Polish J. of Environ. Stud. Vol. 15, No. 6 (2006), 837-844

Original Research

The Protection of Reservoir Water against the Eutrophication Process

W. Balcerzak*

Institute of Water Supply and Environmental Protection, Kraków University of Technology,
ul. Warszawska 24, 31-155 Kraków, Poland

Received: May 27, 2005
Accepted: June 31, 2006

Abstract

The article analyzes methods for the protection of reservoir water against the eutrophication process. It discusses methods for protection against point-source, spatial and dispersed pollution, biological methods and the most frequently applied technical methods. It pays special attention to the application of mathematical modelling to predict changes in water quality. A simulation of water quality changes in the Dobczyce Reservoir, expressed by a change in the concentration of chlorophyll "a," was made. Calculations were made for different pollutant concentrations and different temperatures. It was found that temperature had an important impact on the course of the process in surface segments and that pollutant load exerted an influence in subsurface segments. In sediment segments, the factors did not practically affect the course of the eutrophication process.

Keywords: water protection methods, eutrophication, mathematical modelling.

Introduction

Eutrophication is the process of gradual enrichment of reservoir water with plant food, mainly nitrogen and phosphorus compounds (nutrients). The process is accompanied with an excessive primary vegetation production (growth of aquatic plants) while no secondary production is observed. Aquatic ecosystems with a shortage of plant nutrients (oligotrophic systems) show low biologic productivity and good water clarity. An ecosystem trophicity increases along with nutrient inflow to the system; the ecosystem passes through a mesotrophic phase to a eutrophic phase, with a sufficient supply of nutrients, and then finally it reaches the polytrophic phase with an abundance of nutrients. This conversion, which has been naturally occurring in nature for many years, picked up the pace in recent years and currently the main cause of water contamination with nutrients is anthropogenic eutrophication. At the very beginning, eutrophication was limited to lakes only, where due to a low flow velocity excessive biomass growth was observed. Nowadays eutrophication also affects rivers, though not to such an extent. The most eye-catching indicator of eutrophication are summer algal blooms caused by a rapid and intensive growth of some algae populations. Algae are the predominant species in lakes and water reservoirs while blue-green algae and diatomeae predominate in rivers.

Intensive biological growth and algae blooms generate problems not only of aesthetic and recreational nature but they also can upset both water intake and water treatment plant operation. [1] Eutrophication has a considerable impact on raw water quality and in consequence it influences water treatment technology and finally the quality of the water. Intensive growth of phytoplankton results in higher concentrations of organic suspended solids and toxins in water as well as in oxygen depletion. Therefore, changes in raw water quality characteristics have some important implications for the water treatment process and for the costs of water production and distribution.

*e-mail: wb@vistula.wis.pk.edu.pl

Water Protection Methods

Protection against Pollution from Point Sources

An effective method for the protection of lakes against the inflow of point-source pollution is its complete isolation, purification and directing outside the reception basin. Sewage from small point sources can be purified in natural conditions, i.e. using natural processes of pollutant biodegradation [2]. In the case of large point-source pollution, protection consists in building 3-stage sewage treatment plants [3].

Protection against Spatial Pollution

Most often, spatial pollution is of agricultural origin and in many cases it is the cause of lake overcharging with biogenic compounds. That is why we strive for a decrease in the quantity of biogenic compounds flowing to lakes by:

– creating girdling ditches ending with a tank, which enables water reuse for agricultural purposes;
– increasing the proportion of woodland in the reception basin, at the cost of decreased arable acreage;
– proper crop structure, increased proportion of organic fertilizers, use of slow-dissolving mineral fertilizers;
– adjusting the reception basin development to the distinction and natural diversity of the area,
– constructing storage reservoirs on small watercourses, preliminary retention reservoirs, and changing the watering method.

Protection against Dispersed Pollution

Protection against this pollution consists of:

– cesspool sealing and waste removal to sewage treatment plants or construction of a sewage collector,
– fitting beaches with toilets,
– defining a protection zone around the reservoir and moving buildings to at least 100 m from the shoreline.

