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# APPLICATION OF AN ECOLOGICAL SIMULATION MODEL TO LAKE PÄIJÄNNE

Tiivistelmä

**Simulointimallin soveltaminen Pohjois-Päijänteelle**

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The one-dimensional, deterministic lake ecological simulation model EPAECO was applied to the northern sub-basin of Lake Päijänne in Central Finland. The model was calibrated with the data of 1974 and verified with the corresponding data of 1975 and 1976. The criteria of calibration and verification were subjective. The model was capable of reasonably good simulation of temperature, dissolved oxygen, pH, ammonia nitrogen, nitrate nitrogen, phosphate phosphorus of epilimnion, and the average values of phytoplankton biomass. In addition it reacted correctly to alternative BOD and phosphate phosphorus loadings. However, it could not simulate the observed phytoplankton maxima and the phosphate phosphorus of hypolimnion. Chemical state variables were consistently simulated better than the biological ones. The model appeared to be suitable for making prognoses of water quality, although the simulated results should be interpreted with care.

Index words: Mathematical models, water quality models, ecological models, simulation models, EPAECO-model, water quality prediction, Lake Päijänne.

## 1. INTRODUCTION

One of the tasks of the National Board of Waters is to promote water research, which includes production of water quality data concerning Finnish watercourses. The number of water samples taken and analysed by the National Board of Waters has steadily increased. In 1970 the number of samples was 25 000 while in 1976 it was 45 000. The corresponding numbers of analyses carried out from these samples were 240 000 and 350 000, respectively (National Board of Waters 1977). The data obtained are stored in the water quality register of the National Board of Waters. The number of analyses stored in the register increases by about 300 000 per year. It was therefore considered to be of some importance to ascertain how this data could effectively be used in water management.

One way of utilizing this information is to apply water quality models to lakes and rivers. The National Board of Waters (1976) expressed the need for water quality models as follows: "The planning of water resources needs water quality models that can be used to predict the effects of various loading alternatives on the water quality of lakes, rivers and reservoirs". This implies that water quality models should

be used as a predictive tool in water management and decision-making. However, before water quality models can be used in water management their suitability for this purpose should be tested.

Simulation models are one category of water quality models, in which the aquatic ecosystem is examined as a complete unit. The interactions between the most important factors within the ecosystem are described by differential equations. These factors are often divided into driving variables, state variables and rate variables (de Wit and Arnold 1976). Driving variables, for example rainfall and light, affect the ecosystem although they are external to it. State variables, for example dissolved oxygen and phytoplankton biomass, describe the state of the ecosystem. The values of state variables change as they react with driving variables, other state variables or both. Rate variables characterize the rate of change of state variables at a certain instant. Simulation models usually include several state variables and therefore these models require considerable amounts of data.

Several institutes and universities are engaged in the investigation of water quality models. For example, the International Institute for Applied Systems Analysis (IIASA) is very active in this field. Numerous simulation models have been described in the literature, for example Chen and Orlob (1972), Di Toro et al. (1975), Kelly (1975), Kremer and Nixon (1975), O'Connor et al. (1975), Park et al. (1975) and Gargas (1976). A comprehensive treatise dealing mainly with water quality models has also been published (Ott 1976). Kinnunen et al. (1977, 1978) have described the use of water quality models in Finland. Jørgensen (1978) emphasized that existing models should be applied to different types of water bodies and discouraged model construction if the models are not tested against actual field observations.

This report, carried out as part of the KVT-project (National Board of Waters 1978), presents the results of a case study in which the one-dimensional deterministic simulation model EPAECO (Gaume and Duke 1975) was applied to the northern sub-basin of Lake Päijänne. The model was calibrated with the data of 1974 and verified with the corresponding data of 1975 and 1976. The agreement between the simulated and observed values is evaluated. In addition, the model was used to calculate the effects of four loading alternatives on the water quality of the lake. The use of the model as a management tool is discussed and some suggestions are presented for its further development.

## 2. DESCRIPTION OF THE MODEL

### 2.1 The aquatic ecosystem

The EPAECO model is a one-dimensional deterministic simulation model developed for reservoirs and lakes. Chen and Orlob (1968) and Chen (1970) have presented the principles and equations of the model, and on this basis Chen and Orlob (1972) developed a model for Lake Washington. The U.S. Environmental Protection Agency modified slightly the Lake Washington model, naming the new version the EPAECO-model (Gaume and Duke 1975). The details of the model have been presented in the original articles (Chen and Orlob 1972, Gaume and Duke 1975), and only a brief description of the model will be given here.

The EPAECO-model, like every simulation model, is a simplified representation of the true aquatic ecosystem. Fig. 1 shows the structure of the ecosystem used in the model. The aquatic ecosystem is composed of water, its chemical impurities and different organisms living in the water. Substances are transferred to the ecosystem from soil, air, surrounding waters and through the activities of man.

Phytoplankton produces complex organic compounds from inorganic substances. These organic compounds serve as sources of energy for various animals, for example zooplankton. Dead organisms form detritus which is degraded by micro-organisms into simpler compounds.

Substances dissolved in, and organisms living in the water as well as organic sediment are state variables of the ecosystem. State variables interact through physical, chemical and biological reactions, which in the present content are referred to as rate variables or ecological processes. Ecological processes alter the values of state

variables and therefore transfer the whole ecosystem from one state to another.

Physical processes transfer component substances of the ecosystem by various routes, including the input and output waters of the ecosystem, advection, diffusion, sedimentation and the transfer of substances across the air-water interface. All substances are not transferred by the same mechanisms. For example carbon dioxide and oxygen are transferred only through the water surface. Fish move actively and are unaffected by diffusion and advection. Chemical processes include for example changes in pH and carbon dioxide concentration as well as chemical degradation of biological material. Organic nitrogen consumes oxygen as it progresses through the reactions:

organic matter → $NH_3$ → $NO_2$ → $NO_3$.

The arrows in Fig. 1 show the ecological processes representing the interactions between state variables and the environment of the aquatic ecosystem. Ecological processes include growth, respiration and death of organisms and reactions connected with these processes.

Water quality and the biological reactions of the ecosystem are strongly interrelated. For example organisms alter their environment by utilizing nutrients for their growth and excreting by-products.

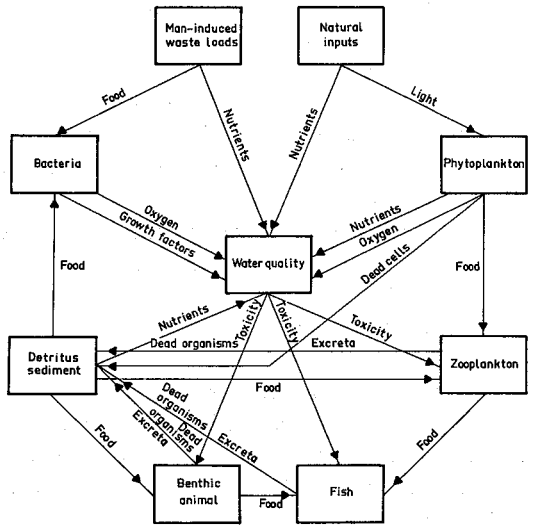


**Fig. 1. Conceptual model of an aquatic ecosystem (Gaume and Duke 1975).**

## 2.2 Principles of the model

The EPAECO-model is based on two fundamental principles, namely the Law of Conservation of Mass and the Kinetic Principle. The Kinetic Principle states that the rate of change in the mass of a variable is equal to the product of a coefficient and the concentrations of one or more variables that interact to cause the change. The values of the coefficients are obtained from field or laboratory measurements, from the literature or by calibration.

## 2.3 Hydraulic elements and time interval

The model assumes that all transfers of mass and energy occur only along the vertical axis of a lake. The lake is divided into laminar sections with planes parallel to the surface of the lake. These sections are called hydraulic elements (Fig. 2). The mass and energy balance equations of the model are applied to these elements. Hydraulic elements are treated as continuously stirred tank reactors with homogeneous properties. Simulated results are interpreted as being average conditions across the lake at a particular elevation. Water, solutes and organisms living in water are transferred from one element to another by advection and diffusion.

The state of a lake, which is described by the values of state variables, is a function of time. Consequently the aquatic ecosystem is dynamic. Time is divided in the model into short, discrete intervals, during each of which it is assumed that each hydraulic element is in a steady state. Thus the dynamic aquatic ecosystem is simulated as a number of sequential steady states. If the time interval is short enough the simulation can be carried out without significant error. The user of the model can select the length of the time interval within certain limits.

## 2.4 Input

### 2.41 Initialization data

Initialization data (Fig. 3) includes all the information required to control the computer program of the model and to describe the state of

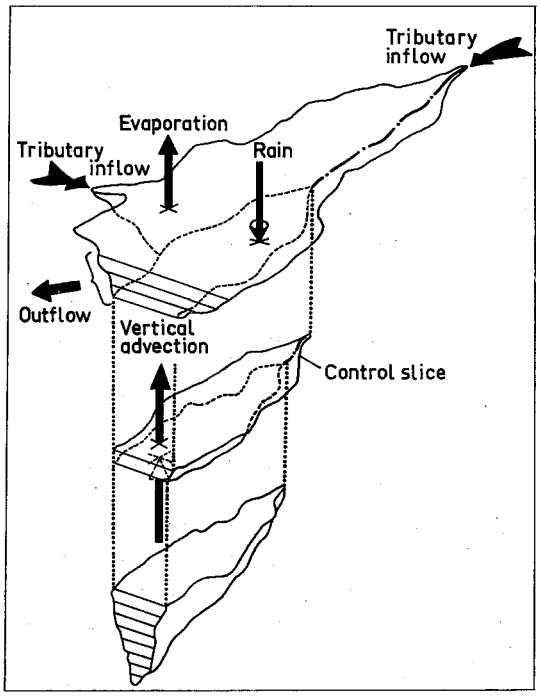


Fig. 2. Geometric representation of a stratified lake (Gaume and Duke 1975, redrawn).

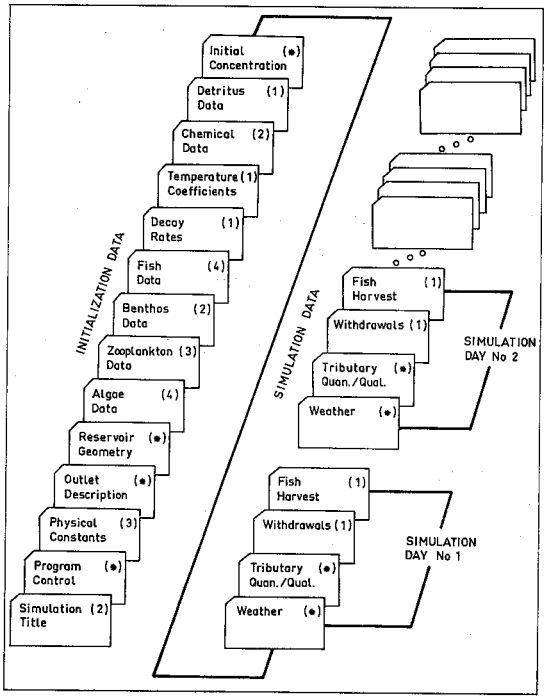


Fig. 3. EPAECO data file. The number in parenthesis indicates the number of data cards in the data set. An asterisk (*)indicates that the number of data cards in the set is variable (Gaume and Duke 1975).

a lake at the beginning of the simulation. Initialization data includes the following information:

- simulation title
- parameters to control the simulation program
- physical constants
- outlet description
- lake geometry
- phytoplankton data
- zooplankton data
- benthos data
- fish data
- decay rates
- temperature coefficients
- chemical data
- detritus data
- initial values for the state variables of the model which are: temperature, dissolved oxygen, biochemical oxygen demand, alkalinity, pH, ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, phosphate phosphorus, coliforms, phytoplankton (two groups), zooplankton, suspended detritus, total dissolved solids, organic sediment, benthic animals and fish (three groups). Carbon dioxide is also a state variable of the model. However its value is calculated using the principles of equilibrium chemistry, from the known alkalinity, total dissolved solids and total inorganic carbon concentrations, and no initial value is needed. The model contains a computer code that reproduces the nomographic relations described in standard methods (American Public Health Association, Inc 1965 pp. 78–81).

Initialization data are fed to the model only at the beginning of the simulation period.

### 2.42 Simulation data

The values of the driving variables of the model form the simulation data (Fig. 3). This information includes weather data, quality and quantity of waters entering the lake, outlets from the lake and fish harvest data.

Simulation data must be fed to the model once during every time interval.

## 2.5 Output

At the beginning of every simulation the model prints out the number of simulation days, number of tributaries, values of coefficients, water stage and the areas and volumes of hydraulic elements. In addition, on desired days the model prints out information including values of solar radiation, wind speed, water stage and biomasses of three fish groups as well as the values of state variables for every hydraulic element. The model prints out a considerable amount of additional information which assists both reading of the simulated values of state variables and calibration of the model.

# 3. APPLICATION OF THE MODEL

## 3.1 Case study lake

The model was applied to northern sub-basin of Lake Päijänne. This lake is situated in Central Finland and is one of the most thoroughly investigated Finnish lakes. A relatively good set of historical data concerning the water quality of this lake therefore exists. The protection of Lake Päijänne is important because the city of Helsinki and its neighbouring municipalities will start to utilize water from this lake in the near future.

According to Tuunainen et al. (1971) the area of Lake Päijänne is 1 090 $km^2$, its volume 17.8 $km^3$, maximum length 120 km, maximum breadth 28 km, maximum depth 104 m, average depth 17 m and mean discharge 209 $m^3s^{-1}$. Assuming a mean discharge of 209 $m^3s^{-1}$ the theoretical detention time is 986 days.

Mäkinen et al. (1975) have divided the lake into five sub-basins (Fig. 4). This division is based on the bottom profile and differences in water quality. The model was applied to the sub-basin No. 1, and sampling station No. 570 was selected as the simulation point. Thus is was assumed that the water quality of this point represents the water quality of the whole sub-basin.

According to Lappalainen and Mäkinen (1974) the area of sub-basin No. 1 is 142 $km^2$, its volume 2.53 $km^3$ and average depth 18 m. If it is assumed that the discharge from this sub-basin is the same as the discharge from the whole lake (209 $m^3s^{-1}$), the theoretical detention time is 140 days. The length of the sub-basin is 28 km and its maximum breadth 16 km, as measured from the map of the lake.

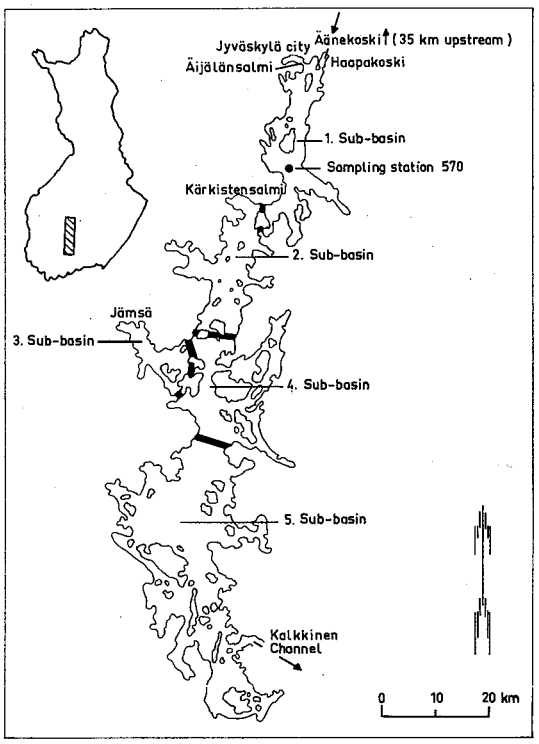


Fig. 4. Division of Lake Päijänne into sub-basins (Mäkinen et al. 1975).

Water authorities commenced investigation of Lake Päijänne in the beginning of the 1960's. Material balances of the lake were calculated more recently (Lappalainen and Mäkinen 1973, 1974, Mäkinen et al. 1975). The lake is one of those included in the eutrophication research being conducted by OECD. Lake Päijänne is polluted by waste waters of the wood-processing industry entering the lake from Äänekoski through the River Haapakoski. In addition the lake is polluted by domestic waste waters from the city of Jyväskylä as well as by domestic waste waters and paper mill effluents in the Jämsä area. Table 1 shows the total waste water loadings to the sub-basins of Lake Päijänne

and also to Lake Jyväsjärvi, which discharges its waters to sub-basin No. 1. Lake Päijänne has been regulated since 1968 (National Board of Waters 1972).

Table 1. Wastewater loadings entering the sub-basins of Lake Päijänne and Lake Jyväsjärvi expressed as $BOD_7$, total nitrogen and total phosphorus in 1975, calculated by the Water District Office of Central Finland. Loading of the River Haapakoski has been added to the loading of sub-basin 1.

| Region | $BOD_7$ $10^3$ kg d$^{-1}$ | Total nitrogen · kg d$^{-1}$ | Total phosphorus kg d$^{-1}$ |
|---|---|---|---|
| Sub-basin 1 | 45.7 | 1 447 | 121 |
| Lake Jyväsjärvi | 2.3 | 289 | 42 |
| Sub-basin 2 | 5.0 | 716 | 70 |
| Sub-basin 3 | 33.5 | 428 | 90 |
| Sub-basin 4 | - | 13 | 1 |
| Sub-basin 5 | - | 41 | 4 |

## 3.2 Sources of data

### 3.21 Initialization data

At the beginning of the simulation the model requires a number of program controls, which include the lengths of the simulation period and time intervals, the number of tributaries and output days. In addition the model requires values for physical constants: evaporation coefficients, thickness of hydraulic elements, diffusion coefficients and water stage.

Values of evaporation and diffusion coefficients used in simulation were taken from the test material of the Ferry Reservoir received with the documentation of the model (Gaume and Duke 1975).

