MODELLING OF BIOGENE REMOVAL IN THE PROCESS OF BIOLOGICAL WASTEWATER TREATMENT IN THE SEQUENTIAL-FLOW TECHNOLOGY

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A b s t r a c t

The paper describes the results of the computer simulations of the sequential-flow technology applied at the Rybnik-Orzepowice treatment plant. The simulation was carried out within the framework of the project No ZR72008C/07051, entitled "The increase in biogene reduction through the optimisation of the biological wastewater treatment process in Rybnik – Orzepowice wastewater treatment plant". The characteristics of the biological wastewater treatment in the sequential-flow technology (BIODENITRO, BIODENIPHO) were presented. A computer model for the existing wastewater treatment plant in Rybnik-Orzepowice was elaborated using BioWin program and then subjected to a dynamic simulation. While conducting the simulation tests, changes of nitrogen and phosphorus concentration in biological chambers and treated wastewater were observed. The simulation was conducted during the operation of the biological chambers in the four-phase cycle in conditions of dissolved oxygen concentrations, during nitrification amounting to 1 mg/l and 2 mg/l. A comparative simulation of the sequential-flow system working in the four- and six-phase cycle was also carried out. The obtained results of the dynamic simulation were used to steer the technological process in real conditions.

S t r e s z c z e n i e

W artykule opisano wyniki symulacji komputerowych technologii sekwencyjno-przepływowej zastosowanej w oczyszczalni Rybnik-Orzepowice. Symulację wykonano w ramach projektu celowego nr 6 ZR72008C/07051 „Zwiększenie redukcji biogenów przez optymalizację procesu biologicznego oczyszczania ścieków w oczyszczalni ścieków Rybnik-Orzepowice". Przedstawiono charakterystykę biologicznego oczyszczania ścieków w technologii sekwencyjno-przepływowej (BIODENITRO, BIODENIPHO). Dla istniejącej oczyszczalni ścieków w Rybniku-Orzepowicach opracowano model komputerowy w programie BioWin, który następnie został poddany symulacji dynamicznej. W czasie badań symulacyjnych obserwowano zmiany stężenia azotu i fosforu w komorach biologicznych oraz w ściekach oczyszczonych. Symulacja była prowadzona podczas pracy komór biologicznych w czterofazowym cyklu, przy stężeniu tlenu rozpuszczonego, w czasie nitryfikacji, wynoszącym 1 oraz 2 mg/l. Wykonano również symulację porównawczą układu sekwencyjno-przepływowego, pracującego w cyklu cztero- i sześciofazowym. Uzyskane wyniki symulacji dynamicznej zostały wykorzystane w sterowaniu procesem technologicznym w warunkach rzeczywistych.

K e y w o r d s: **Sequential flow technology; Modelling; Dissolved oxygen concentration.**

1. INTRODUCTION

In relation to the legally binding regulations the removal of biogenes, particularly the nitrogen removal, requires the assurance of appropriate and repeated conditions of carrying out the technological process at changeable conditions of the wastewater loads flow (Imhoff K., Imhoff K.R. 1996).

In the modelling of nitrogen removal in a wastewater treatment plant working in the sequential-flow technology, the technological parameters of the system as well as decomposition of sewage charge which is dispatched to the biological chambers have to be taken into consideration. The preparation of a computer model for the simulation of changes in the system allows to define the possibility of intensifying the biological processes of nitrogen removal during nitrification and denitrification. The intensification of nitrogen removal allows to determine critical parameters that have an influence upon the proper operation of biological processes in chambers of activated sludge (Zdebik and others; 2009).

The identification of nitrogen change conditions that proceed in the sequential-flow technology due to the unique application of such solutions in wastewater treatment plants which serve huge urban agglomerations, and the determination of their dependence in winter and summer seasons, is useful in formulating a model for steering the operation of wastewater treatment plant (Heidrich, Witkowski, 2005).

On the basis of the developed computer model, an operating wastewater treatment plant simulation was carried out introducing its changeable conditions caused by a hydraulic load or a pollution load. Such simulations enable the evaluation of wastewater treatment effectiveness in real conditions taking into account the influence of the temperature change or the dispense of reacting substance. Carrying out the simulation at changeable conditions of wastewater treatment plant loading and variants of performing the technology of biological biogene removal constitute an important preceding stage of the modification of the real technological system (Zdebik and others, 2008).

The computer model was developed in the BioWin programme that was purchased due to the grant of the Regional Fund to the Environmental Preservation and Water Management in Katowice (Zdebik and others, 2009).

2. THE SEQUENTIAL-FLOW TECHNOLOGY

The sequential-flow technology BIODENITRO, BIODENIPHO was drawn up in a Danish company Krüger. This technology consists in a converting operation of a couple of chambers in which the nitrogen removal takes place. In the BIODENITRO technology, in the four-phase cycle, the inflow of wastewater in the 1^{st} phase is in the chamber A (denitrification). At the same time in chamber B the nitrification process takes place. After the given time expires, the 2^{nd} phase, during which the wastewater flow through from chamber A (denitrification) to chamber B (nitrification), begins in the steering system. This process is conditional upon the time of the set point. The 3^{rd} phase is the opposite of the 1st phase, which means that the inflow of wastewater is to chamber B (denitrification), while in chamber A the nitrification process takes place. The wastewater flow from chamber B to chamber A occurs in the 4^{th} phase. In the six-phase cycle, in chambers A and B additional dual nitrification takes place that is aimed at the reduction of ammonia nitrogen in wastewater (Henze and others 2000a; Klimiuk, Łebkowska 2004; Zdebik and others 2008).