Reservoir Reclamation

More and more water reservoirs are losing or have already lost their landscape, recreational and usable values. In the case of a lake that is excessively polluted it is not enough to isolate the point sources and reduce spatial pollutant loads; the elimination of the negative effects is possible only after lake reclamation has been carried out. Lake reclamation is a drive towards the reversal of the eutrophication processes by applying technical and biological methods [4].

Biological Methods

These methods are treated as auxiliary, adjunct methods enabling the removal of nitrogen and phosphorus from water together with organisms occurring in water. Nitrogen and phosphorus compounds are removed when animals and plants are removed from pelagic water. With high fish catch a significant proportion of phosphorus load can be removed from a lake, and in the case of a heavily weed-grown small lake with a small basin, as much as a few dozen percent of biogenic compounds can be removed with the removal of vegetation, thus limiting internal feeding. Biological reclamation can also be realized by biomanipulation, which means interference in the reservoir ecosystem consisting in increasing the number of predators, which enables self-regulation of the ecosystem and a return to the state of ecological equilibrium.

Technical Methods

Bottom Sediment Removal

This is the most effective method for lake reclamation, but it is also the most expensive, due to the costs of equipment, the need to erect sedimentation tanks, and lengthy processes. This method consists of the removal of the most fertile, the youngest bottom sediments which contain the largest amounts of biogenic compounds. Water quality in the reservoir improves considerably after the deposits have been pumped out, which is connected with reduced internal feeding. Water obtained in this process can be returned to the lake, but only after treatment. The application of this method is justified and gives long-lasting effects for reservoirs to which biogenic matter supply from the catchment has been limited.

Inactivation of Biogenic Compounds

This method consists of direct precipitation of phosphorus from the lake pelagic zone by means of a coagulant, i.e. ferric salts, calcium hydroxide or aluminium sulphate, and its inactivation in bottom sediments. Inactivation of biogenic matter contained in the bottom sediment layer is also applied, which reduces the supply of biogenic compounds from sediments to water in the reservoir. With this end in view, compounds which reduce phosphorus and coagulants are delivered directly to the sediment layer.

Biooxidation of Bottom Sediments

This method is based on oxidation of compounds reduced in the surface layers of bottom deposits, with simultaneous phosphorus fixation by iron, calcium or aluminium compounds.

Lake Aeration

The purpose of this method is a quick oxygenation of bottom water by means of aerators and air grates [5]. These devices cause a complete mixing of water leading to the equalization of water temperature and the consequent heating of bottom sediments. It is an unfavourable phenomenon, because it results in an accelerated mineralization of bottom deposits and increased primary production in the lake, which manifests itself by water blooming. That is why methods causing water mixing are applied in shallow lakes not more than 10 m deep.

Evacuation of Hypolimnion Bottom Water

This procedure consists in laying a pipeline on the bottom, connecting the deepest point in the lake with the outflow. The pipeline serves to evacuate the most fertile, usually deoxidized bottom water. The advantage of this method is a long-lasting improvement in the quality of water and low operating costs.

The Application of Mathematical Modelling

Water engineering is now aided by information technology which is used to program changes occurring in the natural environment. Specially designed mathematical programs serve as a tool to model changes in the natural environment [6-8]. The programs simulate changes in the natural environment as well as fluctuations of such parameters as water temperature, wind intensity and direction, and concentrations of dissolved oxygen, dissolved solids and nutrients in the water reservoir. They may also include other parameters depending on the degree of complexity of the particular simulation program. Mathematical forecasts applied in simulation models include models of pollutant mass transfer and mass and momentum exchange. Such models follow the physical, chemical and biological processes that influence surface and ground water quality. Application of the models to the research work helps better understand the nature of processes taking place in aquatic environments, mainly in natural and man-made water reservoirs.

Programs which model water quality play a vital role in environmental protection, because they make it possible to project the existing condition as well as the anticipated changes in surface water pollution. The application of mathematical modelling to solving problems connected with water quality allows us to analyse the occurring phenomena and to find the interrelations between them. It also enables forecasting of quantitative and qualitative changes occurring in water reservoirs as time goes on under the influence of increasing environmental pollution [9, 10]. There is also research carried out on the application of neural networks for solving such problems [11]. Based on the programs, it is possible to identify specific strategies that would be helpful in the decision making process, concerning not only water management within the reservoir but also throughout the overall catchment area. Such policies could result in complex water quality protection.