Water flows out from sub-basin No. 1 only through the Kärkistensalmi sound. Because discharge measurements are not carried out at this sound, the discharges from sub-basin No. 1 had to be calculated according to the following equation:

$$Q^1_{out} = Q^1_{in} - \frac{A^1}{A}(Q_{in} - Q_{out}) \quad (1)$$

$Q^1_{out}$ = discharge from the sub-basin No. 1 ($m^3s^{-1}$)

$Q^1_{in}$ = discharge entering the sub-basin No. 1 ($m^3s^{-1}$)

$A^1$ = area of the sub-basin No. 1 ($m^2$)

$A$ = area of the whole lake ($m^2$)

$Q_{in}$ = discharge entering the whole lake ($m^3s^{-1}$)

$Q_{out}$ = discharge from the whole lake ($m^3s^{-1}$)

The areas and volumes of hydraulic elements, one meter in thickness, were measured from the bathymetric map of the lake. During the test runs of the model the coefficients for phytoplankton, zooplankton, benthos and fish as well as decay rates, temperature coefficients, chemical data and detritus data were taken from the simulation of Ferry Reservoir (Gaume and Duke 1975). Later on some of the coefficients had to be adjusted to conform with conditions prevailing in the case study lake.

Initial values of physical and chemical state variables were taken from the water quality register of the National Board of Waters. Initial values of biological state variables were taken or estimated from various sources as follows: phytoplankton values (Granberg and Holopainen 1973, Granberg et al. 1976, Granberg and Selin 1977), zooplankton values (Hakkari 1972), benthos values (Selin and Hakkari 1976) and fish values (Tuunainen et al. 1972), organic sediment values (Lappalainen and Mäkinen 1973, Mäkinen 1976). Detritus was not analyzed in Lake Päijänne and therefore values for this variable was taken from the simulation of Lake Washington (Chen and Orlob 1972). The concentration of coliform bacteria was assumed to be 10 bacteria per 100 ml.

Appendices 1–3 present the initial values of state variables used in the calibration run of 1974 and in the verification runs of 1975 and 1976, respectively.

### 3.22 Simulation data

Meteorological data were taken from the observations made at Jyväskylä airport, which is situated about 30 km northwest of sub-basin No. 1. The Meteorological Yearbook of Finland (1975, 1976) provided the following data for the years 1974 and 1975: cloud cover, temperature, wet bulb temperature, air pressure and wind speed. The corresponding data for the year 1976

were obtained from the Finnish Meteorological Institute.

Meteorological observations were made daily at 8.00 a.m., 2.00 p.m. and 8.00 p.m.. The length of the time interval chosen in the simulations was therefore eight hours and the meteorological data was fed to the model three times a day. Meteorological data for the three daily time intervals were calculated from the observations as follows: weather conditions at 4.00 a.m. were chosen to represent the time interval from midnight to 8.00 a.m. and the data for this point of time were calculated by extrapolating from the observations made at 8.00 a.m. and 2.00 p.m. Weather conditions at noon were chosen to represent the time from 8.00 a.m. to 4.00 p.m. and the data for this point of time were interpolated from the observations made at 8.00 a.m. and 2.00 p.m. The observations made at 8.00 p.m. were assumed to represent the time from 4.00 p.m. to midnight.

Water quality and the discharges of tributaries flowing to sub-basin No. 1 were obtained from the water quality register of the National Board of Waters. The daily values of discharges were calculated by interpolating from available observations. Thus the discharges of tributaries remained constant for three time intervals at a time in the model.

The loading from the Nenäniemi wastewater treatment plant of the city of Jyväskylä and the loading entering the sub-basin through precipitation and through runoff from the drainage basin were treated as if they were tributaries flowing to the lake.

The quality and quantity of waters entering the lake from the Nenäniemi wastewater treatment plant were obtained from the regular reports of the plant. Total phosphorus and total nitrogen were analyzed from the water leaving the plant, while phosphate phosphorus and ammonia nitrogen, which are state variables of the model, were not. Therefore it was assumed that the phosphate phosphorus concentration of the outflowing sewage water was equal to that of total phosphorus, and that the concentration of ammonia nitrogen was equal to that of total nitrogen. The values of the other state variables describing the quality of water outflowing from the plant were: oxygen 5.0 mg $l^{-1}$, pH 7.2 and coliform bacteria $5 \cdot 10^3$ bacteria per 100 ml. Temperature of the outflowing water was assumed to be the same as the temperature of the receiving river. BOD-values were obtained from the regular reports of the plant. It was assumed that other state variables of the model did not exist in the water of the wastewater treatment plant. Daily discharges outflowing from the plant were interpolated from observed monthly averages. The discharges were kept constant during groups of three consecutive 8-hour time intervals.

Precipitation data were obtained from the Hydrological Office of the National Board of Waters. Daily average precipitation values were calculated from observed average monthly values. The quality of rainwater was obtained from various sources described below. Phosphate phosphorus was not analyzed from rainwater. Therefore it was assumed that the loading of phosphate phosphorus in rainwater was equal, to that of total phosphorus, which was found to be 1.0 mg $m^{-2}$ $month^{-1}$ in investigations carried out by the laboratory of the National Board of Waters (S. Vuolas, personal communication).

According to the same investigation the nitrate nitrogen loading of rainwater was 12.0 mg $m^{-2}$ $month^{-1}$ and the pH value 4.8. Haapala (1972) has reported the alkalinity of rainwater to be 1.9 mval $m^{-2}$ $month^{-1}$. The concentrations of dissolved oxygen and total dissolved solids in rainwater were assumed to be 10 mg $l^{-1}$ and 50 mg $l^{-1}$, respectively, when calculating the loadings of these state variables entering the lake through precipitation. The temperature of rain was assumed to be equal to the temperature of the surface water of the lake.

The runoff from the immediate drainage area of the sub-basin was calculated using data gathered with measuring weirs. The average value of monthly observations of two measuring weirs, No. 71 (Ruunapuro, Laukaa) and No. 72 (Heinäjoki, Korpilahti) was used in the model. Therefore the value of runoff remained constant for one month at a time. The quality of runoff waters was obtained from various sources. According to Kauppi (1975) the average value for $BOD_5$ in Central and Eastern Finland is 1.6 mg $O_2$ $l^{-1}$, and this value was used for the $BOD_5$ of runoff

waters in the model.

The average value of total nitrogen in runoff waters for the whole country is 1 140 $\mu g\ l^{-1}$ and that of total phosphorus 66 $\mu g\ l^{-1}$ (Kauppi, personal communication). It was assumed that one third of the total nitrogen is ammonia nitrogen and one fourth is nitrate nitrogen, i.e. 380 $\mu g\ l^{-1}$ and 285 $\mu g\ l^{-1}$, respectively. Kohonen (1979) has reported that about half of the total phosphorus of runoff water is phosphate phosphorus. On the basis of this investigation and of the value of total phosphorus for the whole country the value for phosphate phosphorus was estimated to be 33 $\mu g\ l^{-1}$.

In the runoff waters the following values of other state variables were used: dissolved oxygen 11.9 mg $l^{-1}$, alkalinity 6.0 mg $l^{-1}$, pH 6.4 and total dissolved solids 50 mg $l^{-1}$.

The immediate drainage area of sub-basin No. 1 is 878 $km^2$. This figure was calculated by summing the areas of islands in sub-basin No.1, the drainage areas of the sub-basin (National Board of Waters 1972, p. 45) and the immediate drainage area of Lake Tohmajärvi (Seuna 1971, p. 14).

## 3.3 Calibration and verification

Calibration is a procedure in which the coefficients of the model are adjusted so that the model output agrees within certain limits with the observed results. The values of the coefficients can be allowed to vary only within the limits between which they are found to vary in reality. The values are obtained from laboratory measurements, field measurements or from the literature. Values for some coefficients cannot be found in this way and must therefore be determined during the calibration. Criteria for calibration are often rather subjective.

Verification is a procedure in which the calibrated model is used to simulate the response to a new set of data, substantially different from that used in calibration. The simulated results are compared with observed values using the same criteria for acceptance that were used in the calibration. If the criteria are met the model is considered to be verified and it can be used as a tool in planning and decision-making.

The model was calibrated with the data of 1974 and verified with the corresponding data of 1975 and 1976.

The documentation and the computer program of the model (Gaume and Duke 1975) were received from the U.S. Environmental Protection Agengy. The computer program was tested and some minor errors found in it were corrected. Ten simulation runs were required to test the program. Separate computer programs were written for processing the data obtained from the water quality register of the National Board of Waters.

At the beginning of calibration the values of the kinetic coefficients were taken from the test material received together with the documentation of the model. Later on some of the coefficients had to be adjusted to comply with Finnish conditions. Most of the reactions of the model are dependent on temperature and therefore the calibration of temperature was considered very important. The temperature program was separated fom the computer program of the model and temperature was first calibrated with this separate program. Later on, calibration was carried out with the whole model. The specific characteristics of Finnish waters, such as brown color due to humic substances and low temperature, were taken into account in the values of coefficients. Although the model includes two algal groups, only the total biomass of phytoplankton was simulated in this work.

During the calibration some minor changes were introduced to the computer program of the model. The temperature program was modified so that in the model the lake did not begin to stratify until the temperature of the whole water mass of the lake had reached 5.5 °C. After this modification the hypolimnion reached the right temperature before the lake began to stratify. The original version of the model printed out the water quality of tributaries and other sources of loading. This output was modified to include the quality of input waters and the masses of dissolved oxygen, $BOD_7$, ammonia nitrogen, nitrate nitrogen and phosphate phosphorus expressed as kg $d^{-1}$, brought to the lake through tributaries and other sources of loading, such as rain and wastewater treatment plant. In addition, graphical output was added to the model so that

the calculated and observed values of state variables could be read from the same figure. In calibrating the model 42 simulation runs were carried out. During calibration main attention was paid to those state variables of which observed data were available, especially to temperature, dissolved oxygen and phytoplankton biomass.

Simulations were started about three weeks after the breakup of ice in the lake, namely 23 May 1974, 27 May 1975 and 25 May 1976. These dates were selected as the initial dates because a large number of analyses for those days were available. The simulations were continued until the beginning of November. The lengths of simulation periods were about 170 days in all three years.

On the basis of observations for the years 1951–1970, the mean dates of freezing over and break up of ice of the lake were 15 December and 6 May, respectively (Lemmelä and Kuusisto 1975). The winter season, during which the lake is continuously icebound, cannot be simulated with this version of the model. Appendix 4 shows the values of coefficients used in the calibration and verification runs.

# 4. RESULTS OF CALIBRATION AND VERIFICATION

## 4.1 General

The calibration results of 1974 and the verification results of 1975 and 1976 are presented below. The calculated results are compared with the observed values twice during each simulation year, in the middle of June and at the end of August. Comparisons were carried out in 1974, on June 12 and August 21, in 1975 on June 18 and August 26 and in 1976 on June 14 and August 18. In 1976 the observed results are those of August 18 but the simulated ones are those of August 19. These dates were selected because of the large number of analyses available. However, the observed and simulated values of all the state variables could not be compared because of the lack of observed data. Figures 6–16 present the simulated and observed values, or in some cases only the simulated values, of the most important state variables. In addition to this a short description of the state variables presented in the figures as well as of other state variables will be given.

It may be pointed out that the simulated results of those state variables of which no observed data were available could not be calibrated and therefore the simulated results of these variables should be interpretated with care.

Fig. 5 shows the simulated and calculated values of water stage. Accurate simulation of water stage was important, because most of the state variables are expressed as concentrations.

## 4.2 Physical and chemical state variables

### 4.21 Temperature

Fig. 6 shows the simulated and observed temperatures.

In 1974 the difference between the simulated and observed temperatures was greatest near the surface of the lake in June, when the simulated values were about 3 °C higher than the observed ones. In elements 1–20 the simulated and observed temperatures were the same. In August the simulated and observed temperature curves had the same shape, the maximum difference being about 1–2 °C.

In 1975 the simulated temperature curve followed closely the observed values both in June and August. The maximum difference between simulated and observed values was about 1 °C in June while in August it was 1.5 °C.

In June 1976 the simulated values of the uppermost five meters of the lake were 0.5–4 °C higher than the observed ones. However, at deeper levels the agreement between the simulated and observed values was good. In August the model calculated a somewhat steeper thermocline than was observed. The observed values were higher than the simulated ones throughout the whole water column the maximum difference of about 4 °C being in the lower section of the thermocline, in element 60.

### 4.22 Dissolved oxygen

Fig. 7 shows the simulated and observed values of dissolved oxygen.

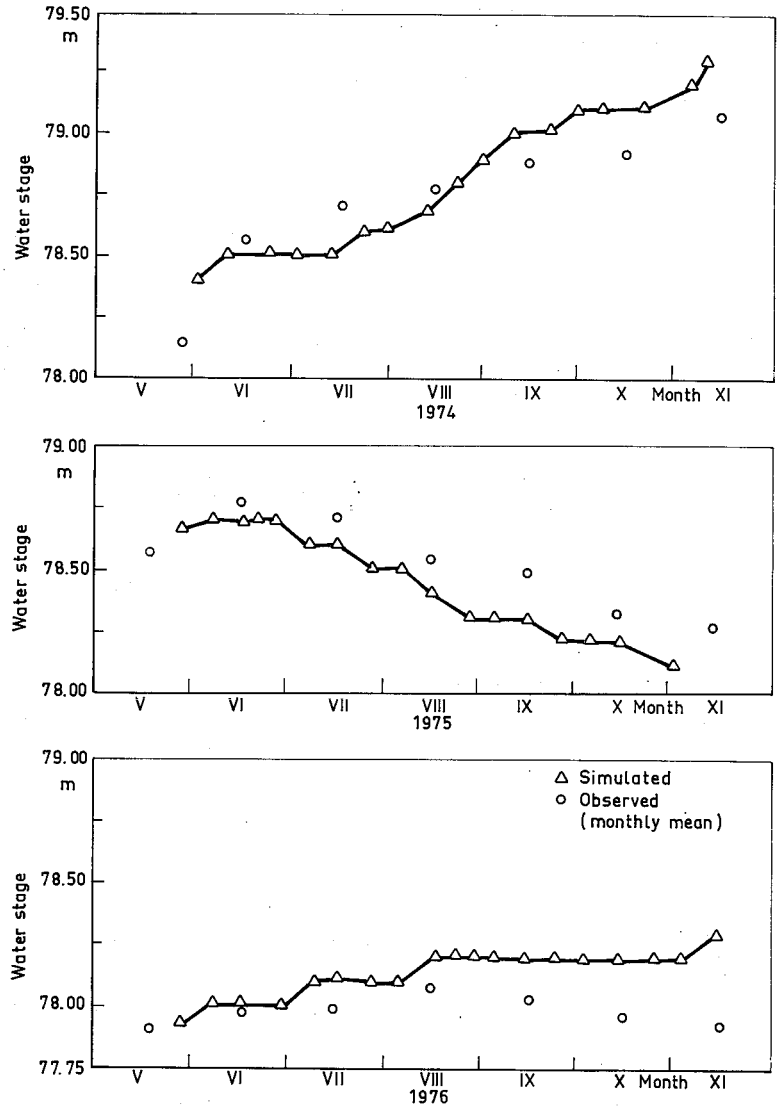


Fig. 5. Observed (o—o) and simulated (△—△) water stage of the calibration year 1974 and of the verification years 1975 and 1976.

In 1974 the simulated dissolved oxygen values were slightly higher in June than the observed ones, with the exception of elements 35—40. The greatest difference was found in the water layer nearest to the bottom of the lake. In August the simulated values of epilimnion were about 1.5 mg $l^{-1}$ higher than the observed values, while in the water layer next to the bottom the difference was less than 1 mg $l^{-1}$.

In June 1975 the simulated values of dissolved oxygen were very close to the observed ones in the uppermost ten meters of the lake, while in the water layer close to the bottom the observed values were about 1 mg $l^{-1}$ greater than the simulated ones. In August the model simulated a somewhat steeper stratification of oxygen than was observed. Near to the bottom the observed values were 1.0—1.5 mg $l^{-1}$ greater than the simulated ones.

In 1976, both in June and August, the simulated values were lower than the observed ones although the curves were of the same shape. In

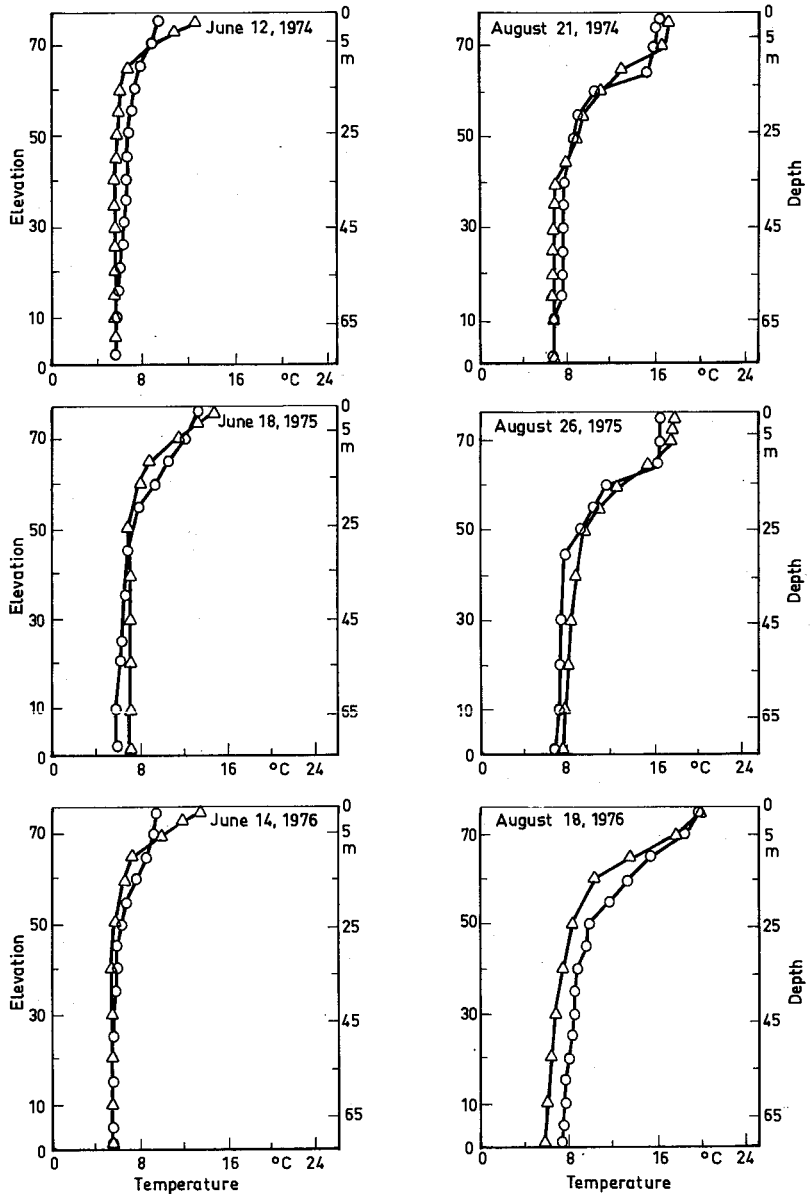


Fig. 6. Observed (o—o) and simulated (△—△) temperatures of the calibration year 1974 and of the verification years 1975 and 1976.