The BIODENIPHO technology is in fact the BIODENITRO technology which is supplemented with an oxygen-free chamber, where the processes of dephosphatation take place, and is located in front of the activated sludge chambers. The sludge, from the secondary settling tanks through the pumping station of the recycled sludge, is conveyed to the oxygen-free chamber and to the reactors.

3. THE CHARACTERISTICS OF BIODENIPHO TECHNOLOGY USED AT THE RYBNIK-ORZEPOWICE WASTEWATER TREATMENT PLANT

The wastewater treatment plant is located in the north-western part of Rybnik, in the Orzepowice district. It is the main wastewater treatment plant in Rybnik agglomeration. From the northern side, its area is limited by the Ruda River, while from the western side by the Nacyna River. The Rybnik Artificial Lagoon on the Ruda River is located at a distance of about 9 hundred meters in the north-western direction from the wastewater treatment plant.

The direct "receiver" of the treated wastewater is the Nacyna River. The canal carrying out the wastewater ends with an opening located above the weir on the Nacyna. The Nacyna waters together with the cleaned wastewater are pumped over to the Ruda River in Studoły, below the Artificial Rybnik Lagoon. The Rybnik-Orzepowice wastewater treatment plant was designed to accept loads of wastewater that amount to: the maximum of 150 000 P.E., the average of 127 500 P.E.

In 2009, the Personal Equivalent that was maintained by the wastewater treatment plant amounted to about 70 000 P.E. (medium-year value). The number of 100 000 P.E. may be exceeded after the wastewater system is built, on the basis of the project partly funded thanks to ISPA/Unity Fund.

In the wastewater treatment plant in Rybnik, at the stage of biological wastewater treatment the sequential-flow process of the activated sludge BIODENIPHO was applied, with the initial oxygen-free chamber and the phase sequence in the reactors. The chamber is adapted to the biological removal of nitrogen and phosphorus. The biological part of the

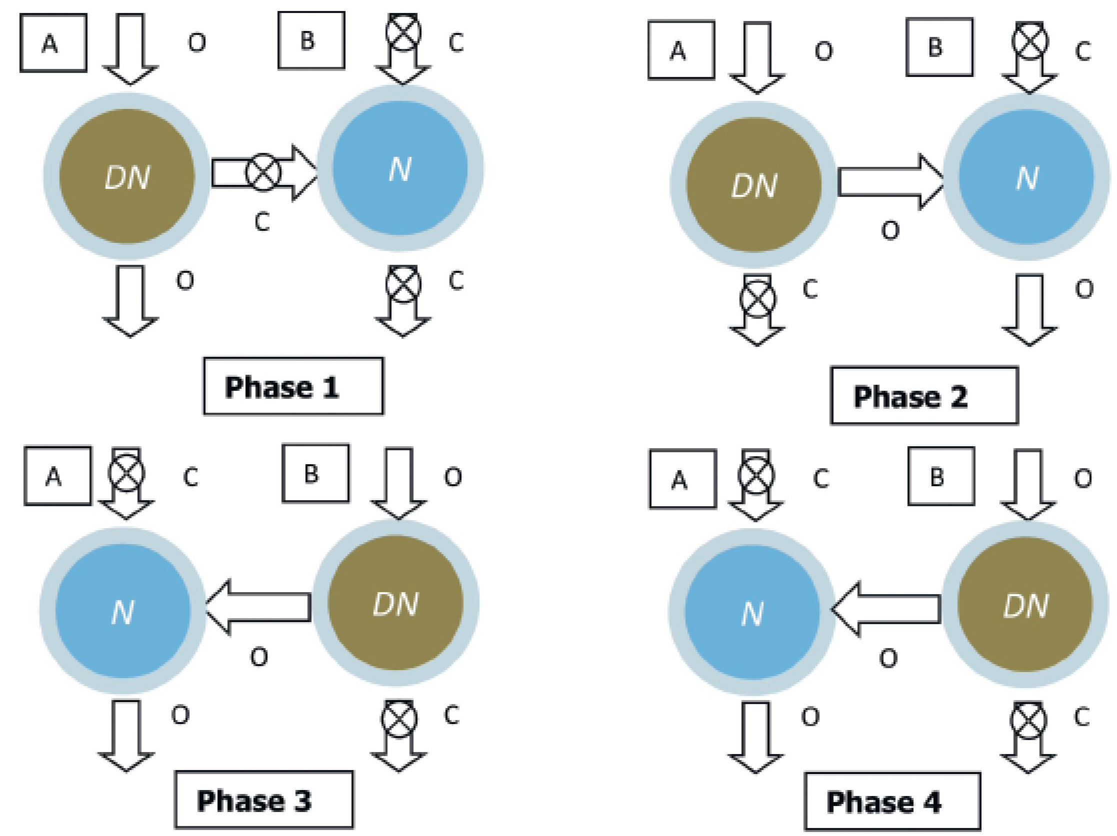

Figure 1.
The BIODENITRO® technology operation scheme in the four-phase system: A, B – activated sludge chambers, o – an open valve, c – a closed valve, N – nitrification, DN – denitrification

wastewater treatment plant may operate in the four-phase and six-phase cycle.

Duration of the four-phase cycle amounts to, in case of:
- phase 1 and 3 – 30 min (max. 90 min),
- phase 2 and 4 – 60 min (max. 120 min).

Duration of the six-phase cycle amounts to, in case of:
- phase 1 and 4 – 30 min (max. 90 min),
- phase 2 and 5 – 120 min (max. 120 min),
- phase 3 and 6 – 30 min (max. 120 min).

These durations have been noted for the real operating conditions, however they may be extended up to the maximum time allowed by the technological system.