The WASP Water Quality Simulation Model

One of the programs used to solve a broad range of problems connected with water quality is the program WASP – The Water Quality Analysis Simulation Program, which was developed under the patronage of the US Environmental Protection Agency [12]. It is used for dynamic modelling of transport phenomena and changes occurring in aqueous environment and the bottom deposit layer. The program is intended for simulating changes in water quality occurring in surface waters, i.e. in streams, rivers, lakes, ponds, artificial reservoirs [13]. It reflects time-variable advection and dispersion processes, taking into account both point-source and territorial inflows, as well as exchange limits. Water quality simulation covers such problems as dissolved oxygen dynamics, eutrophication, water fertilization, chemical pollution, biological pollution, and biological oxygen demand.

WASP comprises two subprograms which deal with modelling of different problems connected with water quality:

- *TOXI* – a model that applies to toxicity
- *EUTRO* – a model analyzing eutrophication and dissolved oxygen concentration.

The *TOXI* program comprises procedures allowing the calculation of changes in chemical pollution in surface waters, it models organic indicators, heavy metals and pollutants contained in sediments.

The *EUTRO* program simulates water enrichment with nutrients, eutrophication and a fall in dissolved oxygen concentration. Simulation can be done at various levels of complexity. The method of solving a given problem depends on the quantity of introduced variables. It models classic pollution indicators which include dissolved oxygen, biochemical oxygen demand, nitrogen compounds, phosphorus compounds, temperature, and Coli bacteria content.

The *EUTRO* program broadly takes into account the problems of phytoplankton development kinetics.

Principal Formulas Used in the WASP Program

The basic formula that is solved by the WASP program is the mass balance equation:

$$\underbrace{\frac{\delta C}{\delta t}}_{\text{Accumulation}} = \underbrace{\frac{\delta\left(A * D_x * \frac{\delta C}{\delta x}\right)}{A * \delta x}}_{\text{Dispersion}} - \underbrace{\frac{\delta\left(A * U_x * C\right)}{A * \delta x}}_{\text{Advection}} + \underbrace{S_K}_{\text{Internal reactions}} + \underbrace{\left(S_B + S_L\right)}_{\text{External sources}} \quad (1)$$

where:

C – pollution indicator concentration [g/m^3]

t – time[d]

A – surface area of stream cross-section [m^2}

D_x – dispersion coefficient along the x-axis [m/d]
x – distance along the stream axis [m]
U – advection velocity along the x-axis [m/d]
S_K– mass yield (loss) due to internal reactions, calculated for segment volume [g/m^3 d]
S_B – mass exchange between adjacent segments "i" and "j" due to longitudinal dispersion, calculated for the i-segment [g/m^3 d]; S_B for the i -segment is defined as:

$$S_{Bi} = \frac{E_{i0}(t) * A_{i0}}{V_i * L_{i0}} * \left(C_{jk} - C_{ik}\right)$$

where:
$E_{i0(t)}$ – dispersion coefficient as a function of time at the beginning of i-segment [m^3/d]
A_{i0} – surface area at the beginning of -i- crosss-section [m^2]
V_i – volume of i-segment [m^3]
L_{i0} – length of i-segment [m]
C_{jk} – concentration of k- pollution indicator in i-segment [g/m^3]
C_{ik} – concentration of k-pollution indicator in i-segment [g/m^3]
S_L – pollution load in an external (side) flow, calculated for a water volume of this segment; S_L for the i-segment and k-pollution indicator is:

$$S_{Lik} = \frac{1000 * L_{ik(t)}}{V_i}$$

where:
$L_{ik(t)}$ – pollution load in an external flow [kg/d]

First two segments of equation (1) describe a pollution transport mechanism in aquatic environment with dispersion and advection processes; two other represent internal reactions and external pollution sources.