June the simulated values were 0.5—2.5 mg $l^{-1}$ smaller and in August 1—2.5 mg $l^{-1}$ smaller than the observed values.

## 4.23 Biological oxygen demand

Because of the lack of observed data only the simulated $BOD_7$ values are presented.

In June 1974 the simulated $BOD_7$ value was 0.76 mg $l^{-1}$ in the epilimnion. From element 60 downwards it was 0.53 mg $l^{-1}$. In August the $BOD_7$ was 0.33 mg $l^{-1}$ in the uppermost five meters, and decreased steadily to a minimum of 0.03 mg $l^{-1}$ in and below element 56.

In June 1975 the simulated value was 0.64 mg $l^{-1}$ in epilimnion, decreasing to a minimum of 0.34 mg $l^{-1}$ by element 38. In August the

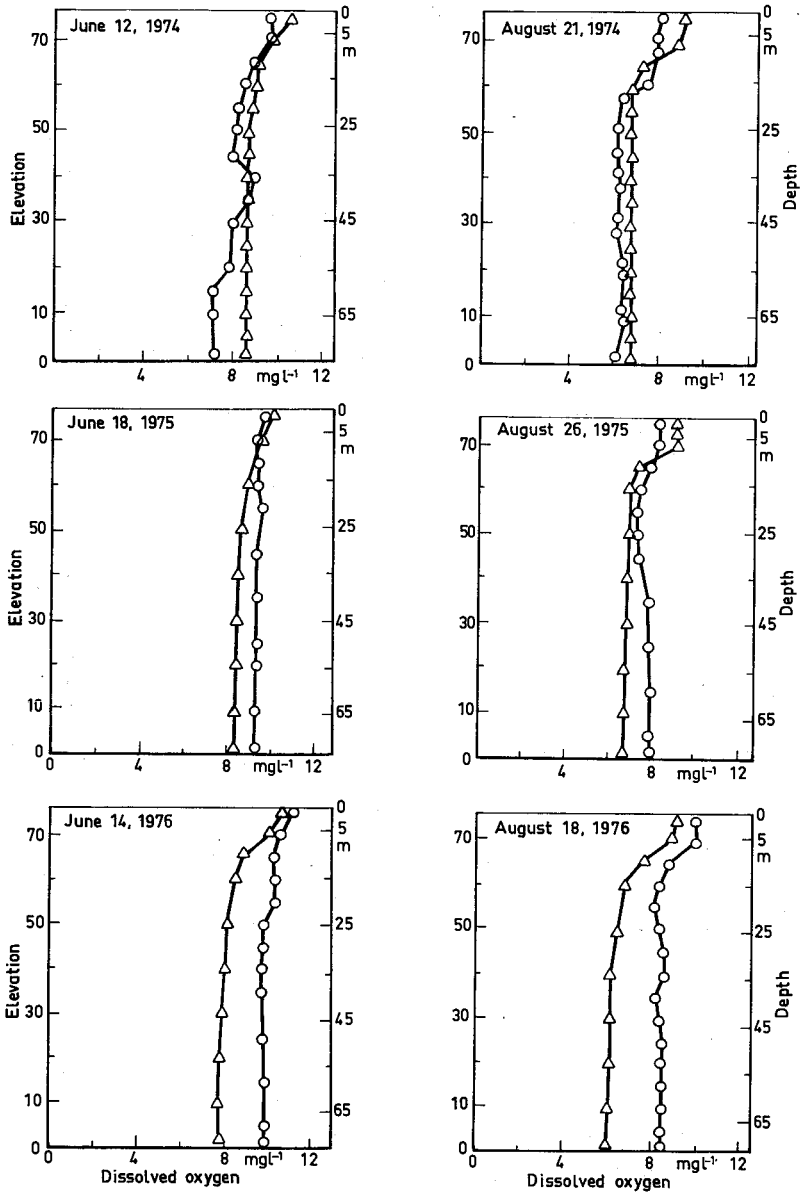


Fig. 7. Observed (o—o) and simulated (△—△) dissolved oxygen concentrations of the calibration year 1974 and of the verification years 1975 and 1976.

simulated values were 0.11 mg $l^{-1}$ in elements 69–75. The maximum values, varying between 0.13 and 0.22 mg $l^{-1}$, were found in elements 64–68. From the element 53 downwards the $BOD_7$ value was 0.01 mg $l^{-1}$.

In June 1976 the simulated value was 0.49 mg $l^{-1}$ and from the element 55 downwards 0.43 mg $l^{-1}$. In August the value was 0.19 mg $l^{-1}$ near the surface of the lake, 0.21 mg $l^{-1}$ in element 72, 0.18 mg $l^{-1}$ in element 70 and from element 59 downwards 0.02 mg $l^{-1}$.

## 4.24 Alkalinity

Fig. 8 shows the simulated and observed alkalinity values expressed as mg $l^{-1}$ $CaCO_3$.

In 1974 the simulated values followed closely

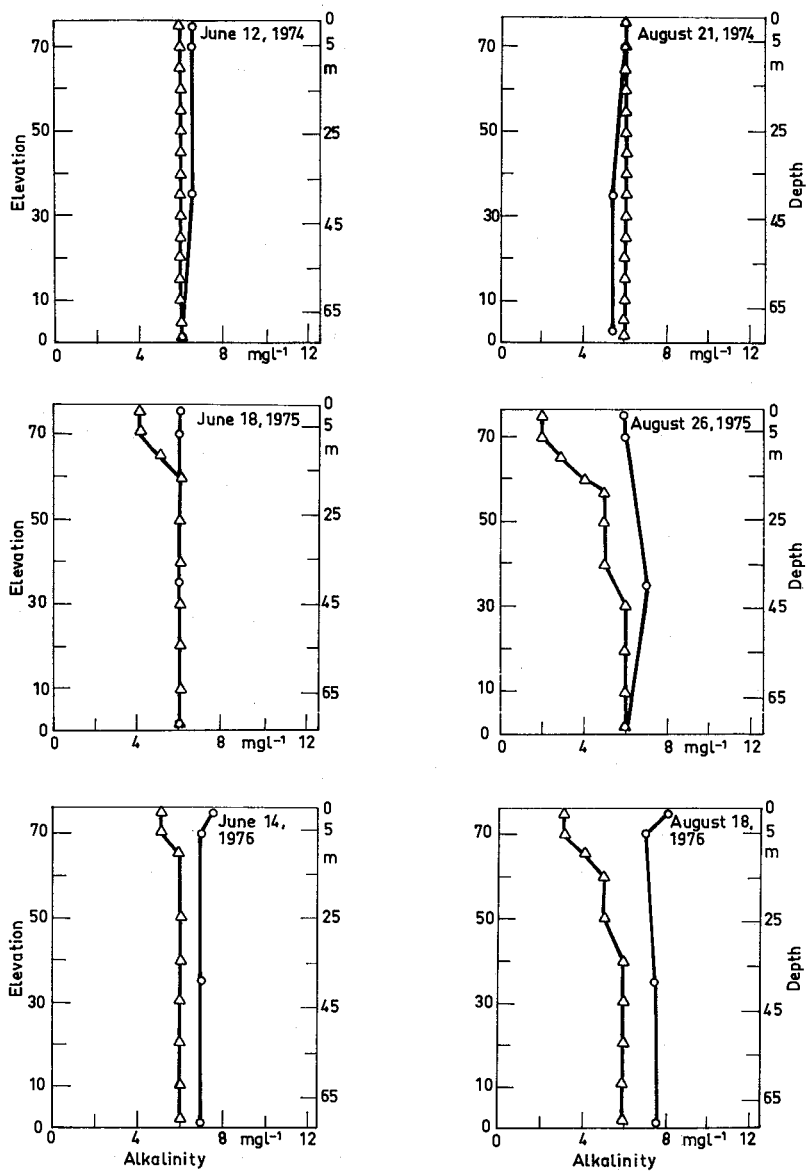


Fig. 8. Observed (o—o) and simulated (△—△) alkalinity values ($CaCO_3$ mg $l^{-1}$) of the calibration year 1974 and of the verification years 1975 and 1976.

the observed ones.

In June 1975 the simulated and observed values were the same in elements 1—60 while in elements 60—75 the observed values were 1—2 mg $l^{-1}$ higher than the simulated ones. In August the simulated values were lower than the observed ones, the difference being greater near the surface than near the bottom of the lake.

In 1976 the model simulated lower values than were observed in the lake in both June and August. In June the difference was in the epilimnion about 2 mg $l^{-1}$ and in elements 1—60 about 1 mg $l^{-1}$. In August the differences between simulated and observed values were greater than in June; in epilimnion about 5 mg $l^{-1}$ and in elements 1—60 about 1.5—2 mg $l^{-1}$.

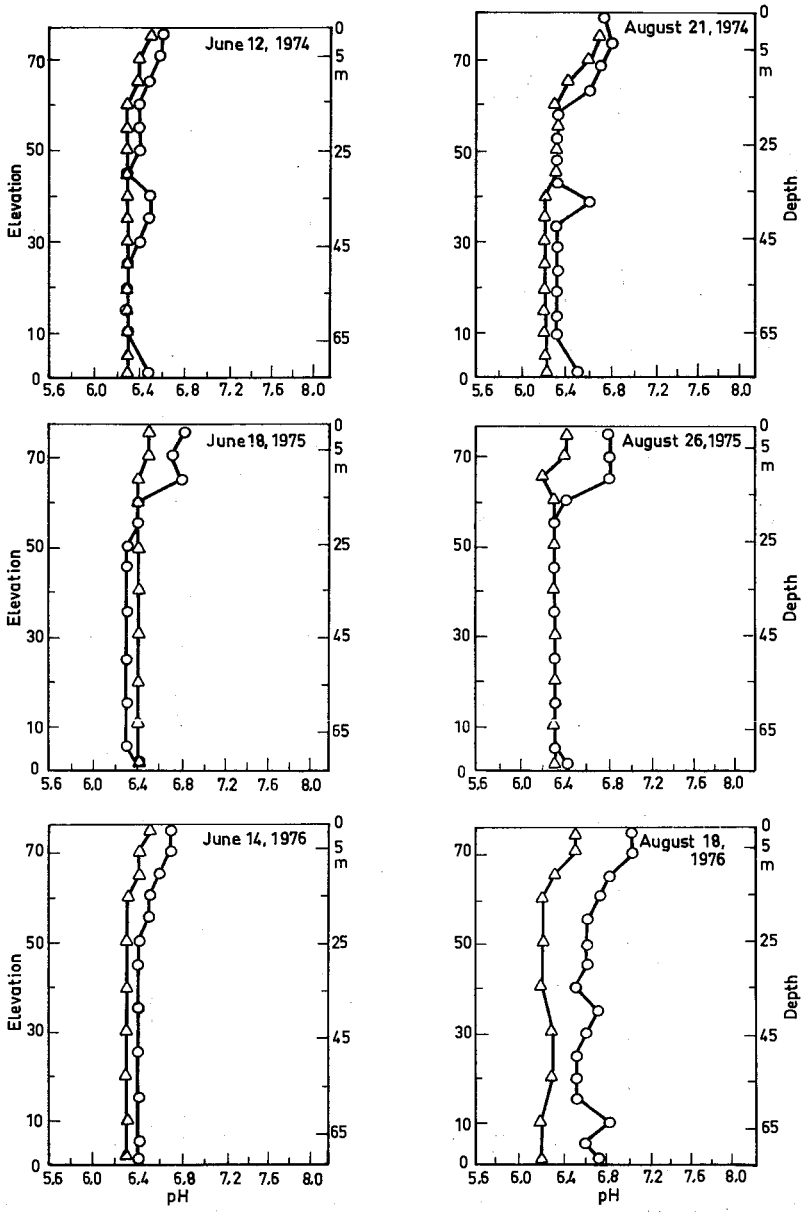


Fig. 9. Observed (○—○) and simulated (△–△) pH-values of the calibration year 1974 and of the verification years 1975 and 1976.

4.25 pH-value

Fig. 9 shows the simulated and observed pH-values.

In 1974 the simulated and observed pH-values followed the observed values reasonably well. In June the maximum difference between the simulated and observed values was 0.2 pH units and in August 0.4 pH units. The model was not able to simulate the high pH-values observed in elements 25—45.

In June 1975 in elements 60—75 the observed pH-values were 0.2—0.4 pH units higher than the simulated ones. In elements 1—60 the simulated values were close to the observed values, the observed values being 0.1 units lower than the simulated ones. In August the simulated and observed values were the same in elements 5—

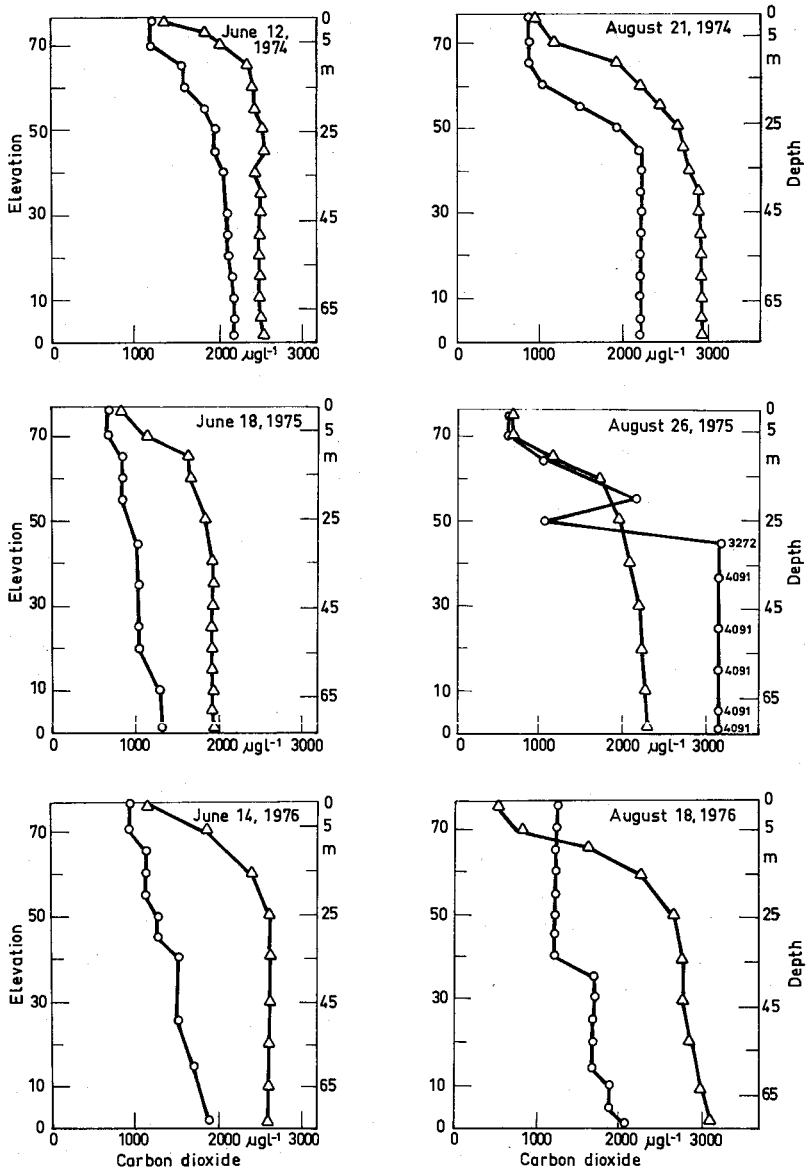


Fig. 10. Observed (○—○) and simulated (△—△) carbon dioxide concentrations ($CO_2$–C) of the calibration year 1974 and of the verification years 1975 and 1976.

55, while near the bottom of the lake the simulated values were 0.1 units lower than the observed ones. In elements 60–75 the observed values were 0.1–0.4 units higher than the simulated ones.

In June 1976 the agreement between the simulated and observed values was good, while in August the simulated values were 0.2–0.6 units lower than the observed ones.

### 4.26 Carbon dioxide

Strictly speaking the model did not simulate carbon dioxide concentrations, because these were calculated on the basis of chemical equilibrium reactions (American Public Health Association, Inc. 1965 pp. 78–81). Fig. 10 shows the calculated and observed carbon dioxide concentrations.

In 1974 the calculated and observed curves were of the same type, the calculated values being higher. In August the maximum difference was about 750 $\mu g\ l^{-1}$.