The BIODENITRO technology operation scheme in the four- and six-phase cycle, omitting the oxygen-free chamber which is a part of the BIODENITRO technology, is presented in pictures 1 and 2.

4. COMPUTER MODELLING

In accordance with the latest global trends, mathematical modelling becomes an inseparable element of the design and functioning of wastewater treatment systems, especially those which use activated sludge (Henze and others, 1987). The use of computer models allows for short time and not expensive analysis of many technological solutions. It also allows for the simulation of events in conditions typical of the real system (Henze and others, 2000a, 2002).

The biochemical mathematical model ASM (Activated Sludge Model) describes changes in organic compounds and nitrogen compounds (Batstone and others, 2002). In its original version it was presented in the report describing the activity of the working group IAWPRC (International Association on Water Pollution Research and Control), developing the practical application of the models in the design and functioning of the biological

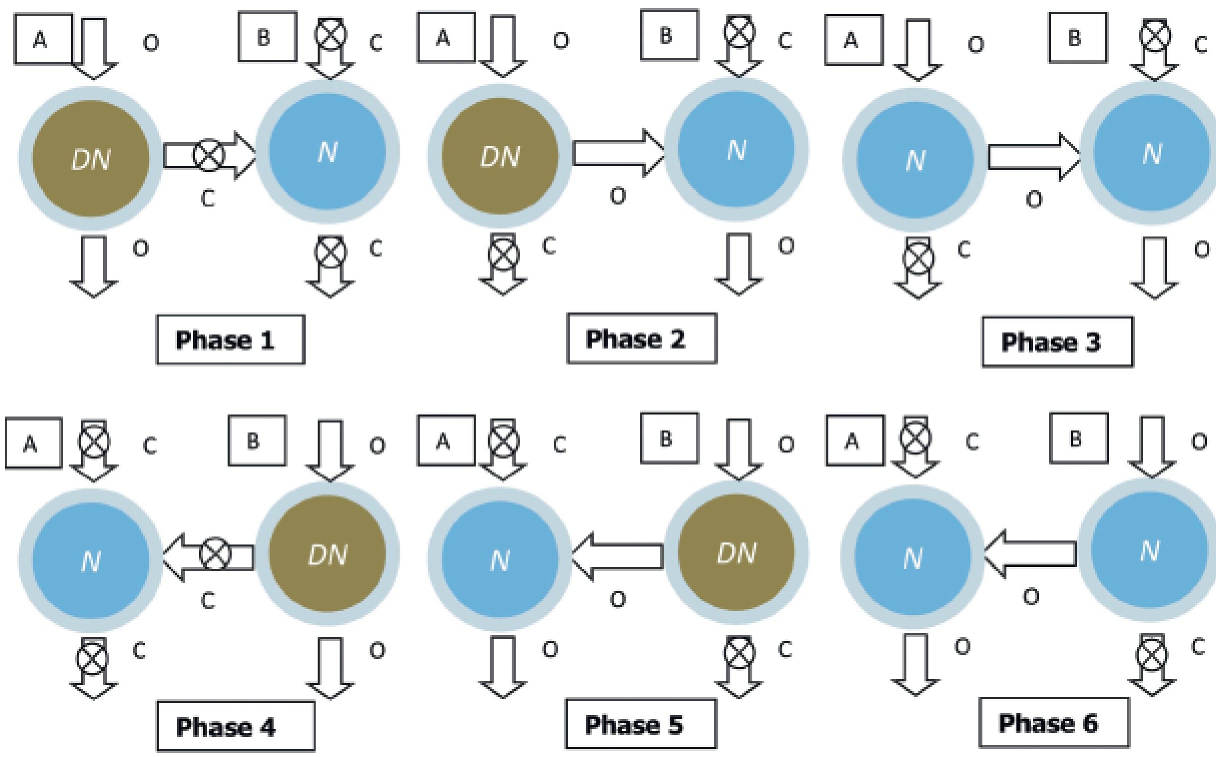

Figure 2.
The BIODENITRO® technology operation scheme in the six-phase system; denotation as in Fig. 1

wastewater treatment systems (Henze and others, 1987). The basis of a model consists of the previously developed ideas (Henze and others, 1987). In its original version it consisted of eight equations presenting the kinetics of the changes with the use of 13 state variables, with the application of the nomenclature recommended by IAWPRC. The matrix equation was used to describe a mathematical record, in order to enable a clear connection between the kinematics of the processes and the velocity of the concentration of the model fractions. This model is based upon the equations of balance mass and upon the stochiometricand kinetics relations. The kinematic equation is based upon Monod's kinetics (1949).

In the following years the model underwent some modifications and development (Henze 1992). It differs mostly in assimilated denitrification and more sophisticated form of the kinematics equations from its original version (Henze and others, 2002; Gernaey and others, 2004). A non-reactive fraction XMIN was also added to the model, especially due to its capability to connecting it with models of different processes more accurately (Henze and others, 2000b).

5. COMPUTER MODEL OF WASTEWATER TREATMENT PLANT IN RYBNIK

The basis of the majority of the results presented here constitute typical indexes. However, in case of more sophisticated problems, it is necessary to refer to variables that can be modified in the model. Proper preparation of the input data consists in the application of the operating parameters of the existing technological system and conditions present in the operating time of the wastewater treatment plant. In the BioWin programme, the user may define and analyse the operation of the most sophisticated scheme of the wastewater treatment plant with one or many wastewater intakes.

The basis of the BioWin programme constitutes a model of the biological process. BioWin is a unique programme thanks to the connection of the biological processes taking place in the activated sludge and to the oxygen-free biological processes. Furthermore, this programme integrates the changes of parameters (e.g. pH, conditions of oxygen uptake etc.) and the processes of chemical phosphorus precipitation (BioWin 2.1.).