Dobczyce Reservoir Pollution Sources

The Dobczyce Reservoir is located in the Raba River. It serves as a main water supply source for the City of Kraków. Due to its geographical locations and landscape configuration the reservoir is classified as a type specific for hilly country. It is large (maximum capacity >100 million m^3), rather deep (average depth >10m), with a long retention time (>100 days) and continuous water discharge [14]. Pollutants contained in water flowing to the reservoir have crucial effect on the quality of water in the reservoir (which is the basic source of water supply for the city of Kraków). Municipal sewage is discharged directly to the River Raba (the main source of supply for the reservoir) in its upper course and to the river's tributaries. Water quality is adversely affected by leachate from unauthorized waste dumps, leaky cesspools and pollution connected with mass recreation. The greatest effect on water quality in the reservoir has sewage discharged from the mechanical and biological sewage treatment plant in Myslenice. This sewage accounts for approximately 86% of the total mineral nitrogen load and approximately 95% of the total mineral phosphorus load. The second largest pollution source for the reservoir is rainwater runoff from built-up areas, mainly from the Krakow–Zakopane expressway.

Water discharge from the reservoir has to proceed with certain reliability. Acceptable reliability of flow should be provided by trouble-free water intake and treatment plant operation, which in turn operate in a satisfactory manner only if water quality in the reservoir remains at a satisfactory level. Temporary water blooming, which deteriorates water quality, disturbs the system and results in a decrease of its reliability [15].

The Simulation Method

The usefulness of the WASP-6 program was verified by modelling the course of the eutrophication process in the Dobczyce Reservoir. In order to project the complexity of the water ecosystem for the purpose of the calculations a spatial model of the analyzed environment should be adopted. To this end, the mass of water is divided into spatial segments of known geometrical dimensions, so that they include all water layers, i.e. epilimnion, hypolimnion, upper layers of the bottom sediment and lower layers of the bottom sediment.

We assessed the effects of supplied pollutants on the concentration of chlorophyll "a," which is an indicator of phytoplankton content and which allows us to assess the intensity of the photosynthesis process.

The geometrical profile of the Dobczyce Reservoir has been presented by means of segments including three different types:

– surface segments, epilimnion – elements l, 2.3;
– subsurface segments, hypolimnion – elements 4, 5, 6, 8, 9;
– sediment-type segments – elements 7.10;

In the model, advectional flows between the segments and dispersive mixing within water column were

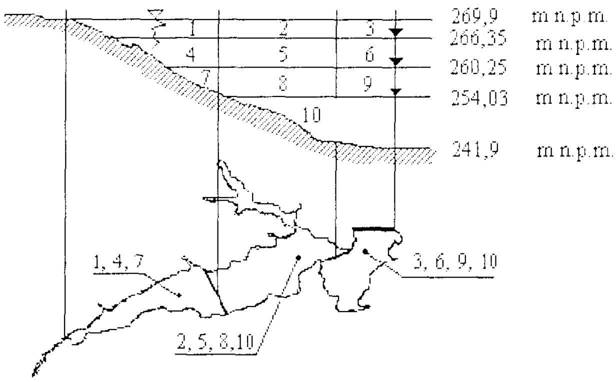

Fig. 1. Schematic division of the reservoir into segments

assumed. The average multiannual flow of 10.6 [m^3/s] for the River Raba was assumed. The simulation of the course of the eutrophication phenomenon was made on a dynamic model for eight process variables, i.e. for ammonium nitrogen, nitrate nitrogen, phosphates, chlorophyll "a," BOD, dissolved oxygen as well as organic phosphorus and nitrogen.

The calculations were made for a simulation period of 365 days and for a time step computed by the model.

It was assumed, in accordance with the underlying concept of the program, that limiting concentrations defined for each of the eight model variables occurred in areas where we had to do with advectional flow or dispersive mixing. Those values determined the boundary values, which were assumed in the model as variable over time, as a result of changes occurring in the pelagic zone during the year.

It was assumed in the simulation model in question that the reservoir was laden with a point-source pollution load coming from the Municipal Sewage Treatment Plant in Myslenice, located on the left bank of the River Raba. The variability of the inflowing biogenic pollutant loads expressed in [kg/d] were described by means of broken functions of pollutant inflow. These functions contain average values of the daily load in successive months of the year.