In June 1975 the calculated and observed curves were again of the same type, with the calculated values being higher. In August the agreement between the calculated and observed curve was good in elements 60–75. In elements 1–60 the differences between calculated and observed values were high, the observed ones being about 1 500 $\mu g\ l^{-1}$ higher than the calculated ones.

In 1976 the calculated and observed curves were of the same type in both June and August, the calculated values being greater except in epilimnion in August.

## 4.27 Nitrogen

### 4.271 Ammonia nitrogen

Fig. 11 shows the simulated and observed ammonia nitrogen values.

In June 1974 the agreement between the simulated and observed values was poor. In elements 65–75 the simulated values were about 10 $\mu g\ l^{-1}$ higher than the observed ones, while in elements 1–65 the simulated values were lower than the observed ones, the maximum difference being about 12 $\mu g\ l^{-1}$. In August the simulated values followed the observed ones reasonably well.

In June 1975 the model simulated lower concentrations of ammonia nitrogen than were observed in the lake. However, in August the agreement between simulated and observed values was rather good.

In June 1976 the simulated values of epilimnion were about 8 $\mu g\ l^{-1}$ higher than the observed ones in elements 65–78, while deeper in the lake they were about 5–8 $\mu g\ l^{-1}$ lower. In August the agreement between simulated and observed values was about the same as in June.

### 4.272 Nitrate nitrogen

Fig. 12 shows the simulated and observed values of nitrate nitrogen.

In June and August 1974 the simulated and observed curves were of the same type, the agreement being best near the surface of the lake in elements 70–75.

In 1975 both of the curves were of the same type, the simulated values being higher than the observed ones.

In 1976 the agreement between the simulated and observed values was about the same as in 1974 and 1975. The curves were of the same type and the agreement was best in elements 70–75.

### 4.273 Nitrite nitrogen

In June 1974 the simulated nitrite nitrogen values varied between 4 and 5 $\mu g\ l^{-1}$, while the observed value was 1 $\mu g\ l^{-1}$ in the whole water mass. In August 1974 the simulated values varied from 2 to 6 $\mu g\ l^{-1}$, while the observed value was again 1 $\mu g\ l^{-1}$, except in the water layer just above the bottom of the lake, where it was lower.

In June 1975 the simulated values were 3–4 $\mu g\ l^{-1}$ while the observed value was 1 $\mu g\ l^{-1}$ in the whole water column except for the water layer just above the bottom of the lake, in which the value was below 1 $\mu g\ l^{-1}$. In August the simulated values varied from 2 to 4 $\mu g\ l^{-1}$, while the observed ones were less than 1 $\mu g\ l^{-1}$.

In June 1976 the simulated values varied between 5 and 7 $\mu g\ l^{-1}$, the observed values being 1 $\mu g\ l^{-1}$ in the whole water mass. In August the simulated values varied between 2 and 5 $\mu g\ l^{-1}$, while the observed ones varied from 1 to 2 $\mu g\ l^{-1}$.

## 4.28 Phosphate phosphorus

Fig. 13 shows the simulated and observed values of phosphate phosphorus.

Both in June and August 1974 the simulated phosphate phosphorus values were higher than the observed ones, especially in the hypolimnion. In June the simulated values were 5–10 $\mu g\ l^{-1}$ higher and in August 2–20 $\mu g\ l^{-1}$ higher than those observed.

Both in June and August 1975 the simulated

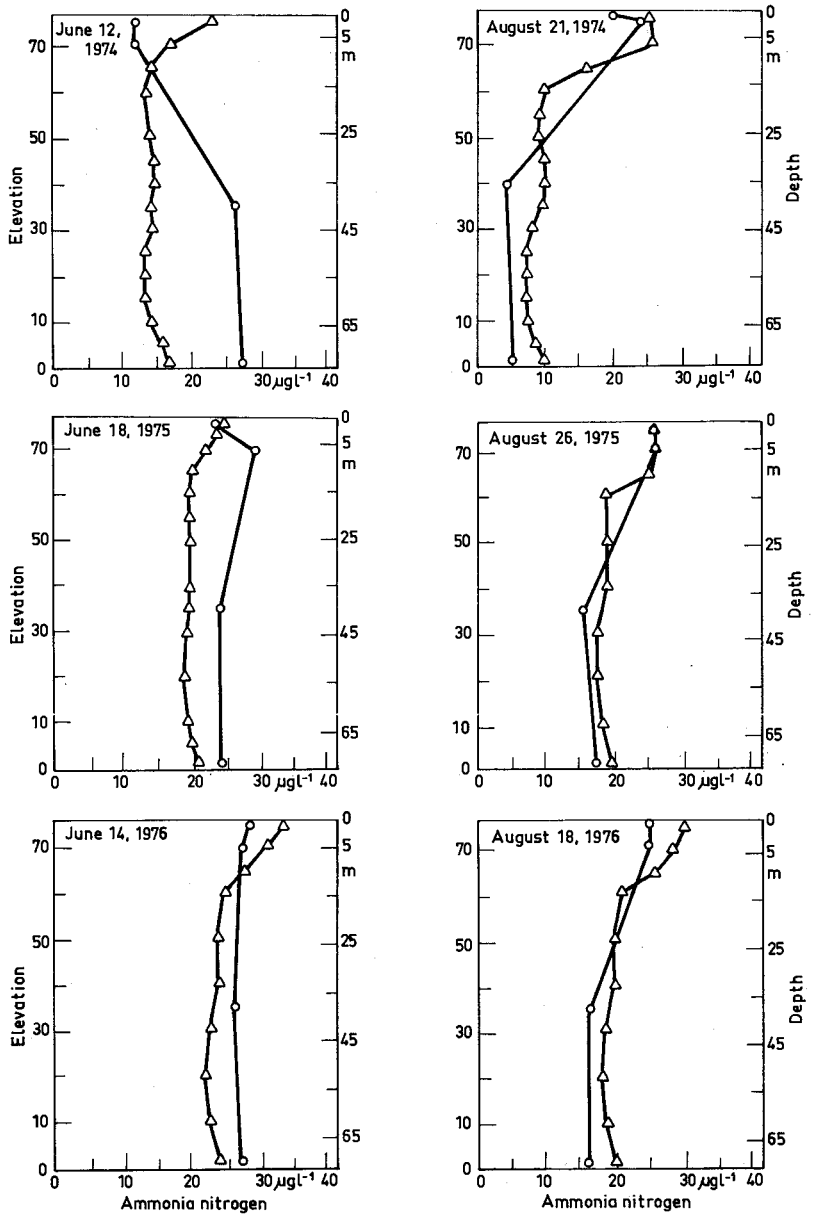


Fig. 11. Observed (o—o) and simulated (△—△) ammonia nitrogen concentrations of the calibration year 1974 and of the verification years 1975 and 1976.

values were higher than the observed ones. The difference was rather small in the epilimnion but it increased towards the bottom of the lake.

In June 1976 the simulated and observed values were about the same near the surface of the lake in elements 70–75, while deeper in the lake the difference grew to about 7–8 $\mu g\ l^{-1}$. In August 1976 the simulated curve was of the same type as the curve for August 1974 and 1975. Observed values for August 1976 were not available.

## 4.29 Total dissolved solids

The simulated values for total dissolved solids

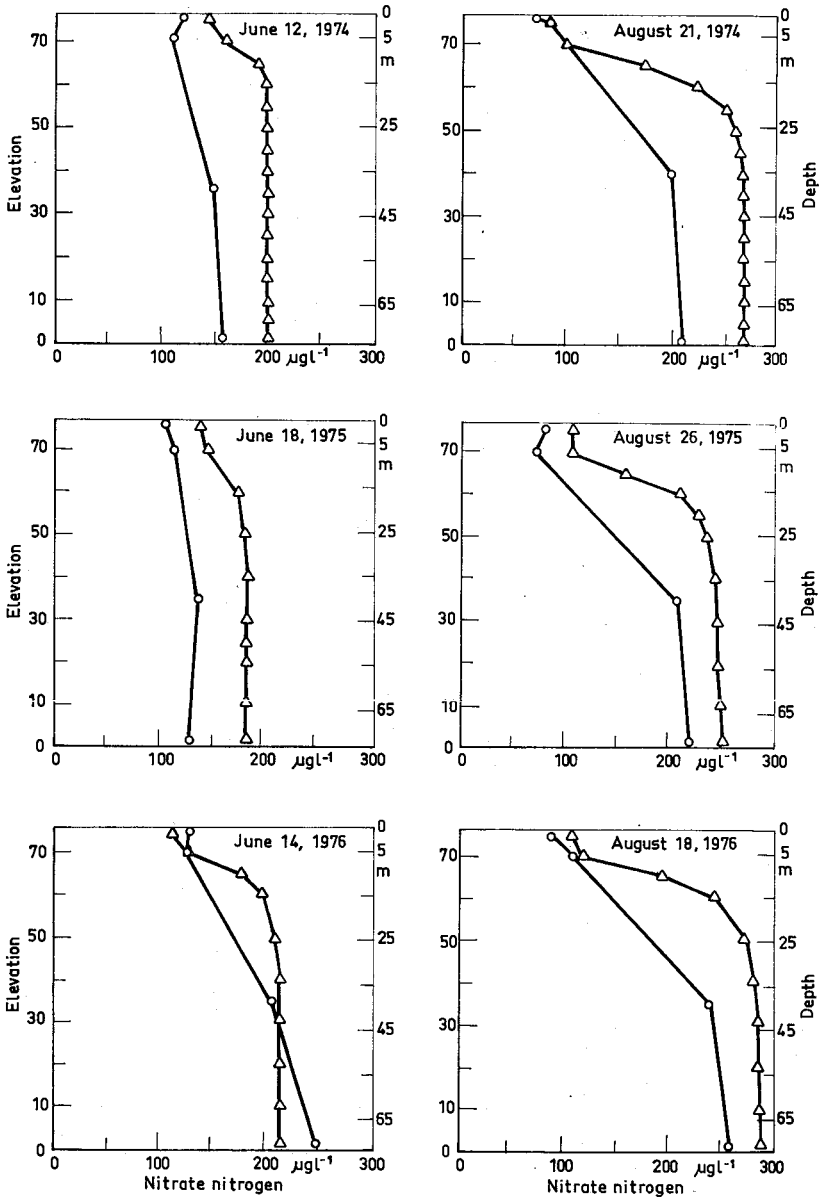


Fig. 12. Observed (o—o) and simulated (△—△) nitrate nitrogen concentrations of the calibration year 1974 and of the verification years 1975 and 1976.

varied between 54 and 60 mg $l^{-1}$ in all three simulation years. The lowest value was simulated in epilimnion in August 1975 and the highest one in the water layer just above the bottom of the lake in 1975 and 1976.

Comparisons between the simulated and observed values could not be carried out because of the lack of observed data.

## 4.3 Biological state variables

### 4.31 Coliform bacteria

Because of the lack of observed data only the simulated results are presented.

In June 1974 the simulated value of coliform bacteria in epilimnion was 1.6 per 100 ml and in element 53 and downwards 0.5 per 100

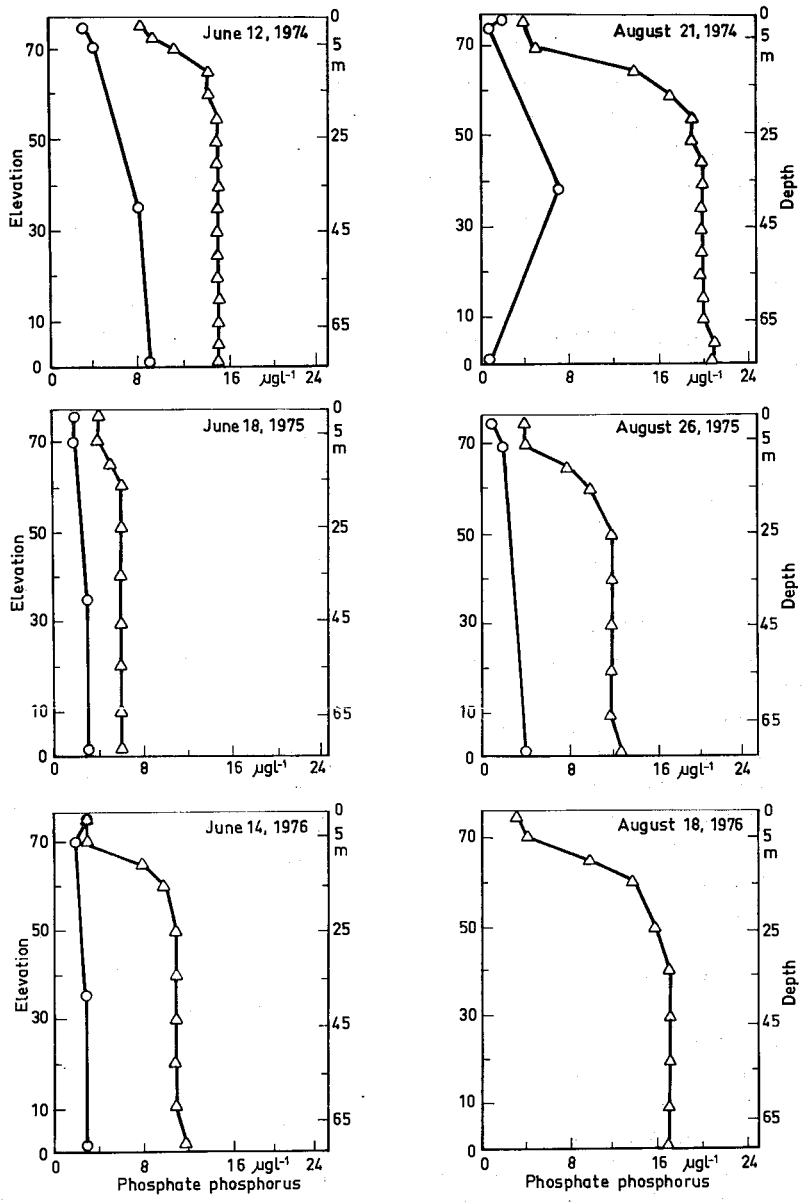


Fig. 13. Observed (○—○) and simulated (△—△) phosphate phosphorus concentrations of the calibration year 1974 and of the verification years 1975 and 1976.

ml. In August the number of bacteria in epilimnion was 0.77 per 100 ml and in the water layer close to the bottom of the lake only $1.7 \cdot 10^{-7}$ bacteria per 100 ml.

In June 1975 the simulated values of bacteria in the epilimnion and in the water layer close to the bottom of the lake were 1.0 per 100 ml and $5.4 \cdot 10^{-2}$ per 100 ml, respectively. In August the respective values were $1.2 \cdot 10^{-1}$ and $3.1 \cdot 10^{-8}$ bacteria per 100 ml.

In June 1976 the simulated values of bacteria in the epilimnion and in the water layer close to the bottom were 0.97 and 0.15 bacteria per 100 ml, respectively. In August the respective values were $5.2 \cdot 10^{-1}$ and $2.8 \cdot 10^{-7}$.

### 4.32 Phytoplankton

Fig. 14 shows the simulated and observed values of phytoplankton biomass. The simulated biomass presented is an average of the total algal biomass in the ten uppermost hydraulic elements. Deeper in the lake the algal biomass was insignificantly small.

Chlorophyll-a values were transformed to biomass values using the following equation and observational data from Lake Päijänne (Granberg and Selin 1977):

$$x = \frac{y - 0.753}{0.009} \qquad (2)$$

y = observed chlorophyll-a value (mg $m^{-3}$)
x = phytoplankton biomass (mg $m^{-3}$)

Biomass values calculated with this equation were used in addition to the observed biomass values when the simulated and observed phytoplankton biomass values were compared.

In the early summer of 1974 the agreement between the simulated and observed values was good. Unfortunately, no observed data are available for early June and July. In August the simulated values tended to be higher than the observed ones. At the end of August and in early September the observed values decreased earlier than the simulated ones. At the end of the simulation period both the simulated and observed values were about the same.

In 1975 the model simulated a curve of phytoplankton biomass without any clear maxima. The model was unable to simulate the high observed values of May and September.

In 1976 the model simulated a curve of phytoplankton biomass with a maximum value in June. The values decreased steadily from this maximum until late summer. The model was unable to simulate the high observed values of May and August.

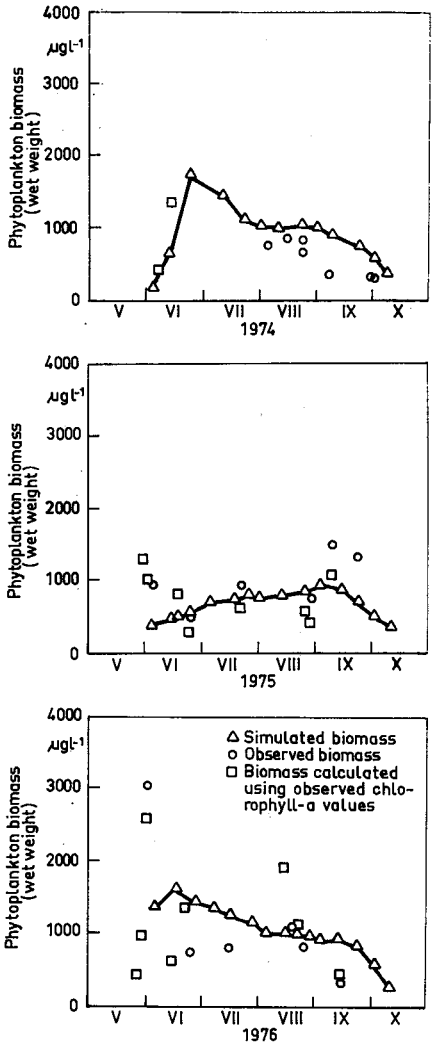


Fig. 14. Observed and simulated phytoplankton biomass concentrations of the calibration year 1974 and of the verification years 1975 and 1976.