The BioWin programme consists of two modules:

- condition fixed for the systems analysis, whose basis constitute the constant flow values and/or weighted average of the flow in time; this module is a very useful tool to balance the mass in complicated wastewater treatment plants,
- dynamic, with the help of which the process of filtration during the simulation can be observed and changed; this module is a good tool to analyse the response of the filtration system at the moment of any changes in time data or the way of wastewater treatment plant operation.

In the programme the variables may be given in the following elements:

- kinematic parameters of temperature in individual units,
- simulation of biological reactions in secondary settling tank,
- decomposition of different operation parameters, such as: temperature, concentration of soluble oxygen, the oxygen flow, distribution of the flow (BioWin 2.1.).

In picture 3 the technological scheme of the wastewater treatment plant is presented. This technological scheme was used while creating the model in the BioWin programme. The model, which was applied while conducting the dynamic computer simulations is presented in the picture 4.

The data typical of a wastewater treatment plant, is a distribution of wastewater inflow together with its concentration in a period of at least one week – for the existing object (Sadecka 2010). These values can be obtained from the current monitoring of wastewater inflow to the wastewater treatment plant by hour tests during the week. Such a domain of data has to be analysed with special attention given to the correctness of the received measurement results as well as to the elimination of the measurement errors made by the devices installed in wastewater treatment plants (it mainly concerns the measurement of wastewater flow) before introducing it to the model.

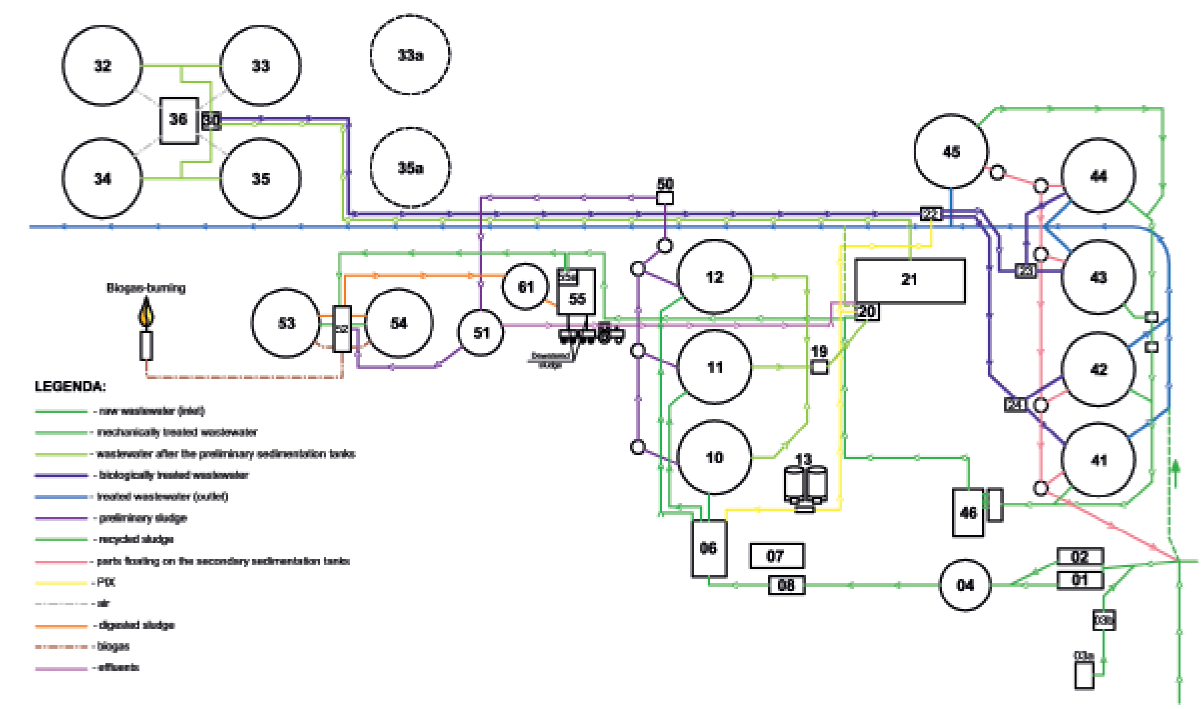

Figure 3.
Technological scheme of the wastewater treatment plant in Rybnik-Orzepowice: 01, 02 – mechanical bar screens, 03a, 03b – tank station of delivered wastewaters, 04 – main pumping station, 06 – sand trap, 07 – sand separator, 08 – measuring trough, 10, 11, 12 – preliminary sedimentation tank, 13 – PIX proportioning station, 19, 20 – separation chamber, 21 – anoxic chamber, 22, 23, 24 – aeration chambers (distributors), 30 – pumping station of sludges and effluents, 32, 33, 34, 35 – activated sludge chambers, 33a, 35a – excluded from use activated sludge chambers, 36 – blower station, 41, 42, 43, 44, 45 – secondary sedimentation tank, 46 – recirculate pumping station, 50 – initial sludge pumping station, 51 – gravitational thickener, 52 – operational building, boiler-house, 53, 54 – separated fermentation chambers, 55a – mechanical thickener, 55 – sludge dewatering station, 61 – sludge storage tank