The impact of the climatic factors which shape the course of the reservoir's water eutrophication phenomenon and which include: temperature, insolation, daylight percentage and wind, was taken into account in the calculations, and the variability of these values has also been presented by means of a broken variability time function.

As the input data the parameters describing water quality in the reservoir in 2000 were used. The data were obtained from the laboratory of MPWiK S. A. (water and sewage utility) in Kraków. The utility is responsible for water supply for the Kraków agglomeration; water is taken from the varying depth, equivalent to segments 6 and 9.

The values of the initial concentrations of the model variables in individual segments were assumed as the value of these parameters on 30th December 1999. In this way the daily variability of the phytoplankton population expressed as chlorophyll "a" concentration in water [$\mu g/dm^3$], as well as the daily variability of the other seven model variables, were obtained.

Within the framework of the study a simulation of the eutrophication phenomenon was carried out for three computing cases.

Computing Case l

The first simulation was carried out in the following way. After all parameters characterizing the reservoir environment had been fed into the WASP6 program, pollutants flowing into the reservoir in 2000 were fed to the program. Pollutant loads were calculated on the basis of the results of surveys of the River Raba water quality carried out in the cross-section downstream of the outlet of sewage treatment plant in Myslenice, assuming that the water flow in the river was 10.6 [m^3/s].

Computing Case 2

The second simulation was made assuming that the flow of biogenic compounds had increased. A 50% increase in the ammonia, nitrates and phosphates loads in relation to the loads used in the first computing example was assumed.

Such a situation corresponds to a case where the sewage treatment plant in Myslenice is fed sewage containing compounds that are toxic to the activated sludge.

Computing Case 3

The third simulation was made assuming an increase in temperature in the spring and summer-autumn period within 2–5°C.

Results Summary

In surface segments (l, 2, 3), the largest concentration of chlorophyll "a" was received for computing case No. 3, that is for the case where temperature was increased (Fig. 2).

In subsurface segments (4, 5, 6, 8, 9), the largest concentration of chlorophyll "a" was received for computing case No. 2, it is for the situation where the flow of pollutant loads to the reservoir had been increased (Fig. 3).

In segments describing the upper sediment layers (7, 10), differences in chlorophyll "a" concentrations are insignificant (Fig. 4).

The results of the calculations lead to the conclusion that in surface segments it is temperature and other climatic factors which are crucial to changes in the concentration of chlorophyll "a." As the depth of the reservoir increases, the influence of temperature on the course of the eutrophication process decreases, but the role of external pollutant loads fed to the reservoir increases. In sediment segments, the impact of both temperature and pollutant loads on the course of the eutrophication process is insignificant.

Conclusions

1. Water protection against eutrophication is an indispensable process because the possible occurrence of intensive blooming may lead to the deterioration of water quality and cause difficulties in the treatment of such water.
2. Application of specially developed mathematical programs is one of the best methods used to forecast

water quality changes, e.g. the eutrophication process. They allow us to specify the time, place and range of water quality fluctuations (such as eutrophication)

3. Calculations confirmed the usefulness of the WASP-6 program for spatial and qualitative modelling of water in the Dobczyce reservoir. Defining qualitative changes occurring in this reservoir, the program allows us to send an early warning to the water