### 4.33 Zooplankton

Fig. 15 shows the simulated values of zooplankton biomass. Observed data were not available for comparisons.

In 1974 zooplankton biomass decreased from its initial value until mid-June. After this the value increased to a maximum of 55 µg $l^{-1}$ in July-August. In late August the concentration started to decrease and was 10–15 µg $l^{-1}$ in late October.

In 1975 the simulated zooplankton biomass decreased from its initial value to 15 µg $l^{-1}$ in late July, increased in mid-September to 23 µg $l^{-1}$ and decrease again to 10 µg $l^{-1}$ in late August.

In 1976 the biomass curve rose rapidly from early June until early July, when a plateau with a maximum value of 120 µg $l^{-1}$ was reached.

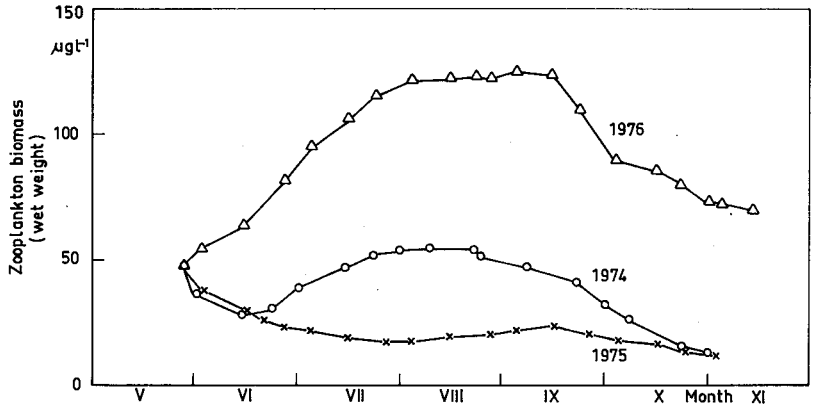


Fig. 15. The dynamics of simulated zooplankton biomass concentrations in 1974, 1975 and 1976.

In mid-September the values began to decrease. However, even in early November the values were still about 70 $\mu g\ l^{-1}$, which was higher than the initial value.

### 4.34 Detritus

Because of the lack of observed data only the simulated results are presented.

The simulated concentrations of detritus remained at the same level throughout the three simulation periods.

In June 1974 the concentrations in epilimnion and in the water layer close to the bottom of the lake were 0.2 and 0.3 mg $l^{-1}$, respectively. The corresponding values for August were 0.1 and 0.6 mg $l^{-1}$.

In 1975 the corresponding values in June were 0.1 and 0.4 mg $l^{-1}$ while the values for August were the same as for August 1974.

In 1976 the corresponding values in June were 0.2 and 0.4 mg $l^{-1}$. In August the values were the same as for August 1974 and 1975.

### 4.35 Organic sediment

Because of the lack of observed data only the simulated results are presented.

The initial values of organic sediment in the hydraulic elements of epilimnion were 187 g $m^{-2}$. The initial values increased steadily from this value towards the bottom of the lake. The initial value in the hydraulic element just above the bottom of the lake was 250 g $m^{-2}$.

In each simulation year the simulated values were practically the same as the initial values of the different hydraulic elements. For example in June 1974 the simulated value for hydraulic elements in epilimnion was 186 g $m^{-2}$ and near the bottom 249 g $m^{-2}$. In August 1974 the respective values were 183 g $m^{-2}$ and 243 g $m^{-2}$.

### 4.36 Benthic animals

Because of the lack of observed data only the simulated values are presented.

The same initial value of 187 mg $m^{-2}$ was used for benthic animals in every hydraulic element. In each simulation year the biomass of benthic animals developed in the same way: the biomass decreased in early June in every element to a value of about 10–30 mg $m^{-2}$ and remained constant until the end of the simulation period.

### 4.37 Fish

Because of the lack of observed data only the simulated values of fish biomass are presented.

The following three groups of fish were simulated in the model: cold water zooplankton feeders, warm water zooplankton feeders and

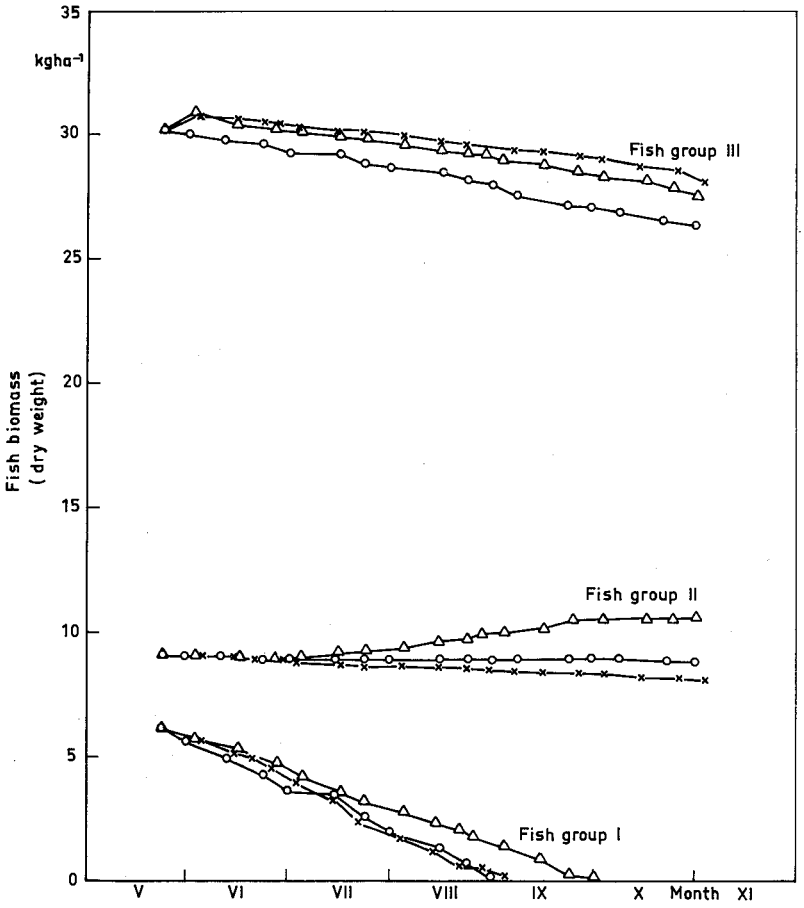


Fig. 16. The dynamics of simulated fish biomass concentrations in 1974 (o–o), 1975 (x–x) and 1976 (Δ–Δ). Fish groups I and II include cold water and warm water zooplankton feeders, respectively. Fish of group III were eaters of benthic animals.

fish that feed on benthic animals. The lower and upper temperature limits used for the growth of these groups were: 5 °C and 20 °C; 10 °C and 30 °C; 5 °C and 30 °C, respectively.

Fig. 16 shows the simulated biomasses of the three fish groups.

The biomass of the cold water zooplankton feeders decreased every year from the initial value of 6 kg $ha^{-1}$ to 0.05 kg $ha^{-1}$, which was reached in September-October.

The biomass of warm water zooplankton feeders in 1974 remained on the same level as the initial value, which was 9 kg $ha^{-1}$. In 1975 the biomass decreased from the initial value, reaching 8 kg $ha^{-1}$ at the end of the simulation period. However, in 1976 the biomass started to increase from early July and the maximum value of 10.5 kg $ha^{-1}$ was reached in October.

The biomass of fish that feed on benthic animals decreased steadily in 1974 from its initial value of 30 kg $ha^{-1}$ towards late September. In 1975 and 1976 the biomass developed in the same way except for a minor maximum in early June.

# 5. THE EFFECTS OF FOUR LOADING ALTERNATIVES ON THE WATER QUALITY OF SUB-BASIN NO. 1 OF LAKE PÄIJÄNNE AS CALCULATED BY THE MODEL

## 5.1 The effects of phosphorus loading discharged from the Nenäniemi wastewater treatment plant on phytoplankton biomass

The reference simulation in this experiment was the verification run of 1975. Two simulations were carried out. The phosphate phosphorus loading from the Nenäniemi wastewater treatment plant was first increased by 30 % and in another simulation decreased by 30 % from the loading of 1975. All the other data were held at the same values as in the verification run of 1975. It was assumed that all the phosphorus discharged from the water treatment plant was phosphate phosphorus.

The phosphate phosphorus loading discharged from the Nenäniemi wastewater treatment plant was 27.4 % of the total phosphate phosphorus loading entering the sub-basin in 1975. A change of 30 % in the loading of phosphate phosphorus discharged from the wastewater treatment plant therefore implied a change of 8.2 % in the total loading of phosphate phosphorus entering the sub-basin.

Fig. 17 shows the concentration of phytoplankton biomass calculated with the data of 1975 and with the two alternative loadings. The effects of the alternative loadings on the phytoplankton biomass were relatively small, the greatest differences in biomass being about 50–100 $\mu g\ l^{-1}$ compared to the reference level. The changes introduced to phosphate phosphorus loadings had no effect on the calculated concentrations of dissolved oxygen.

## 5.2 The effect of BOD7 loading on the concentration of dissolved oxygen

Two simulations were carried out with the model. The BOD7 loading values entering sub-basin No. 1 through the River Haapakoski were first increased by 30 % and then decreased by 30 % from the values of the reference simulation of 1975.

The BOD7 loading entering sub-basin No. 1 through the River Haapakoski forms 94 % of the total BOD7 loading of the sub-basin. A change of 30 % in the loading entering the sub-basin through the River Haapakoski therefore implies a change of 28.2 % in the total BOD7 loading of the sub-basin.

The loading alternatives affected the calculated concentrations of dissolved oxygen in sub-basin No. 1 only very slightly. When the BOD7 loading was increased by 30 % the concentration of dissolved oxygen decreased by about 0.1–0.3 $mg\ l^{-1}$ at a depth of 15 m, near to the thermocline. With a 30 % BOD7 decrease the concentration of dissolved oxygen increased by the same amount in the same region of the lake. The changes of BOD7-loadings had no effect on the oxygen concentrations in other depths.

# 6. DISCUSSION

## 6.1 Results of calibration and verification

The model was calibrated so that it would simulate reasonably well those state variables of which sufficient amount of observed data were available, especially temperature, dissolved oxygen and phytoplankton. Several state variables, for example benthic animals and fish could not be calibrated due to the lack of observed data. One problem encountered was that of specifying criteria for the acceptance of calibration and verification. Because of the lack of mathematical methods for this purpose the acceptance of calibration and verification was made simply by examining the graphical representation of the simulated and observed results. This is of course a subjective method.

Inclusion of confidence limits with the observed results would have helped the comparison of the observed and simulated results considerably. However, confidence limits for the observed results were not available.

Water stage and the other state variables for which observed data were available are considered first. These state variables are; temperature,

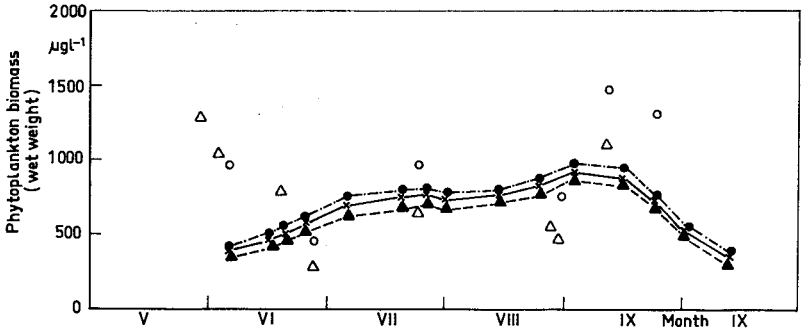


Fig. 17. Phytoplankton biomass concentrations in the sub-basin No. 1 calculated for three phosphorus loadings with the model.
x—x = simulated results with the data of 1975
o—o = simulated results obtained when the phosphorus loading entering the sub-basin from the Nenäniemi waste water treatment plant was increased by 30 % from the loading of 1975.
△—△ = simulated results obtained when the phosphorus loading entering the sub-basin from the Nenäniemi waste water treatment plant was decreased by 30 % from the loading of 1975.
o = observed phytoplankton biomass value
△ = biomass calculated using observed chlorophyll-a values

dissolved oxygen, alkalinity, pH, carbon dioxide, ammonia-, nitrate- and nitrite nitrogen, phosphate phosphorus and phytoplankton biomass.

Because most of the state variables were expressed as concentrations it is important that the model should simulate the water stage of the lake with good accuracy. Differences between simulated and observed water stage values varied from about 10 to 40 cm. These differences tended to increase towards the end of the simulation period. Thus the error introduced by water stage to the concentration of the state variables also increased towards the end of the simulation period. The direction of this error varied in the three simulation years. In 1974 and 1976 the simulated values were higher than the observed ones after the mid-summer, while in 1975 they were lower. However, the differences between the simulated and observed values of water stage were not sufficient to explain the differences between the simulated and observed values of the state variables. Equation 1 was used in the calculation of water stage. Further investigation is required to ascertain whether this equation could be modified to obtain better agreement between the simulated and observed values.

Most of the reactions simulated by the model were dependent on temperature. Any error in temperature therefore introduced an error to temperature-dependent state variables. The temperature program was separated from the computer program of the model and calibration of temperature was carried out with the separate temperature program before calibration later on with the complete computer program of the model.

For the surface layer of the lake the model calculated somewhat higher temperatures than were observed. Part of this difference may be explained by the fact that the model did not take into account the mixing effect of wind. In the model the wind affects only the evaporation of surface water.

In nature, however, the wind affects the epilimnion of lakes, which is mixed with the cold waters of hypolimnion. The surface of the lake does not therefore warm up as much as it would without the mixing effect of wind. If the simulation period is very windy the wind also affects the hypolimnion. In June 1976 there were a number of exceptionally windy days. The spring turnover lasted longer than usual and the hypolimnion thus became warmer than usual. Because the mixing effect of wind was not included, the model simulated lower temperatures for the whole water column of the simulation

point in August 1976.

Hydraulic elements of different thickness cannot be used in the model. However, investigation is required to determine whether the simulated results could be improved by choosing a different thickness for the hydraulic elements.

Water Resources Engineers (1969, p. 25) have simulated the temperature profile of a reservoir with a simulation model resembling the temperature program used in the EPAECO-model. These authors assumed that the simulation of temperature near the lake surface could be improved by allowing the thickness of the surface elements to vary between one and two times the standard element thickness.

Perhaps the best results could be obtained with a model allowing the user to specify the thicknes of hydraulic elements at any depth of a lake, especially near the surface and near the bottom.

The calibration results of dissolved oxygen were reasonably good. In the verification runs the observed values were higher than the simulated ones, the differences being higher in 1976 than in 1975. The model did not include the mixing effect of wind, which may explain at least part of these differences. In a windy season the spring turnover lasts longer than usual and more dissolved oxygen is transferred to the hypolimnion than normally. In 1976 the spring turnover lasted longer than usual and the model could not simulate the observed results. In addition temperature profile of lake affects the concentration of dissolved oxygen. Dissolved oxygen values were verified reasonably well in 1975 while in 1976 the verification was poor.

The calibration of alkalinity values was good. The difference between the observed and simulated values was greater in August than in June both in 1975 and 1976.

In 1974 the model was unable to simulate the high pH-values observed in elements 30–40. High pH-values also occured in the same region in August 1976. These high observed values were probably caused by the waste waters flowing in at this depth. However, in June 1974 a minor maximum of dissolved oxygen occured in elements 30–40, which does not comply with the presence of waste waters in this layer. It is possible that the waste waters contained toxic compounds which inhibited biological oxygen-consuming reactions.

In 1975 the agreement between the simulated and observed values was good except in elements 60–75. In June 1976 the pH-values were considered verified, while in August the simulated values were lower than the observed ones. Overall, pH was calibrated and verified reasonably well except in August 1976.

The calculation of carbon dioxide values was based on chemical equilibrium reactions. The observed and simulated curves were of the same type. However, the simulated values were higher than the observed ones. The model simulated carbon dioxide concentrations rather well, the calibration results being better than the verification results.

Ammonia-, nitrate- and nitrite nitrogen take part in various biological and chemical reactions and their simulation therefore required the utilization of comparatively complicated equations. The calibration of ammonia nitrogen was good in August 1974 but not in June. Both in 1975 and 1976 the agreement between the simulated and observed values was good, in 1975 also at the surface layer of the lake. The simulated curve of nitrate nitrogen was of the same shape as the observed curve in all three years, the agreement being best in epilimnion and the simulated values being typically higher than the observed ones. For every year and throughout the whole water column, the model calculated too high values for nitrite nitrogen. Of the three forms of nitrogen the model simulated ammonia- and nitrate nitrogen better while the simulated results for nitrite nitrogen were less accurate.

The calibration results for phosphate phosphorus were discouraging. In the surface layer, which is the productive layer of the lake, the differences between the simulated and observed values were relatively small. Towards the bottom of the lake, however, the difference increased considerably, the simulated values being higher than the observed ones. The simulated curves behaved identically for all three years. In the model phosphate phosphorus accumulated to the hypolimnion. The model produced too much phosphate phosphorus to the hypolimnion, where it was not consumed at all. Thus the model can be considered to be verified only for

epilimnion.

It should be investigated if total phosphorus could be taken as a state variable into the model instead of phosphate phosphorus.

The model simulated correctly phytoplankton biomass on the average, but was unable to calculate the observed maximum values. The fact that only total phytoplankton biomass was simulated explains this phenomenon. Calibration was made difficult by a lack of observed data in July 1974. The initial values for phytoplankton biomass were obtained on the basis of only few observations. Because of the high growth rate of phytoplankton in May-June the initial values may be erroneous. Simulation with different initial values for phytoplankton should reveal the effect of initial values on the simulated results. Additional observed data of phytoplankton biomass would help to calibrate and verify the model accurately. Division of phytoplankton into two or three groups would be likely to improve the simulation of observed maxima.