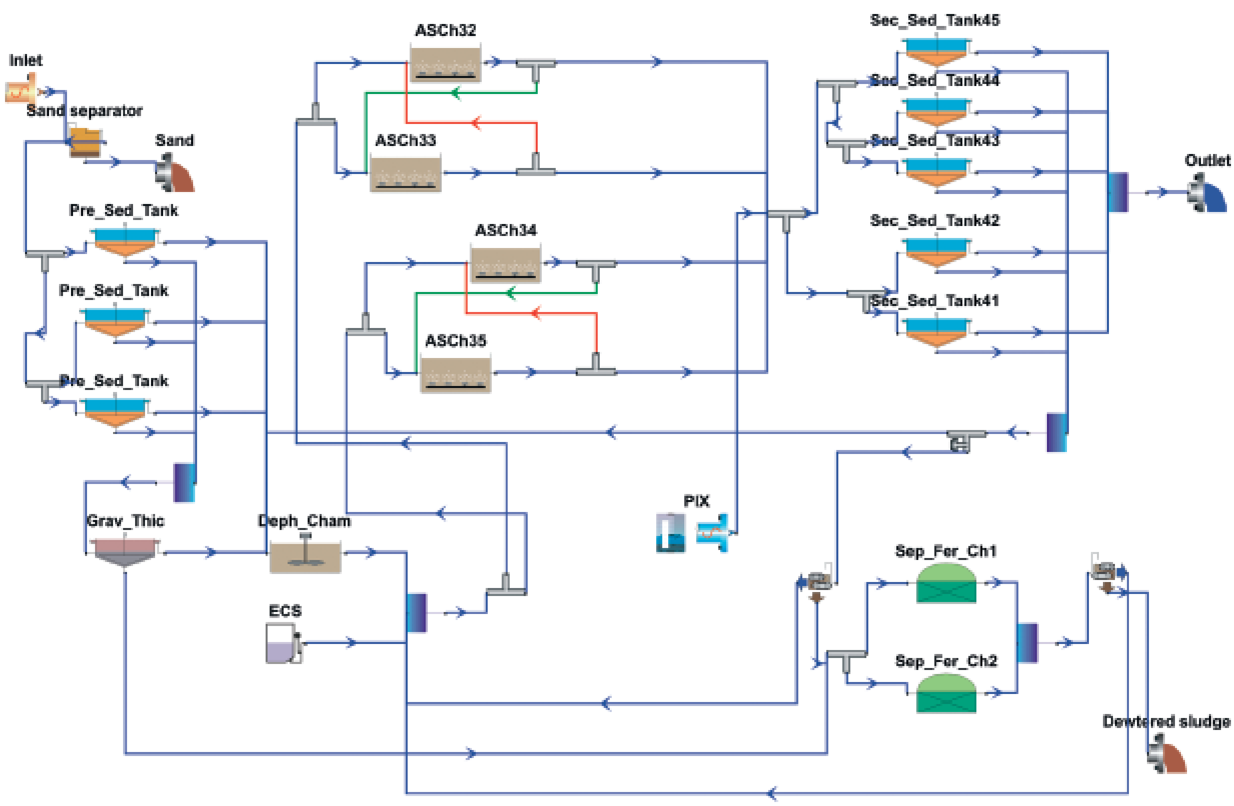

Figure 4.
Computer simulation model of the wastewater treatment plant in Rybnik: Pre_Sed_Tank – preliminary sedimentation tank, Grav_Thic – gravitational thickener, Deph_Cham – dephosphatation chamber, ASCh (32-35) – activated sludge chambers, Sec_Sed_Tank (41 – 45) – secondary sedimentation tank, Sep_Fer_Ch (1-2) – separated fermentation chambers, ECS – external source of organic carbon, PIX – coagulant

6. RESULTS OF THE DYNAMIC SIMULATION WITH THE USE OF COMPUTER MODEL

In the modelling the following were used:

- steering of the concentration of dissolved oxygen in the activated sludge chambers,
- change of the working cycle of a biological part in the four-phase or six-phase systems which were changed during the dynamic simulation.

Conducting simulations for both different dissolved oxygen concentrations and phases of the cycle aims at checking the efficiency of removing nitrate nitrogen during the nitrification phase (Zdebik and others, 2009).

Steering of the concentration of the dissolved oxygen

Steering of the concentration of the dissolved oxygen in the activated sludge chambers when conducting the computer simulation, the following concentrations of dissolved oxygen in activated sludge chambers were assumed:

Model I: concentration of oxygen of 1 mg/l (values that currently are maintained by the user).

Model II: concentration of oxygen of 2 mg/l (extreme value).

Oxygen content during the nitrification process (green line) is proper provided that at the beginning of delivery it has a clear top point (Fig. 5). While in case of the line going up at the beginning of oxygen delivery, it can be found that there is not enough oxygen in the chamber to conduct the process. A violent decrease of oxygen in the final part of nitrification indicates that it is smaller than required. If in the final part of nitrification the line presenting oxygen content stabilizes or rises, nitrification can be finished and we can start denitrification. In that way the amount of oxygen delivered to the process can be reduced.

Concentration changes of ammonia nitrogen ($N\text{-}NH_4$) and nitrate nitrogen ($N\text{-}NO_3$) in chambers