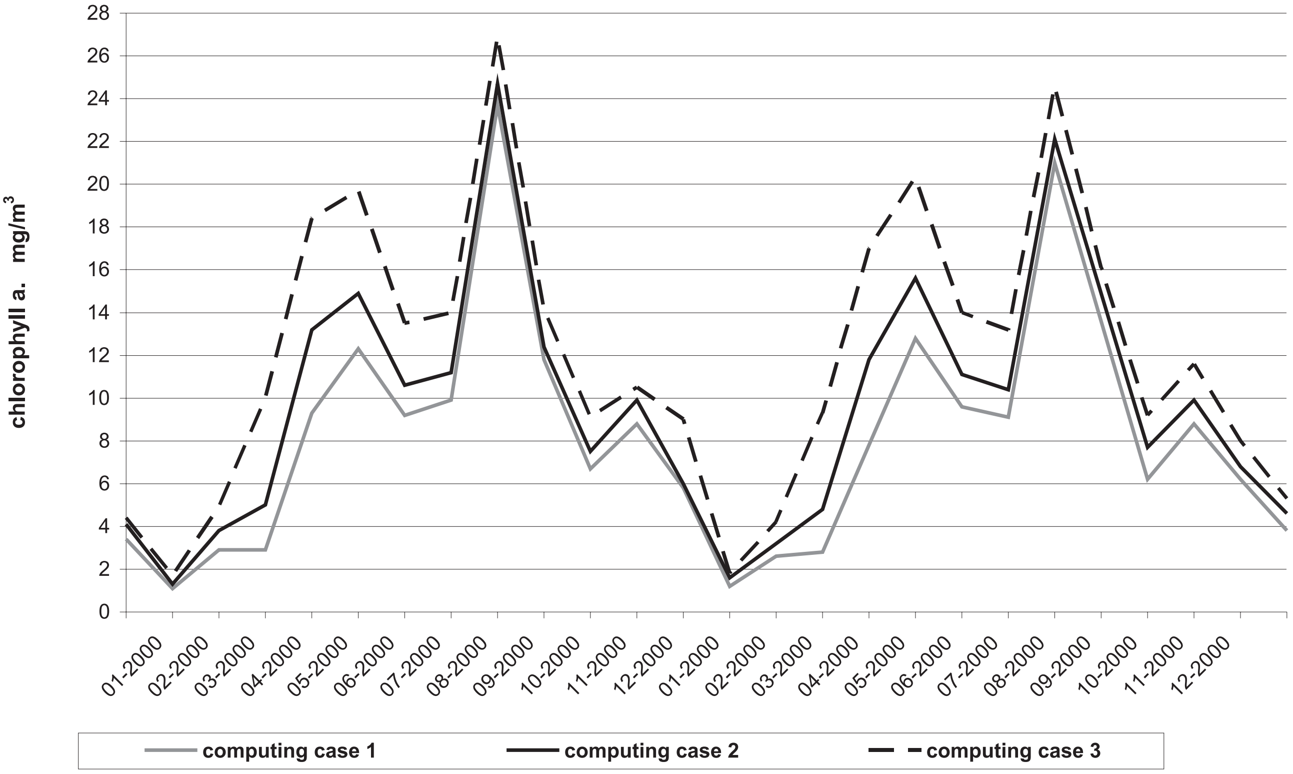

Fig. 2. Variation in concentration of chlorophyll a – surface segment no. 3.