The values for the following state variables are discussed below: BOD, coliform bacteria, detritus, total dissolved solids, organic sediment, zooplankton, benthic animals and fish biomass. No observed data were available for these state variables and threfore they could not be calibrated or verified. The results of these state variables should be considered tentative.

In every simulation the calculated $BOD_7$ values behaved basically in the same way: in epilimnion they varied between 0.5 and 0.75 mg $l^{-1}$, decreasing steadily towards the bottom of the lake. The model assigned the input waters to the hydraulic element having the same temperature value as the input waters. Because the model simulated mainly summer time the input waters were assigned to the epilimnion and the BOD-values of epilimnion were therefore higher than those of hypolimnion.

Coliform bacteria were simulated in the model with a first order decay reaction. The calibration of coliform bacteria was impossible because there were no observed data. The concentration of bacteria decreased from the surface to the bottom of the lake, because it was assumed that coliform bacteria enter the lake only with waste waters, and waste waters were assigned to hydraulic elements according to their temperature, i.e. usually to epilimnion.

It was assumed that there were no detritus inputs through tributaries entering the lake. The concentration of detritus therefore remained very close to the initial value in every hydraulic element throughout the simulations.

The simulated values of total dissolved solids behaved in the same way as the values for detritus. The initial value of total dissolved solids was 50 mg $l^{-1}$, which was the same as the corresponding value of the input waters. The simulated values remained very close to the initial value throughout the simulations.

In the model, detritus, phytoplankton and fish all produced organic sediment, which was consumed by benthic animals and decayed by microbial action. The simulated organic sediment values were close to the initial values in every element. Organic sediment appeared to be in a steady state.

In 1974 and 1976 the simulated maxima of zooplankton occurred after the simulated phytoplankton maximum. Thus in these years the model simulated correctly the dynamics of the balance between phyto- and zooplankton. However in 1975 the model did not simulate a zooplankton maximum at all. The simulated biomass curve of phytoplankton in 1975 did not have any clear maximum which may explain this. Because of the lack of observed data the calibration and verification of zooplankton could not be performed.

The biomass of benthic animals decreased rapidly from the initial value of 187 mg $m^{-2}$, which was the observed value in Lake Päijänne. It seems that the model was not capable of maintaining the biomass of benthic animals at the right level. Fish seemed to consume benthic animals fast.

It is difficult to divide the fish population into the three groups described in the model. In addition, the initial values and catches of fish for these groups were difficult to obtain. The cold water zooplankton feeders died in early September in 1974 and 1975. In 1976, when the model simulated high zooplankton concentrations, this fish group lived longer, until early October. However, the amount of zooplankton alone was not sufficient to explain the behaviour of this fish group. In the model

fish were assumed to swim in pursuit of their food. For example cold water zooplankton feeders swam to the epilimnion to feed on zooplankton. However, the water of the surface layer was warm and may have inhibited the growth of this fish group. The biomasses of warm water zooplankton feeders and consumers of benthic animals remained close to the initial values in all three years. It should be pointed out that the data needed for the simulation of fish biomass is rarely available for Finnish lakes.

The EPAECO-model is one-dimensional, and thus represents a simplification of a real lake. This simplification may explain at least some of the differences between the simulated and observed values of state variables. The sensitivity analysis of the model was not carried out.

## 6.2 Simulations with four loading alternatives

Simulation models can be used to estimate the effects of various loading alternatives on the water quality of lakes. In this work the model was used to calculate the effects of BOD- and phosphate phosphorus loadings on the water quality of the case study lake. The verification year 1975 was selected as reference year, although other years could have been selected.

When the phosphate phosphorus loading of the Nenäniemi water treatment plant was first increased and then decreased by 30 per cent, the model reacted correctly by respectively increasing and decreasing the phytoplankton biomass. These results cannot be verified, because although the model reacted in the right way, the responses are impossible to verify quantitatively. The model should be applied to lakes for which observed data are available before and after loading alteration in order to determine it the model could be verified. For example water quality data are available for Lake Washington before and after sewage diversion (Chen and Orlob 1972). However, if the model has been calibrated and verified it is perhaps acceptable to trust the simulated results with alternative loadings, although these results can rarely be verified. The only alternative would be to predict water quality without any model at all. Such prediction is however extremaly difficult. It is possible to take into account more factors affecting water quality with a model than without.

The changes of BOD-loadings entering Lake Päijänne through the River Haapakoski did not affect the concentrations of dissolved oxygen at all. This calculated result is in accordance with observations. In the summer the BOD-loading flowed into the epilimnion, where it decayed. Epilimnion receives oxygen from the atmosphere and thus the oxygen concentration is high. The BOD-loading is likely to affect the oxygen concentration in winter, when the lake is ice-covered. Unfortunately the model cannot simulate the water quality of lakes that are frozen over.

## 6.3 The use of the model in decision-making

According to the National Board of Waters (1974, 1976) the water quality of lakes, reservoirs and rivers must be taken into account before new measures that may affect water quality are carried out. This implies that there must be a method of predicting the water quality of a water body subjected to different loading alternatives. The predictions of water quality under various loading alternatives are often based on estimates made by experts in the fields of limnology, biology, hydrology and engineering. In these estimates only a limited number of factors can be taken into account at the same time. The use of water quality models allows a considerable number of factors to be taken into account at the same time.

The adaptation of the EPAECO-model to Lake Päijänne gave rise to a number of problems. The model requires large amount of input data, all of which was not available. Some of the input data had to be taken from other model applications. The lack of observed data made calibration and verification difficult. These facts should be borne in mind when estimating the potential application of the model.

The model simulated most accurately the chemical state variables. The agreement between the simulated and observed values of temperature, dissolved oxygen, pH, and ammonia- and nitrate nitrogen can be considered statisfactory. Phos-

phate phosphorus was simulated rather well in epilimnion but in hypolimnion the simulated results were poor. Biological state variables were not simulated as well as the chemical ones. The agreement between the simulated and observed biological state variables became worse as the trophic level became higher. The simulation of phytoplankton biomass was reasonable, the dynamics between zooplankton and phytoplankton appeared to be correct, but the simulated results of fish biomass were poor.

The model can be recommended for use as an aid in decision-making when the accuracy of the simulation is taken into account. Inclusion of the wind effect and ice cover would certainly extend the use of the model. On the other hand it may well be considered unnecessary to simulate all the state variables when the lake is frozen over. In this case a simpler model than EPAECO, for example an oxygen model, would probably be more suitable.

## 6.4 Conclusions

1. By using the model the aquatic ecosystem could be examined as a whole.
2. The model seemed to be suitable for use as a management tool when the accuracies of the simulated results were taken into account.
3. The agreement between the simulated and observed values of chemical state variables was better than that of biological state variables.
4. The model reacted in the right direction with different BOD and phosphate phosphorus loadings.
5. The lack of observed data, especially of the biological state variables, made the calibration and verification difficult. Before applying the model to a new lake sufficient data should be gathered.
6. A version of the model that could be applied to lakes that freeze over would improve the potential application of the model.
7. Addition of a wind effect would be likely to improve the simulated results.

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Helsinki, October 1978

Jorma Niemi

## LOPPUTIIVISTELMÄ

Työssä sovellettiin EPAECO nimistä determinististä ekologista simulointimallia Pohjois-Päijänteelle. Malli perustuu aineen häviämättömyyden lakiin sekä kineettiseen periaatteeseen. Kineettinen periaate tarkoittaa sitä, että mallin tietyn muuttujan muutosnopeus on yhtä suuri kuin yhden tai useamman muutoksen aiheuttavan muuttujan ja tietyn kertoimen tulo. Mallissa järvi jaetaan pinnan suuntaisilla tasoilla viipaleiksi, joiden paksuus on mallin käyttäjän määrättävissä. Viipaleita kutsutaan hydraulisiksi elementeiksi ja niiden oletetaan olevan vesimassaltaan täysin homogeenisia. Advektio ja diffuusio siirtävät vettä ja siinä olevia aineita elementistä toiseen. Mallin muuttujille on kirjoitettu differentiaalimuodossa olevat massatasapainoyhtälöt, jotka ratkaistaan numeerisesti tietokoneella.

Malli vaatii seuraavat tiedot: hydraulisten elementtien pinta-alat ja tilavuudet, säätietoja simulointiajalta (ilmanpaine, pilvisyysprosentti, tuulen nopeus, kuiva ja märkä lämpötila), kertoimet ekosysteemissä tapahtuvia reaktioita kuvaaville yhtälöille, alkuarvot seuraaville kahdeksalletoista veden laatua kuvaavalle muuttujalle, jokaiselle hydrauliselle elementille: lämpötila, happi, BHK,

alkaliniteetti, pH, hiilidioksidi, ammoniakki-, nitriitti- ja nitraattityppi, fosfaattifosfori, koliformiset bakteerit, levät (kaksi koon ja kasvuominaisuuksien mukaan jaettua ryhmää), eläinplankton, detritus, haihdutusjäännös, orgaaninen sedimentoituva aines, pohjaeläimet ja kalat (kolme ryhmää). Lisäksi malli tarvitsee järveen tulevien jokien virtaamat ja vedenlaatutiedot (edellä mainitut kahdeksantoista muuttujaa), järvestä lähtevien jokien virtaamat (lähtevän veden laatutiedot malli laskee), sekä arvot kalabiomassalle ja kalansaaliille. Järveen tulevan säteilyn malli laskee järven pituus- ja leveysasteen, päivämäärän sekä pilvisyysprosentin avulla.

Malli tulostaa halutuin aikavälein jokaiselle hydrauliselle elementille edellä mainittujen kahdeksantoista veden laatua kuvaavan muuttujan arvot.

Malli kalibroitiin vuoden 1974 tiedoilla ja verifioitiin vuosien 1975 ja 1976 vastaavilla tiedoilla.

Kemiallisten muuttujien simulointitulokset olivat parempia kuin biologisten muuttujien tulokset. Kemiallisista muuttujista malli simuloi parhaiten lämpötilaa, happea, pH:ta, ammoniumtyppeä ja nitraattityppeä sekä fosfaattifosforia pintavedessä. Sen sijaan alusveden simuloidut fosfaattifosforiarvot olivat paljon havaittuja arvoja suuremmat. Biologisista muuttujista malli simuloi parhaiten kasviplanktonin biomassaa. Kalibrointia ja verifiointia haittasi havaittujen arvojen puute, eräiden muuttujien kohdalla havaitut arvot puuttuivat kokonaan.

Mallilla tehtiin neljä kuormitusvaihtoehtoajoa, joissa järveen tulevia fosfaattifosfori- ja BHK kuormitusten annettiin vaihdella. Malli reagoi kuormitusmuutoksiin oikeaan suuntaan.

Mallilla voidaan simuloida vain avovesikautta, mikä rajoittaa sen käyttöä. Tuulen vettä sekoittavan vaikutuksen sisällyttäminen malliin parantaisi todennäköisesti simulointituloksia.

Mallia voidaan suositella käytettäväksi käytännön vesiensuojelutyössä kun mallin laskemien tulosten perusteella johtopäätöksiä tehtäessä otetaan huomioon tulosten tarkkuus.

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App. 1. Initial conditions of the sub-basin No. 1 in 1974.

INITIAL CONDITIONS OF THE ECOSYSTEM

| ELEV M | TEMP C | DO MG/L | BOD5 MG/L | ALKA MG/L | PH | CO2C UG/L | NH3N UG/L | NO3N UG/L | NO2N UG/L | PO4P UG/L | COLIFM MPN/100 | ALGA1 UG/L | ALGA2 UG/L | ZOO UG/L | DETRI MG/L | TDS MG/L | SEDM G/M2 | BENTH MG/M2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76.5 | 4.10 | 7.50 | 1.10 | 5. | 6.3 | 2386. | 60. | 120. | 0. | 11. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 75.5 | 4.10 | 7.50 | 1.10 | 6. | 6.3 | 2386. | 60. | 120. | 0. | 11. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 74.5 | 4.07 | 7.50 | 1.10 | 6. | 6.3 | 2387. | 58. | 127. | 0. | 12. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 73.5 | 4.05 | 7.50 | 1.10 | 6. | 6.3 | 2388. | 55. | 135. | 0. | 13. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 72.5 | 4.02 | 7.50 | 1.10 | 6. | 6.3 | 2389. | 53. | 143. | 0. | 13. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 71.5 | 4.00 | 7.50 | 1.10 | 6. | 6.3 | 2390. | 50. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 70.5 | 4.00 | 7.49 | 1.10 | 6. | 6.3 | 2425. | 51. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 69.5 | 4.00 | 7.49 | 1.10 | 6. | 6.3 | 2461. | 51. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 68.5 | 4.00 | 7.48 | 1.10 | 6. | 6.3 | 2497. | 52. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 67.5 | 4.00 | 7.47 | 1.10 | 6. | 6.3 | 2534. | 53. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 66.5 | 4.00 | 7.47 | 1.10 | 6. | 6.3 | 2572. | 53. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 65.5 | 4.00 | 7.46 | 1.10 | 6. | 6.3 | 2610. | 54. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 64.5 | 4.00 | 7.45 | 1.10 | 6. | 6.3 | 2649. | 55. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 63.5 | 4.00 | 7.45 | 1.10 | 6. | 6.2 | 2688. | 55. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 62.5 | 4.00 | 7.44 | 1.10 | 6. | 6.2 | 2727. | 56. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 61.5 | 4.00 | 7.43 | 1.10 | 6. | 6.2 | 2768. | 57. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 60.5 | 4.00 | 7.43 | 1.10 | 6. | 6.2 | 2809. | 57. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 59.5 | 4.00 | 7.42 | 1.10 | 6. | 6.2 | 2850. | 58. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 58.5 | 4.00 | 7.41 | 1.10 | 6. | 6.2 | 2893. | 59. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 57.5 | 4.00 | 7.41 | 1.10 | 6. | 6.2 | 2936. | 59. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 56.5 | 4.00 | 7.40 | 1.10 | 6. | 6.2 | 2979. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 187. | 187. |
| 55.5 | 4.00 | 7.38 | 1.10 | 6. | 6.2 | 2895. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 189. | 187. |
| 54.5 | 4.00 | 7.36 | 1.10 | 6. | 6.2 | 2814. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 191. | 187. |
| 53.5 | 4.00 | 7.34 | 1.10 | 6. | 6.2 | 2734. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 194. | 187. |
| 52.5 | 4.00 | 7.32 | 1.10 | 6. | 6.3 | 2657. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 196. | 187. |
| 51.5 | 4.00 | 7.30 | 1.10 | 6. | 6.3 | 2583. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 198. | 187. |
| 50.5 | 4.00 | 7.28 | 1.10 | 6. | 6.3 | 2510. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 200. | 187. |
| 49.5 | 4.00 | 7.26 | 1.10 | 6. | 6.3 | 2439. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 202. | 187. |
| 48.5 | 4.00 | 7.24 | 1.10 | 6. | 6.3 | 2373. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 205. | 187. |
| 47.5 | 4.00 | 7.22 | 1.10 | 6. | 6.3 | 2304. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 207. | 187. |
| 46.5 | 4.00 | 7.20 | 1.10 | 6. | 6.4 | 2239. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 209. | 187. |
| 45.5 | 4.00 | 7.18 | 1.10 | 6. | 6.4 | 2175. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 211. | 187. |
| 44.5 | 4.00 | 7.16 | 1.10 | 6. | 6.4 | 2114. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 213. | 187. |
| 43.5 | 4.00 | 7.14 | 1.10 | 6. | 6.4 | 2055. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 216. | 187. |
| 42.5 | 4.00 | 7.12 | 1.10 | 6. | 6.4 | 1997. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 218. | 187. |
| 41.5 | 4.00 | 7.10 | 1.10 | 6. | 6.4 | 1940. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 220. | 187. |
| 40.5 | 4.00 | 7.08 | 1.10 | 6. | 6.4 | 1885. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 222. | 187. |
| 39.5 | 4.00 | 7.06 | 1.10 | 6. | 6.5 | 1832. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 224. | 187. |
| 38.5 | 4.00 | 7.04 | 1.10 | 6. | 6.5 | 1780. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 227. | 187. |
| 37.5 | 4.00 | 7.02 | 1.10 | 6. | 6.5 | 1730. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 229. | 187. |
| 36.5 | 4.00 | 7.00 | 1.10 | 6. | 6.5 | 1681. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 231. | 187. |
| 35.5 | 4.00 | 6.99 | 1.10 | 6. | 6.5 | 1689. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 232. | 187. |
| 34.5 | 4.00 | 6.98 | 1.10 | 6. | 6.5 | 1697. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 232. | 187. |
| 33.5 | 4.00 | 6.97 | 1.10 | 6. | 6.5 | 1705. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 233. | 187. |
| 32.5 | 4.00 | 6.95 | 1.10 | 6. | 6.5 | 1713. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 233. | 187. |
| 31.5 | 4.00 | 6.94 | 1.10 | 6. | 6.5 | 1721. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 234. | 187. |
| 30.5 | 4.00 | 6.93 | 1.10 | 6. | 6.5 | 1729. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 234. | 187. |
| 29.5 | 4.00 | 6.92 | 1.10 | 6. | 6.5 | 1737. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 235. | 187. |
| 28.5 | 4.00 | 6.91 | 1.10 | 6. | 6.5 | 1745. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 236. | 187. |
| 27.5 | 4.00 | 6.90 | 1.10 | 6. | 6.5 | 1753. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 236. | 187. |
| 26.5 | 4.00 | 6.89 | 1.10 | 6. | 6.5 | 1761. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 237. | 187. |
| 25.5 | 4.00 | 6.87 | 1.10 | 6. | 6.5 | 1769. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 237. | 187. |
| 24.5 | 4.00 | 6.86 | 1.10 | 6. | 6.5 | 1777. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 238. | 187. |
| 23.5 | 4.00 | 6.85 | 1.10 | 6. | 6.5 | 1785. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 238. | 187. |
| 22.5 | 4.00 | 6.84 | 1.10 | 6. | 6.5 | 1793. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 239. | 187. |
| 21.5 | 4.00 | 6.83 | 1.10 | 6. | 6.5 | 1801. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 240. | 187. |
| 20.5 | 4.00 | 6.82 | 1.10 | 6. | 6.5 | 1809. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 240. | 187. |
| 19.5 | 4.00 | 6.81 | 1.10 | 6. | 6.5 | 1817. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 241. | 187. |
| 18.5 | 4.00 | 6.79 | 1.10 | 7. | 6.5 | 1825. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 241. | 187. |
| 17.5 | 4.00 | 6.78 | 1.10 | 7. | 6.5 | 1833. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 242. | 187. |
| 16.5 | 4.00 | 6.77 | 1.10 | 7. | 6.5 | 1841. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 242. | 187. |
| 15.5 | 4.00 | 6.76 | 1.10 | 7. | 6.5 | 1849. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 243. | 187. |
| 14.5 | 4.00 | 6.75 | 1.10 | 7. | 6.5 | 1857. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 244. | 187. |
| 13.5 | 4.00 | 6.74 | 1.10 | 7. | 6.5 | 1865. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 244. | 187. |
| 12.5 | 4.00 | 6.73 | 1.10 | 7. | 6.5 | 1873. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 245. | 187. |
| 11.5 | 4.00 | 6.71 | 1.10 | 7. | 6.5 | 1881. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 245. | 187. |
| 10.5 | 4.00 | 6.70 | 1.10 | 7. | 6.5 | 1889. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 246. | 187. |
| 9.5 | 4.00 | 6.69 | 1.10 | 7. | 6.5 | 1897. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 246. | 187. |
| 8.5 | 4.00 | 6.68 | 1.10 | 7. | 6.5 | 1905. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 247. | 187. |
| 7.5 | 4.00 | 6.67 | 1.10 | 7. | 6.5 | 1913. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 248. | 187. |
| 6.5 | 4.00 | 6.66 | 1.10 | 7. | 6.5 | 1921. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 248. | 187. |
| 5.5 | 4.00 | 6.65 | 1.10 | 7. | 6.5 | 1929. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 249. | 187. |
| 4.5 | 4.00 | 6.63 | 1.10 | 7. | 6.5 | 1937. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 249. | 187. |
| 3.5 | 4.00 | 6.62 | 1.10 | 7. | 6.5 | 1945. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 250. | 187. |
| 2.5 | 4.00 | 6.61 | 1.10 | 7. | 6.5 | 1953. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 250. | 187. |
| 1.5 | 4.00 | 6.60 | 1.10 | 7. | 6.5 | 1961. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 251. | 187. |
| .5 | 4.00 | 6.60 | 1.10 | 7. | 6.5 | 1961. | 60. | 150. | 0. | 14. | 1.0+01 | 28. | 3. | 14. | .3 | 60. | 251. | 187. |