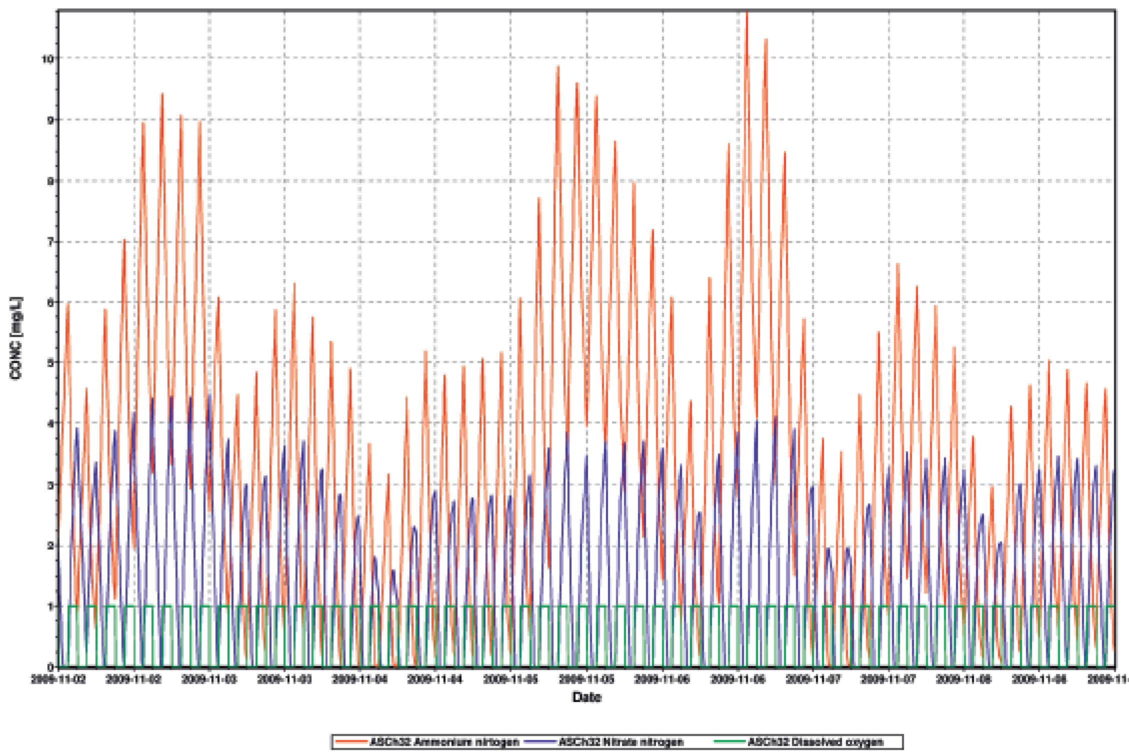

Figure 5.
Concentration changes of nitrates, ammonia and oxygen content in chamber A, in conditions of dissolved oxygen concentration of 1 mg/l

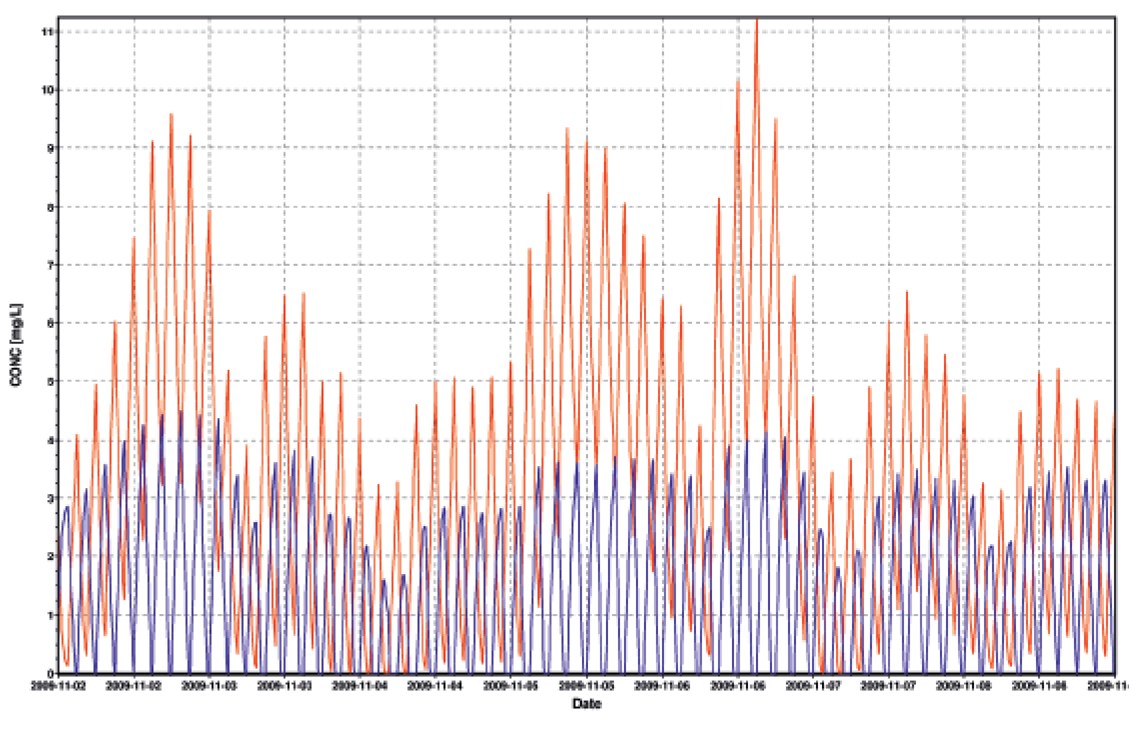

Figure 6.
Concentration changes of nitrates and ammonia in chamber B, in conditions of dissolved oxygen concentration of 1 mg/l

