ÖWW (together with K.-H.Zwirnmann, R.Enderlein)

?? Air pollution and water quality: coupling the media. IIASA WP together with E.Runca

?? Adaptation and Self-Organization in Multi-Species Phytoplankton Communities: a modeling approach. (IIASA CP) (together with M.Straskraba).

?? Lake Water Quality as a Resource Management Problem: a case study of Austrian lake systems. proposal for a IIASA-Wiley Series book.

(C) A selective bibliography on methods and applications

This selected bibliography is split into three major parts, the first one including the references cited in the above report, and background information on the Austrian lakes studied. The second part contains a collection of references on environmental systems analysis in general, providing a somewhat broader interdisciplinary framework for the third part, which concentrates on water quality problems, and specifically on aspects of lake ecosystems management and eutrophication control. The latter section is biased towards modeling and model application.

PART 1: Literature cited and background information on Austrian lakes

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