App. 2. Initial conditions of the sub-basin No. 1 in 1975.

INITIAL CONDITIONS OF THE ECOSYSTEM

| ELEV M | TEMP C | DO MG/L | BOD5 MG/L | ALKA MG/L | PH | CO2C UG/L | NH3N UG/L | NO3N UG/L | NO2N UG/L | PO4P UG/L | COLIFM MPN/100 | ALGA1 UG/L | ALGA2 UG/L | ZOO UG/L | DETRI MG/L | TDS MG/L | SEDM G/M2 | BENTH MG/M2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 76.5 | 9.98 | 10.20 | 1.10 | 6. | 6.6 | 1187. | 16. | 150. | 3. | 3. | 1.0+01 | 237. | 3. | 14. | .3 | 60. | 187. | 187. |
| 75.5 | 9.98 | 10.20 | 1.10 | 6. | 6.6 | 1187. | 16. | 150. | 3. | 3. | 1.0+01 | 237. | 3. | 14. | .3 | 60. | 187. | 187. |
| 74.5 | 9.57 | 10.20 | 1.10 | 6. | 6.6 | 1190. | 16. | 150. | 3. | 3. | 1.0+01 | 237. | 3. | 14. | .3 | 60. | 187. | 187. |
| 73.5 | 9.25 | 10.20 | 1.10 | 6. | 6.6 | 1194. | 17. | 150. | 3. | 3. | 1.0+01 | 237. | 3. | 14. | .3 | 60. | 187. | 187. |
| 72.5 | 8.92 | 10.20 | 1.10 | 6. | 6.6 | 1217. | 17. | 150. | 3. | 3. | 1.0+01 | 237. | 3. | 14. | .3 | 60. | 187. | 187. |
| 71.5 | 8.60 | 10.20 | 1.10 | 6. | 6.6 | 1221. | 18. | 150. | 3. | 3. | 1.0+01 | 237. | 3. | 14. | .3 | 60. | 187. | 187. |
| 70.5 | 8.38 | 10.17 | 1.10 | 6. | 6.6 | 1260. | 18. | 150. | 3. | 3. | 1.0+01 | 222. | 3. | 14. | .3 | 60. | 187. | 187. |
| 69.5 | 8.16 | 10.15 | 1.10 | 6. | 6.6 | 1300. | 18. | 150. | 3. | 3. | 1.0+01 | 207. | 3. | 14. | .3 | 60. | 187. | 187. |
| 68.5 | 7.94 | 10.12 | 1.10 | 6. | 6.6 | 1342. | 18. | 150. | 3. | 3. | 1.0+01 | 192. | 3. | 14. | .3 | 60. | 187. | 187. |
| 67.5 | 7.72 | 10.09 | 1.10 | 6. | 6.5 | 1403. | 18. | 150. | 2. | 3. | 1.0+01 | 176. | 3. | 14. | .3 | 60. | 187. | 187. |
| 66.5 | 7.50 | 10.07 | 1.10 | 6. | 6.5 | 1448. | 18. | 150. | 2. | 3. | 1.0+01 | 161. | 3. | 14. | .3 | 60. | 187. | 187. |
| 65.5 | 7.28 | 10.04 | 1.10 | 6. | 6.5 | 1494. | 18. | 150. | 2. | 3. | 1.0+01 | 146. | 3. | 14. | .3 | 60. | 187. | 187. |
| 64.5 | 7.06 | 10.01 | 1.10 | 6. | 6.5 | 1542. | 18. | 150. | 2. | 3. | 1.0+01 | 131. | 3. | 14. | .3 | 60. | 187. | 187. |
| 63.5 | 6.84 | 9.99 | 1.10 | 6. | 6.5 | 1592. | 18. | 150. | 2. | 3. | 1.0+01 | 116. | 3. | 14. | .3 | 60. | 187. | 187. |
| 62.5 | 6.62 | 9.96 | 1.10 | 6. | 6.5 | 1644. | 18. | 150. | 2. | 3. | 1.0+01 | 101. | 3. | 14. | .3 | 60. | 187. | 187. |
| 61.5 | 6.40 | 9.93 | 1.10 | 6. | 6.5 | 1718. | 18. | 150. | 2. | 3. | 1.0+01 | 86. | 3. | 14. | .3 | 60. | 187. | 187. |
| 60.5 | 6.18 | 9.91 | 1.10 | 6. | 6.5 | 1774. | 18. | 150. | 2. | 3. | 1.0+01 | 71. | 3. | 14. | .3 | 60. | 187. | 187. |
| 59.5 | 5.96 | 9.88 | 1.10 | 6. | 6.4 | 1831. | 18. | 150. | 1. | 3. | 1.0+01 | 55. | 3. | 14. | .3 | 60. | 187. | 187. |
| 58.5 | 5.74 | 9.85 | 1.10 | 6. | 6.4 | 1891. | 18. | 150. | 1. | 3. | 1.0+01 | 40. | 3. | 14. | .3 | 60. | 187. | 187. |
| 57.5 | 5.52 | 9.83 | 1.10 | 6. | 6.4 | 1976. | 18. | 150. | 1. | 3. | 1.0+01 | 25. | 3. | 14. | .3 | 60. | 187. | 187. |
| 56.5 | 5.30 | 9.80 | 1.10 | 6. | 6.4 | 2041. | 18. | 150. | 1. | 3. | 1.0+01 | 10. | 3. | 14. | .3 | 60. | 187. | 187. |
| 55.5 | 5.28 | 9.82 | 1.10 | 6. | 6.4 | 2041. | 18. | 150. | 1. | 3. | 1.0+01 | 10. | 3. | 14. | .3 | 60. | 189. | 187. |
| 54.5 | 5.26 | 9.83 | 1.10 | 6. | 6.4 | 2042. | 18. | 150. | 1. | 3. | 1.0+01 | 9. | 3. | 14. | .3 | 60. | 191. | 187. |
| 53.5 | 5.24 | 9.85 | 1.10 | 6. | 6.4 | 2043. | 18. | 150. | 1. | 3. | 1.0+01 | 9. | 3. | 14. | .3 | 60. | 194. | 187. |
| 52.5 | 5.22 | 9.86 | 1.10 | 6. | 6.4 | 2043. | 18. | 150. | 1. | 3. | 1.0+01 | 9. | 3. | 14. | .3 | 60. | 196. | 187. |
| 51.5 | 5.20 | 9.88 | 1.10 | 6. | 6.4 | 2044. | 18. | 150. | 1. | 3. | 1.0+01 | 8. | 3. | 14. | .3 | 60. | 198. | 187. |
| 50.5 | 5.18 | 9.89 | 1.10 | 6. | 6.4 | 2044. | 18. | 150. | 1. | 4. | 1.0+01 | 8. | 3. | 14. | .3 | 60. | 200. | 187. |
| 49.5 | 5.16 | 9.91 | 1.10 | 6. | 6.4 | 2045. | 18. | 150. | 1. | 4. | 1.0+01 | 8. | 3. | 14. | .3 | 60. | 202. | 187. |
| 48.5 | 5.14 | 9.92 | 1.10 | 6. | 6.4 | 2046. | 18. | 150. | 1. | 4. | 1.0+01 | 7. | 3. | 14. | .3 | 60. | 205. | 187. |
| 47.5 | 5.12 | 9.93 | 1.10 | 6. | 6.4 | 2046. | 18. | 150. | 1. | 4. | 1.0+01 | 7. | 3. | 14. | .3 | 60. | 207. | 187. |
| 46.5 | 5.10 | 9.95 | 1.10 | 6. | 6.4 | 2047. | 18. | 150. | 1. | 4. | 1.0+01 | 7. | 3. | 14. | .3 | 60. | 209. | 187. |
| 45.5 | 5.08 | 9.96 | 1.10 | 6. | 6.4 | 2047. | 17. | 150. | 1. | 4. | 1.0+01 | 6. | 3. | 14. | .3 | 60. | 211. | 187. |
| 44.5 | 5.06 | 9.98 | 1.10 | 6. | 6.4 | 2048. | 17. | 150. | 1. | 4. | 1.0+01 | 6. | 3. | 14. | .3 | 60. | 213. | 187. |
| 43.5 | 5.04 | 9.99 | 1.10 | 6. | 6.4 | 2049. | 17. | 150. | 1. | 4. | 1.0+01 | 6. | 3. | 14. | .3 | 60. | 216. | 187. |
| 42.5 | 5.02 | 10.01 | 1.10 | 6. | 6.4 | 2049. | 17. | 150. | 1. | 4. | 1.0+01 | 5. | 3. | 14. | .3 | 60. | 218. | 187. |
| 41.5 | 5.00 | 10.02 | 1.10 | 6. | 6.4 | 2050. | 17. | 150. | 1. | 4. | 1.0+01 | 5. | 3. | 14. | .3 | 60. | 220. | 187. |
| 40.5 | 4.98 | 10.04 | 1.10 | 6. | 6.4 | 2050. | 17. | 150. | 1. | 5. | 1.0+01 | 5. | 3. | 14. | .3 | 60. | 222. | 187. |
| 39.5 | 4.96 | 10.05 | 1.10 | 6. | 6.4 | 2051. | 17. | 150. | 1. | 5. | 1.0+01 | 4. | 3. | 14. | .3 | 60. | 224. | 187. |
| 38.5 | 4.94 | 10.07 | 1.10 | 6. | 6.4 | 2052. | 17. | 150. | 1. | 5. | 1.0+01 | 4. | 3. | 14. | .3 | 60. | 227. | 187. |
| 37.5 | 4.92 | 10.08 | 1.10 | 6. | 6.4 | 2052. | 17. | 150. | 1. | 5. | 1.0+01 | 4. | 3. | 14. | .3 | 60. | 229. | 187. |
| 36.5 | 4.90 | 10.10 | 1.10 | 6. | 6.4 | 2053. | 17. | 150. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 231. | 187. |
| 35.5 | 4.89 | 10.10 | 1.10 | 6. | 6.4 | 2048. | 17. | 151. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 232. | 187. |
| 34.5 | 4.88 | 10.09 | 1.10 | 6. | 6.4 | 2043. | 17. | 151. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 232. | 187. |
| 33.5 | 4.87 | 10.09 | 1.10 | 6. | 6.4 | 2039. | 17. | 152. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 233. | 187. |
| 32.5 | 4.87 | 10.09 | 1.10 | 6. | 6.4 | 2034. | 17. | 152. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 233. | 187. |
| 31.5 | 4.86 | 10.09 | 1.10 | 6. | 6.4 | 2030. | 17. | 153. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 234. | 187. |
| 30.5 | 4.85 | 10.08 | 1.10 | 6. | 6.4 | 2025. | 17. | 153. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 234. | 187. |
| 29.5 | 4.84 | 10.08 | 1.10 | 6. | 6.4 | 2020. | 17. | 154. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 235. | 187. |
| 28.5 | 4.83 | 10.08 | 1.10 | 6. | 6.4 | 2016. | 17. | 155. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 235. | 187. |
| 27.5 | 4.82 | 10.07 | 1.10 | 6. | 6.4 | 2011. | 18. | 155. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 236. | 187. |
| 26.5 | 4.81 | 10.07 | 1.10 | 6. | 6.4 | 2006. | 18. | 156. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 236. | 187. |
| 25.5 | 4.81 | 10.07 | 1.10 | 6. | 6.4 | 2002. | 18. | 156. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 237. | 187. |
| 24.5 | 4.80 | 10.07 | 1.10 | 6. | 6.4 | 1997. | 18. | 157. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 238. | 187. |
| 23.5 | 4.79 | 10.06 | 1.10 | 6. | 6.4 | 1992. | 18. | 157. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 238. | 187. |
| 22.5 | 4.78 | 10.06 | 1.10 | 6. | 6.4 | 1988. | 18. | 158. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 239. | 187. |
| 21.5 | 4.77 | 10.06 | 1.10 | 6. | 6.4 | 1983. | 18. | 159. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 239. | 187. |
| 20.5 | 4.76 | 10.05 | 1.10 | 6. | 6.4 | 1979. | 18. | 159. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 240. | 187. |
| 19.5 | 4.75 | 10.05 | 1.10 | 6. | 6.4 | 1974. | 18. | 160. | 1. | 5. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 240. | 187. |
| 18.5 | 4.75 | 10.05 | 1.10 | 6. | 6.4 | 1969. | 18. | 160. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 241. | 187. |
| 17.5 | 4.74 | 10.05 | 1.10 | 6. | 6.4 | 1965. | 18. | 161. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 241. | 187. |
| 16.5 | 4.73 | 10.04 | 1.10 | 6. | 6.4 | 1960. | 18. | 161. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 242. | 187. |
| 15.5 | 4.72 | 10.04 | 1.10 | 6. | 6.4 | 1955. | 18. | 162. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 242. | 187. |
| 14.5 | 4.71 | 10.04 | 1.10 | 6. | 6.4 | 1951. | 18. | 163. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 243. | 187. |
| 13.5 | 4.70 | 10.03 | 1.10 | 6. | 6.4 | 1946. | 18. | 163. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 243. | 187. |
| 12.5 | 4.69 | 10.03 | 1.10 | 6. | 6.4 | 1941. | 18. | 164. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 244. | 187. |
| 11.5 | 4.69 | 10.03 | 1.10 | 6. | 6.4 | 1937. | 18. | 164. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 245. | 187. |
| 10.5 | 4.68 | 10.03 | 1.10 | 6. | 6.4 | 1932. | 18. | 165. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 245. | 187. |
| 9.5 | 4.67 | 10.02 | 1.10 | 6. | 6.4 | 1927. | 19. | 165. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 246. | 187. |
| 8.5 | 4.66 | 10.02 | 1.10 | 6. | 6.4 | 1923. | 19. | 166. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 246. | 187. |
| 7.5 | 4.65 | 10.02 | 1.10 | 6. | 6.4 | 1918. | 19. | 167. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 247. | 187. |
| 6.5 | 4.64 | 10.01 | 1.10 | 6. | 6.4 | 1913. | 19. | 167. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 247. | 187. |
| 5.5 | 4.63 | 10.01 | 1.10 | 6. | 6.4 | 1909. | 19. | 168. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 248. | 187. |
| 4.5 | 4.63 | 10.01 | 1.10 | 6. | 6.4 | 1904. | 19. | 168. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 248. | 187. |
| 3.5 | 4.62 | 10.01 | 1.10 | 6. | 6.4 | 1899. | 19. | 169. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 249. | 187. |
| 2.5 | 4.61 | 10.00 | 1.10 | 6. | 6.4 | 1895. | 19. | 169. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 249. | 187. |
| 1.5 | 4.60 | 10.00 | 1.10 | 5. | 6.4 | 1890. | 19. | 170. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 250. | 187. |
| .5 | 4.60 | 10.00 | 1.10 | 5. | 6.4 | 1890. | 19. | 170. | 0. | 4. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 250. | 187. |

App. 3. Initial conditions of the sub-basin No. 1 in 1976.