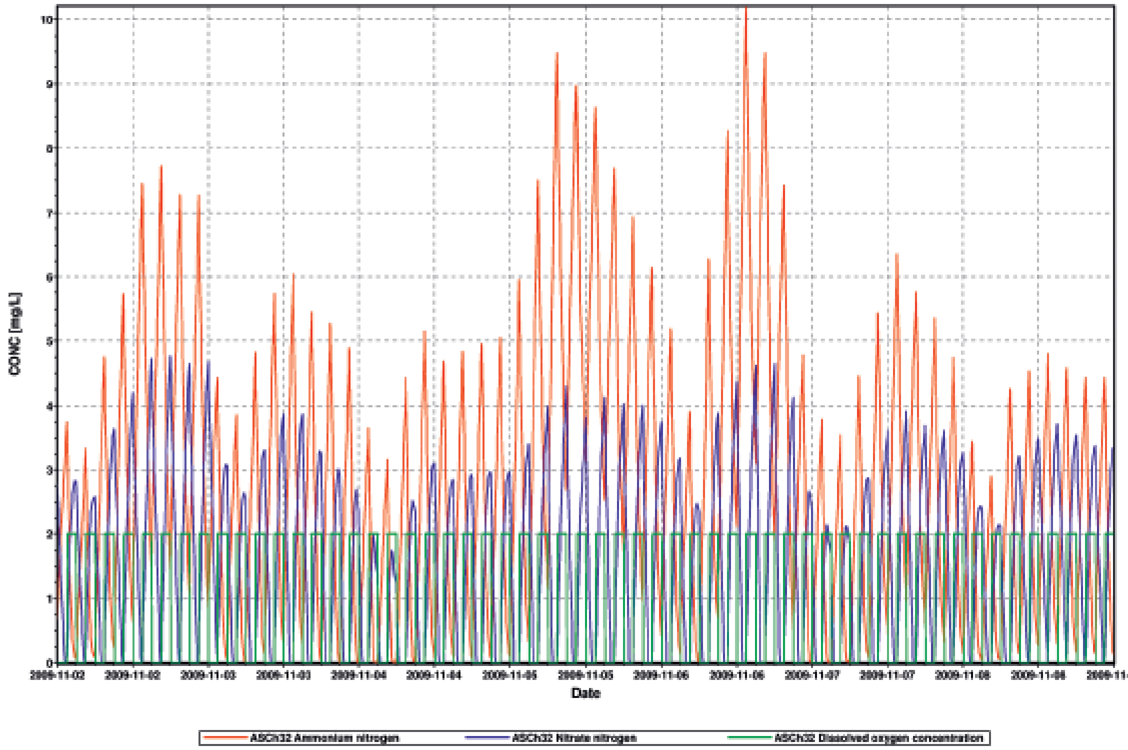

Figure 7.
Concentration changes of nitrates, ammonia, and oxygen content in chamber A, in conditions of dissolved oxygen concentration of 2 mg/l

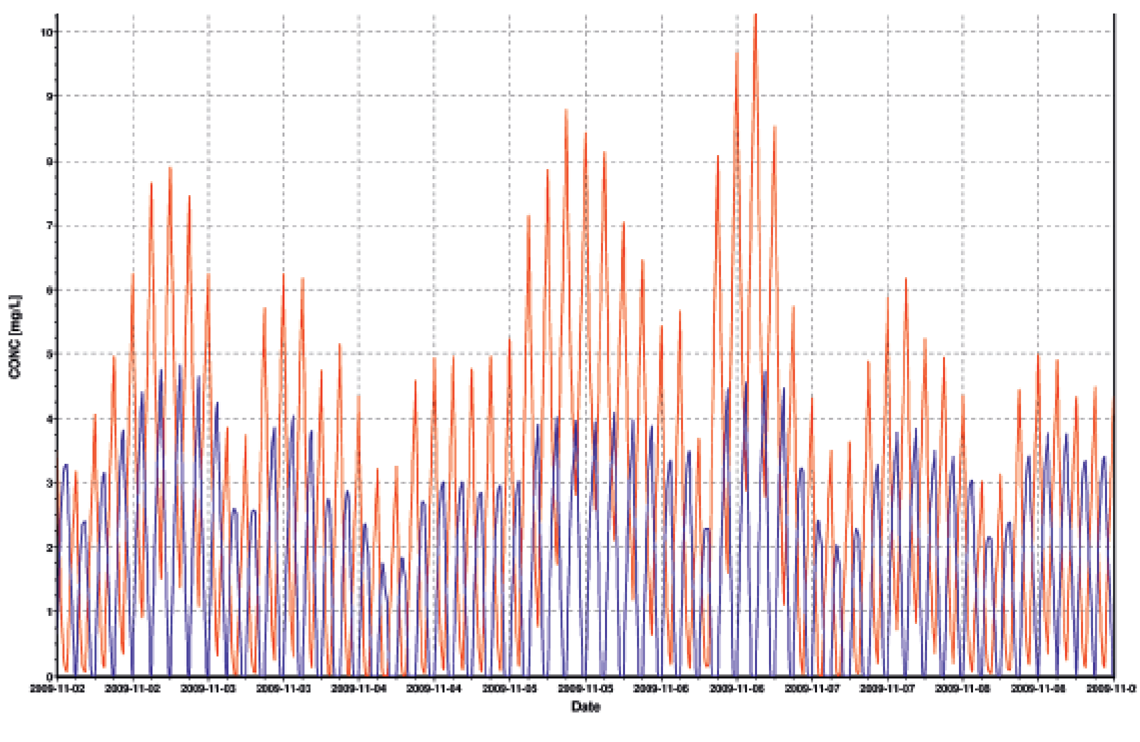

Figure 8.
Concentration changes of nitrates and ammonia in chamber B, in conditions of dissolved oxygen concentration of 2 mg/l

A and B, in conditions of nitrification and denitrification according to the concentration of dissolved oxygen of 1 and 2 mg/l, are presented in pictures 5 and 6 as well as 7 and 8.

On the basis of the results of dynamic modelling it was found that the content of 2 mg/l of dissolved oxygen in the chambers is correct at the time of the most intensive inflow of wastewater loads. At the time when the inflow decreases, the concentration of oxygen can be reduced to 0.5-1.5 mg/l.