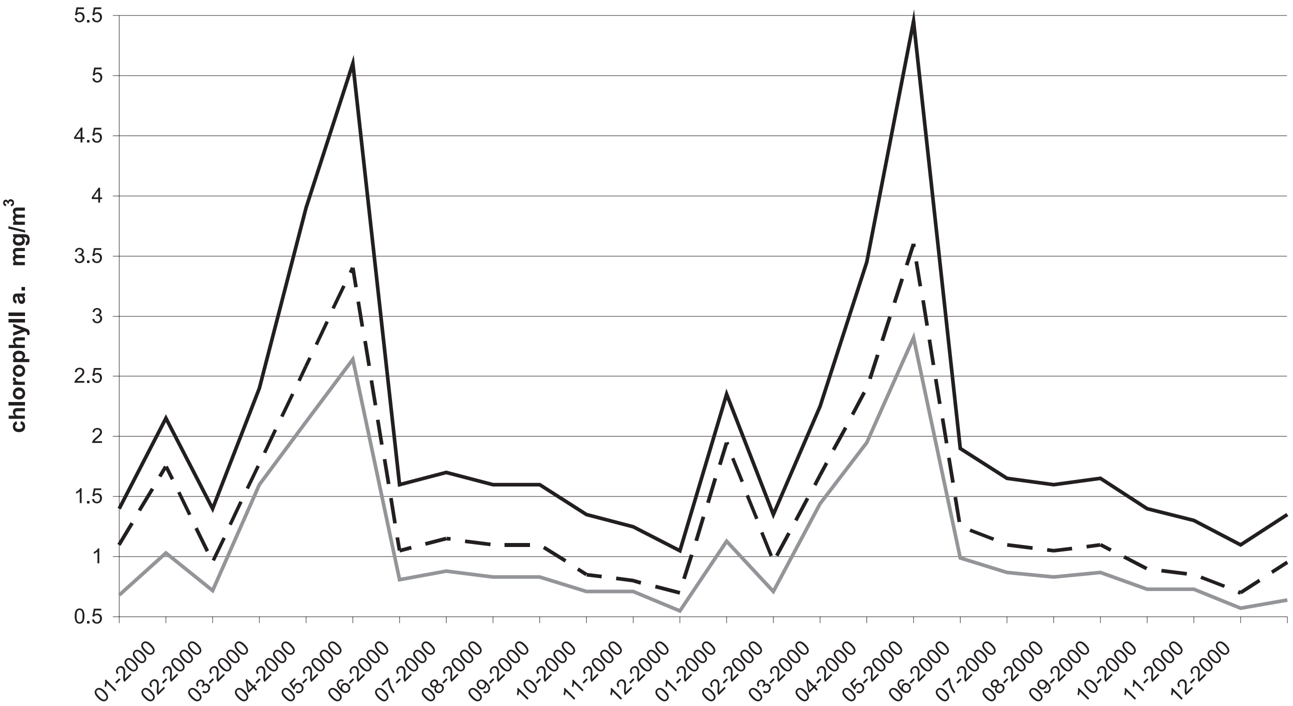

Fig. 3. Variation in concentration of chlorophyll a – subsurface segment no. 6.