INITIAL CONDITIONS OF THE ECOSYSTEM

| ELEV M | TEMP C | DO MG/L | BOD5 MG/L | ALKA MG/L | PH | CO2C UG/L | NH3N UG/L | NO3N UG/L | NO2N UG/L | PO4P UG/L | COLIFM MPN/100 | ALGA1 UG/L | ALGA2 UG/L | ZOO UG/L | DETRI MG/L | TDS MG/L | SEDM G/M2 | BENTH MG/M2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75.5 | 10.40 | 8.90 | 1.10 | 6. | 6.3 | 2248. | 42. | 130. | 1. | 7. | 1.0+01 | 480. | 3. | 14. | .3 | 60. | 187. | 187. |
| 74.5 | 9.17 | 9.15 | 1.10 | 6. | 6.3 | 2185. | 39. | 140. | 1. | 7. | 1.0+01 | 480. | 3. | 14. | .3 | 60. | 187. | 187. |
| 73.5 | 7.95 | 9.40 | 1.10 | 6. | 6.3 | 2125. | 36. | 150. | 1. | 8. | 1.0+01 | 480. | 3. | 14. | .3 | 60. | 187. | 187. |
| 72.5 | 6.72 | 9.65 | 1.10 | 6. | 6.4 | 2069. | 32. | 160. | 1. | 8. | 1.0+01 | 480. | 3. | 14. | .3 | 60. | 187. | 187. |
| 71.5 | 5.50 | 9.90 | 1.10 | 6. | 6.4 | 2024. | 29. | 170. | 1. | 9. | 1.0+01 | 480. | 3. | 14. | .3 | 60. | 187. | 187. |
| 70.5 | 5.41 | 9.91 | 1.10 | 6. | 6.4 | 2056. | 29. | 170. | 1. | 9. | 1.0+01 | 449. | 3. | 14. | .3 | 60. | 187. | 187. |
| 69.5 | 5.33 | 9.91 | 1.10 | 6. | 6.4 | 2089. | 29. | 170. | 1. | 9. | 1.0+01 | 417. | 3. | 14. | .3 | 60. | 187. | 187. |
| 68.5 | 5.24 | 9.92 | 1.10 | 6. | 6.4 | 2122. | 29. | 170. | 1. | 9. | 1.0+01 | 386. | 3. | 14. | .3 | 60. | 187. | 187. |
| 67.5 | 5.15 | 9.93 | 1.10 | 6. | 6.4 | 2156. | 29. | 170. | 1. | 9. | 1.0+01 | 355. | 3. | 14. | .3 | 60. | 187. | 187. |
| 66.5 | 5.07 | 9.93 | 1.10 | 6. | 6.4 | 2213. | 29. | 170. | 1. | 9. | 1.0+01 | 323. | 3. | 14. | .3 | 60. | 187. | 187. |
| 65.5 | 4.98 | 9.94 | 1.10 | 6. | 6.4 | 2249. | 29. | 170. | 1. | 9. | 1.0+01 | 292. | 3. | 14. | .3 | 60. | 187. | 187. |
| 64.5 | 4.89 | 9.95 | 1.10 | 6. | 6.4 | 2285. | 29. | 170. | 1. | 9. | 1.0+01 | 261. | 3. | 14. | .3 | 60. | 187. | 187. |
| 63.5 | 4.81 | 9.95 | 1.10 | 6. | 6.3 | 2321. | 30. | 170. | 1. | 8. | 1.0+01 | 229. | 3. | 14. | .3 | 60. | 187. | 187. |
| 62.5 | 4.72 | 9.96 | 1.10 | 6. | 6.3 | 2358. | 30. | 170. | 1. | 8. | 1.0+01 | 198. | 3. | 14. | .3 | 60. | 187. | 187. |
| 61.5 | 4.63 | 9.97 | 1.10 | 6. | 6.3 | 2396. | 30. | 170. | 1. | 8. | 1.0+01 | 167. | 3. | 14. | .3 | 60. | 187. | 187. |
| 60.5 | 4.55 | 9.97 | 1.10 | 6. | 6.3 | 2435. | 30. | 170. | 1. | 8. | 1.0+01 | 135. | 3. | 14. | .3 | 60. | 187. | 187. |
| 59.5 | 4.46 | 9.98 | 1.10 | 6. | 6.3 | 2474. | 30. | 170. | 1. | 8. | 1.0+01 | 104. | 3. | 14. | .3 | 60. | 187. | 187. |
| 58.5 | 4.37 | 9.99 | 1.10 | 6. | 6.3 | 2514. | 30. | 170. | 1. | 8. | 1.0+01 | 73. | 3. | 14. | .3 | 60. | 187. | 187. |
| 57.5 | 4.29 | 9.99 | 1.10 | 6. | 6.3 | 2555. | 30. | 170. | 1. | 8. | 1.0+01 | 41. | 3. | 14. | .3 | 60. | 187. | 187. |
| 56.5 | 4.20 | 10.00 | 1.10 | 6. | 6.3 | 2596. | 30. | 170. | 1. | 8. | 1.0+01 | 10. | 3. | 14. | .3 | 60. | 187. | 187. |
| 55.5 | 4.19 | 9.89 | 1.10 | 6. | 6.3 | 2597. | 30. | 173. | 1. | 8. | 1.0+01 | 10. | 3. | 14. | .3 | 60. | 189. | 187. |
| 54.5 | 4.19 | 9.79 | 1.10 | 6. | 6.3 | 2597. | 30. | 176. | 1. | 8. | 1.0+01 | 9. | 3. | 14. | .3 | 60. | 191. | 187. |
| 53.5 | 4.18 | 9.68 | 1.10 | 6. | 6.3 | 2597. | 30. | 179. | 1. | 8. | 1.0+01 | 9. | 3. | 14. | .3 | 60. | 194. | 187. |
| 52.5 | 4.18 | 9.58 | 1.10 | 6. | 6.3 | 2597. | 30. | 182. | 1. | 8. | 1.0+01 | 9. | 3. | 14. | .3 | 60. | 196. | 187. |
| 51.5 | 4.17 | 9.47 | 1.10 | 6. | 6.3 | 2597. | 30. | 185. | 1. | 8. | 1.0+01 | 8. | 3. | 14. | .3 | 60. | 198. | 187. |
| 50.5 | 4.17 | 9.37 | 1.10 | 6. | 6.3 | 2598. | 30. | 188. | 1. | 7. | 1.0+01 | 8. | 3. | 14. | .3 | 60. | 200. | 187. |
| 49.5 | 4.16 | 9.26 | 1.10 | 6. | 6.3 | 2598. | 30. | 191. | 1. | 7. | 1.0+01 | 8. | 3. | 14. | .3 | 60. | 202. | 187. |
| 48.5 | 4.16 | 9.16 | 1.10 | 6. | 6.3 | 2598. | 30. | 194. | 1. | 7. | 1.0+01 | 7. | 3. | 14. | .3 | 60. | 205. | 187. |
| 47.5 | 4.15 | 9.06 | 1.10 | 6. | 6.3 | 2598. | 30. | 197. | 1. | 7. | 1.0+01 | 7. | 3. | 14. | .3 | 60. | 207. | 187. |
| 46.5 | 4.15 | 8.95 | 1.10 | 6. | 6.3 | 2598. | 30. | 200. | 1. | 7. | 1.0+01 | 7. | 3. | 14. | .3 | 60. | 209. | 187. |
| 45.5 | 4.14 | 8.85 | 1.10 | 6. | 6.3 | 2599. | 30. | 203. | 1. | 7. | 1.0+01 | 6. | 3. | 14. | .3 | 60. | 211. | 187. |
| 44.5 | 4.14 | 8.74 | 1.10 | 6. | 6.3 | 2599. | 30. | 206. | 1. | 7. | 1.0+01 | 6. | 3. | 14. | .3 | 60. | 213. | 187. |
| 43.5 | 4.13 | 8.64 | 1.10 | 6. | 6.3 | 2599. | 30. | 209. | 1. | 7. | 1.0+01 | 6. | 3. | 14. | .3 | 60. | 216. | 187. |
| 42.5 | 4.13 | 8.53 | 1.10 | 6. | 6.3 | 2599. | 30. | 212. | 1. | 7. | 1.0+01 | 5. | 3. | 14. | .3 | 60. | 218. | 187. |
| 41.5 | 4.12 | 8.43 | 1.10 | 6. | 6.3 | 2600. | 30. | 215. | 1. | 7. | 1.0+01 | 5. | 3. | 14. | .3 | 60. | 220. | 187. |
| 40.5 | 4.12 | 8.32 | 1.10 | 6. | 6.3 | 2600. | 30. | 218. | 1. | 6. | 1.0+01 | 5. | 3. | 14. | .3 | 60. | 222. | 187. |
| 39.5 | 4.12 | 8.22 | 1.10 | 6. | 6.3 | 2600. | 30. | 221. | 1. | 6. | 1.0+01 | 4. | 3. | 14. | .3 | 60. | 224. | 187. |
| 38.5 | 4.11 | 8.11 | 1.10 | 6. | 6.3 | 2600. | 30. | 224. | 1. | 6. | 1.0+01 | 4. | 3. | 14. | .3 | 60. | 227. | 187. |
| 37.5 | 4.11 | 8.01 | 1.10 | 6. | 6.3 | 2600. | 30. | 227. | 1. | 6. | 1.0+01 | 4. | 3. | 14. | .3 | 60. | 229. | 187. |
| 36.5 | 4.10 | 7.90 | 1.10 | 6. | 6.3 | 2601. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 231. | 187. |
| 35.5 | 4.10 | 7.94 | 1.10 | 6. | 6.3 | 2617. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 232. | 187. |
| 34.5 | 4.10 | 7.98 | 1.10 | 6. | 6.3 | 2634. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 232. | 187. |
| 33.5 | 4.10 | 8.02 | 1.10 | 6. | 6.3 | 2650. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 233. | 187. |
| 32.5 | 4.10 | 8.06 | 1.10 | 6. | 6.3 | 2667. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 233. | 187. |
| 31.5 | 4.10 | 8.10 | 1.10 | 6. | 6.3 | 2684. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 234. | 187. |
| 30.5 | 4.10 | 8.14 | 1.10 | 6. | 6.3 | 2701. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 234. | 187. |
| 29.5 | 4.10 | 8.18 | 1.10 | 6. | 6.3 | 2718. | 30. | 230. | 1. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 235. | 187. |
| 28.5 | 4.10 | 8.22 | 1.10 | 6. | 6.3 | 2735. | 30. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 235. | 187. |
| 27.5 | 4.10 | 8.26 | 1.10 | 6. | 6.3 | 2752. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 236. | 187. |
| 26.5 | 4.10 | 8.30 | 1.10 | 6. | 6.3 | 2769. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 236. | 187. |
| 25.5 | 4.10 | 8.34 | 1.10 | 6. | 6.3 | 2787. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 237. | 187. |
| 24.5 | 4.10 | 8.38 | 1.10 | 6. | 6.3 | 2804. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 238. | 187. |
| 23.5 | 4.10 | 8.42 | 1.10 | 6. | 6.3 | 2822. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 238. | 187. |
| 22.5 | 4.10 | 8.46 | 1.10 | 6. | 6.3 | 2840. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 239. | 187. |
| 21.5 | 4.10 | 8.50 | 1.10 | 6. | 6.3 | 2858. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 239. | 187. |
| 20.5 | 4.10 | 8.54 | 1.10 | 6. | 6.3 | 2876. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 240. | 187. |
| 19.5 | 4.10 | 8.58 | 1.10 | 6. | 6.3 | 2894. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 240. | 187. |
| 18.5 | 4.10 | 8.62 | 1.10 | 6. | 6.2 | 2912. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 241. | 187. |
| 17.5 | 4.10 | 8.66 | 1.10 | 6. | 6.2 | 2931. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 241. | 187. |
| 16.5 | 4.10 | 8.70 | 1.10 | 6. | 6.2 | 2949. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 242. | 187. |
| 15.5 | 4.10 | 8.74 | 1.10 | 6. | 6.2 | 2968. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 242. | 187. |
| 14.5 | 4.10 | 8.78 | 1.10 | 6. | 6.2 | 2987. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 243. | 187. |
| 13.5 | 4.10 | 8.82 | 1.10 | 6. | 6.2 | 3005. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 243. | 187. |
| 12.5 | 4.10 | 8.86 | 1.10 | 6. | 6.2 | 3024. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 244. | 187. |
| 11.5 | 4.10 | 8.90 | 1.10 | 6. | 6.2 | 3044. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 245. | 187. |
| 10.5 | 4.10 | 8.94 | 1.10 | 6. | 6.2 | 3063. | 31. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 245. | 187. |
| 9.5 | 4.10 | 8.98 | 1.10 | 6. | 6.2 | 3082. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 246. | 187. |
| 8.5 | 4.10 | 9.02 | 1.10 | 6. | 6.2 | 3102. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 246. | 187. |
| 7.5 | 4.10 | 9.06 | 1.10 | 6. | 6.2 | 3121. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 247. | 187. |
| 6.5 | 4.10 | 9.10 | 1.10 | 6. | 6.2 | 3141. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 247. | 187. |
| 5.5 | 4.10 | 9.14 | 1.10 | 6. | 6.2 | 3161. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 248. | 187. |
| 4.5 | 4.10 | 9.18 | 1.10 | 6. | 6.2 | 3181. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 248. | 187. |
| 3.5 | 4.10 | 9.22 | 1.10 | 6. | 6.2 | 3201. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 249. | 187. |
| 2.5 | 4.10 | 9.26 | 1.10 | 6. | 6.2 | 3221. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 249. | 187. |
| 1.5 | 4.10 | 9.30 | 1.10 | 6. | 6.2 | 3242. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 250. | 187. |
| .5 | 4.10 | 9.30 | 1.10 | 6. | 6.2 | 3242. | 32. | 230. | 0. | 6. | 1.0+01 | 3. | 3. | 14. | .3 | 60. | 250. | 187. |

App. 4. Values of coefficients used in the simulations.

DECAY COEFFICIENTS

| | |
|---|---|
| BOD, PER DAY | .100 |
| NH3-N, PER DAY | .150 |
| NO2-N, PER DAY | .750 |
| DETRITUS, PER DAY | .001 |
| COLIFORM, PER DAY | .400 |

TEMPERATURE COEFFICIENTS

| | |
|---|---|
| Q10-BOD | 1.047 |
| Q10-NH3 | 1.020 |
| Q10-NO2 | 1.040 |
| Q10-DETRITUS | 1.040 |
| Q10-COLIFORM | 1.040 |
| Q10-BIOLOGIC | 1.020 |

CHEMICAL COMPOSITIONS OF BIOTA

| | C | N | P |
|---|---|---|---|
| ALGAE | .500 | .100 | .010 |
| ZOOPLANKTON | .500 | .100 | .010 |
| FISH | .500 | .100 | .010 |
| BENTHO | .500 | .100 | .010 |
| DETRITUS | .500 | .100 | .010 |

DIGESTIVE EFFICIENCY OF BIOTA

| | |
|---|---|
| ZOOPLANKTON | .700 |
| FISH | .500 |
| BENTHO | .600 |

MORTALITY RATES

| | NATURAL | TOXICITY |
|---|---|---|
| ZOOPLANKTON | .500E-02 | |
| FISH | .300E-03 | |
| BENTHO | .100E-02 | |

RESPIRATION RATES, PER DAY

| | ACTIVE | PASSIVE |
|---|---|---|
| PHYTOPLANKTON | .100+00 | .100-02 |
| ZOOPLANKTON | .200-01 | .100-02 |
| FISH | .100-02 | .100-03 |
| BENTHO | .100-02 | .100-03 |

DETRITUS SETTLING, METER/DAY .15000

OTHER PHYTOPLANKTON DATA

| | | |
|---|---|---|
| SETTLING, METER/DAY | .20000 | .20000 |
| OXYGENATION FACTOR | 1.800 | |
| PREFERANCE | .900 | .100 |
| SELFSHADING PER MG/L/M | .150 | |

MAXIMUM SPECIFIC GROWTH RATE, PER DAY

| | | | |
|---|---|---|---|
| PHYTOPLANKTON, 2 GROUPS | .140+01 | .260+01 | |
| ZOOPLANKTON | .220+00 | | |
| FISH, 3GROUPS | .300-01 | .250-01 | .200-01 |
| BENTHO | .300-01 | | |

HALF-SATURATION CONSTANTS OF ALGAE

| | LIGHT | CO2 | N | PO4 |
|---|---|---|---|---|
| ALGAE 1 | .003 | .025 | .050 | .020 |
| ALGAE 2 | .005 | .025 | .200 | .060 |

HALF-SATURATION CONSTANTS FOR ZOO, FISH AND BENTHO

| | |
|---|---|
| ZOO GRAZE ON ALGAE | .600 |
| FISH 1 GRAZE ON ZOO | .050 |
| FISH 2 GRAZE ON ZOO | .100 |
| FISH GRAZE ON BENTHO | 50.000 |
| BENTHO GRAZE ON SEDMT | 50.000 |

STOICHIOMETRIC EQUIVALENCE OF CHEMICAL TRANSFORMATION

| | |
|---|---|
| O2-NH3 | 3.500 |
| O2-NO2 | 1.140 |
| O2-DETRITUS | 1.450 |
| O2-BIOMASS | 1.600 |
| CO2-BOD | .200 |

TEMPERATURE TOLERANCE LIMITS, DEGREE C

| | | |
|---|---|---|
| ZOOPLANKTON | 5.000 | 30.000 |
| ALGAE 1 | .500 | 35.000 |
| ALGAE 2 | 1.000 | 35.000 |
| FISH 1 | 5.000 | 20.000 |
| FISH 2 | 10.000 | 30.000 |
| FISH 3 | 5.000 | 30.000 |
| BENTHO | 5.000 | 30.000 |