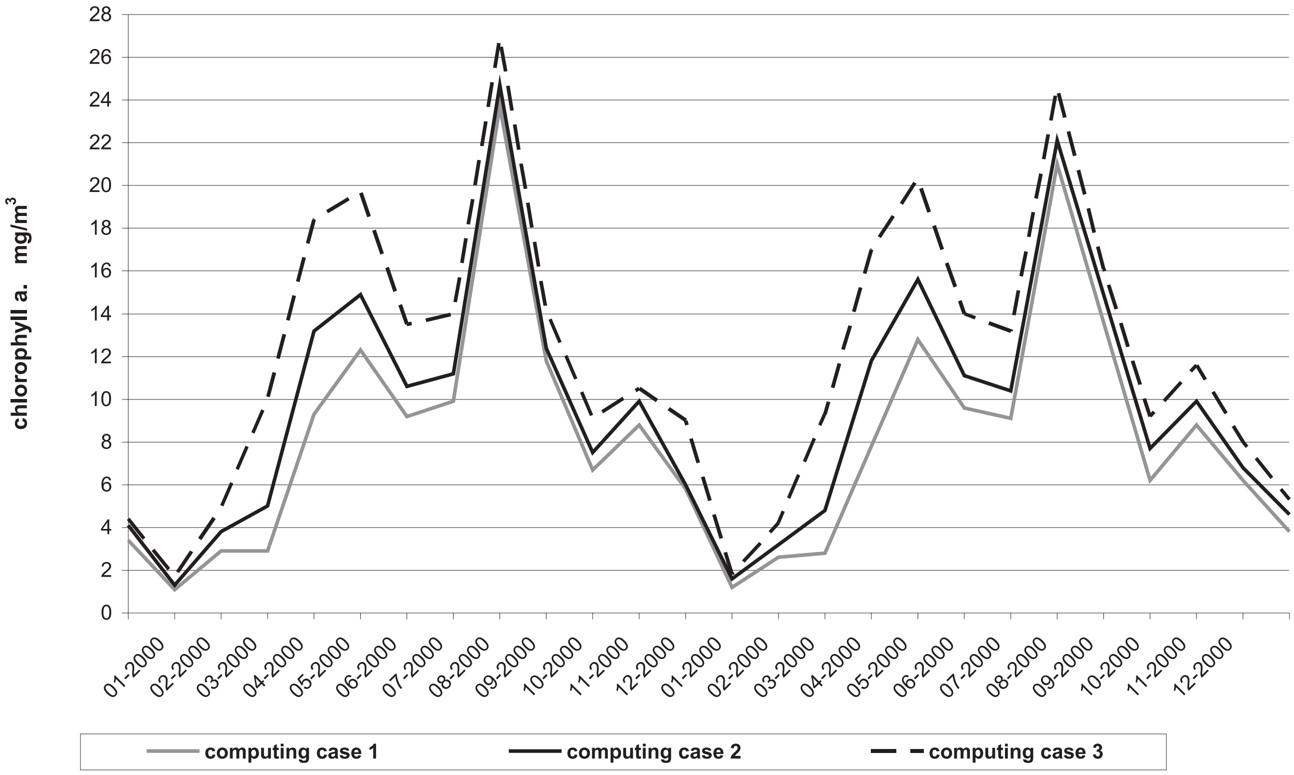

Fig. 4. Variation in concentration of chlorophyll a – top layers benthos segment no. 10.

treatment plant about potential operating problems related to the treatment of eutrophicated water.

4. The computation level can be adjusted to the user's needs. The reliability of the obtained results depends mainly upon the accurateness of the description of the reservoir ecosystem, the environmental parameters, the parameters of the processes occurring therein and the pollution sources.

References

1. BOCHNIA T. Water pollution with toxins produced by blue-green algae – case study for the city of Kraków (in Polish) Doctoral dissertation at the AGH, Kraków **2001**,
2. OLESZKIEWICZ J. Effects of nutrients on surface water quality and the need to change the folklore in design of nutrient removal plants. II International Conference "Municipal and rural water supply and water quality", Poznań, Poland **1996**, pp 3 – 20
3. CYWIŃSKI B., GDULA S., KĘPA E., KURBIEL J., PŁOSZAŃSKI H. Municipal waste water treatment (in Polish). Arkady, Warszawa **1983**
4. SZYPER H., GOŁDYN R. Protection and restoration of water bodies (in Polish). IV International Conference "Municipal and Rural Water Supply and Water Quality, Kraków **2000**, pp 253 – 264
5. GŁADKI W., STYKA W., STYPKA A. Oxygen/mixers system restores the quality of water body. Water pollution VII "Modelling, measuring and prediction", WIT Press **2003**
6. BALCERZAK W. Application of selected mathematical models to estimating changes of water quality (in Polish), IV International Conference "Water Supply and Water Quality", Kraków, Poland **2000**, pp 157 – 165
7. ELEKTOROWICZ M., GALANG C. Availability of surface water quality modelling software. V International Scientific and Technical Conference "Water Supply and Water Quality", Poznań – Gdańsk, Poland **2002**, pp 69 – 83
8. MALMAEUS J.M., HAKANSON L. Development of a lake eutrophication model. Ecological Modelling, **171**, 35, **2004.**
9. CIOFFI F., GALLERANO F. Management strategies for the control of eutrophication processes in Fogliano lagoon (Italy): a long-term analysis using a mathematical model. Applied Mathematical Modelling **25**, 385, **2001.**
10. KOELMANS A.A., VAN DER HEIJDE A., KNIJFF L.M., AALDERINK R.H. Integrated modelling of eutrophication and organic contaminant fate & effects in aquatic ecosystems. A review. Wat. Res. **35** (15), 3517, **2001.**
11. WEI B., SUGIURA N., MAEKAWA T. Use of artificial neural network in the prediction of algal blooms. Wat. Res. **35** (8), 2022, **2001.**
12. WOOL T. A., AMBROSE R.B., MARTIN J.L., COMER E.A. Water Quality Analysis Simulation Program (WASP) – version 6.0, Draft: User's Manual, US Environmental Protection Agency, Atlanta G.A, **2001**
13. KUBIAK W., SOWIŃSKI M. Application of computer program WASP5 to water quality modelling in the middle part of the Warta river (in Polish). III International Conference "Municipal and rural water supply and water quality", Poznań **1998**, pp 269 – 280

14. MAZURKIEWICZ – BOROŃ G. Factors influencing the eutrophication processes in dam reservoirs located in a hilly country (in Polish) “Suplementa ad acta Hydrobiologica” Vol. 2., **2002**,

15. BALCERZAK W. Influence of the eutrophication process on water treatment technology (in Polish) “Monograph of the Environmental Engineering Committee of the Polish Academy of Science”, **32**, 113, **2005**