Concentration of dissolved oxygen amounting to 1 mg/l is an insufficient value to maintain the nitrification process correctly at the increased inflow of wastewater load to the biological chambers. On the other hand, it is sufficient for oxidation of ammonia at the non-peak-time hours, i.e. with the decreased inflow of wastewater load.

Change of the biological chambers working cycle in a four- or six-phase system

The modelling was performed at the dissolved oxygen concentration of 2 mg/l for the following cycles:
Model A: four-phase cycle,
Model B: six-phase cycle.

Duration time for Model A (four-phase cycle) is as follows:
- phase 1 and 3 – 30 min (max. 90 min),
- phase 2 and 4 – 60 min (max. 120 min),

witch has been shown in Table 1.

Table 1.
Duration time of particular phases of nitrification/denitrification in a four phase cycle

Phase	Denitrification	Nitrification
1	30 min	–
2	60 min	–
3	–	30 min
4	–	60 min
TOTAL	90 min	90 min

Duration time of the cycle in Model A was 180 min, while the denitrification-nitrification ratio was 50/50% of the duration time of the technological cycle.

In case of Model B (six-phase cycle) duration time amounted to:
- phase 1 and 4 – 30 min (max. 90 min),
- phase 2 and 5 – 120 min (max. 120 min),
- phase 3 and 6 – 30 min (max. 120 min),

which has been shown in Table 2.

Table 2.
Duration time of particular phases of nitrification/denitrification in a six phase cycle

Phase	Denitrification	Nitrification
1	30 min	–
2	120 min	–
3	–	30 min
4	–	30 min
5	–	120 min
6	–	30 min
TOTAL	150 min	210 min

Duration time of the cycle in Model A was 360 min, while the denitrification-nitrification ratio was 42/58% of the duration time of technological cycle.

Figures 9-12 show the results of the models of steering the content of dissolved oxygen in the activated sludge chambers discussed above in relation to ammonium nitrate and nitrogen nitrate being removed.

The results of the simulation acquired due to the use of a computer model were close to the values of treated wastewater parameters, that were obtained in operating conditions at the wastewater treatment plant in Rybnik-Orzepowice.

The functioning of the chambers in the four-phase cycle speeded up the process of nitrification and denitrification. The concentration of the general nitrogen in treated wastewater is lower than the concentration in a six-phase process. The six-phase process was working effectively in case of increased inflow at the time of heavy rainfall.

In the four-phase cycle, the parameters of treated wastewater were lower than the parameters in the six-phase cycle, that resulted from the fact that the nitrification phase was used more effectively (oxygen was more available). In the six-phase cycle, a decrease of ammonia quantity in treated wastewater was observed, which was caused by lengthening of the nitrification zone in relation to the four-phase cycle.

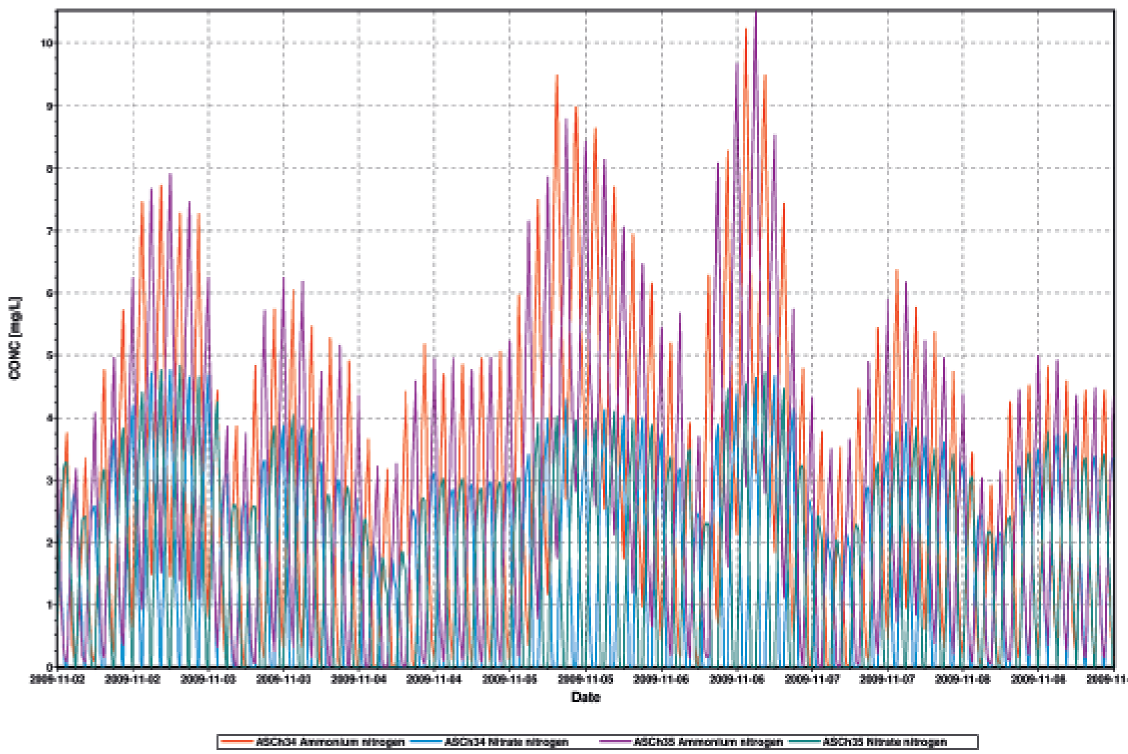

Figure 9.
Concentration changes of nitrates and ammonia in conditions of two cooperating activated sludge chambers (A and B) and dissolved oxygen concentration of 2 mg/l in the four-phase cycle

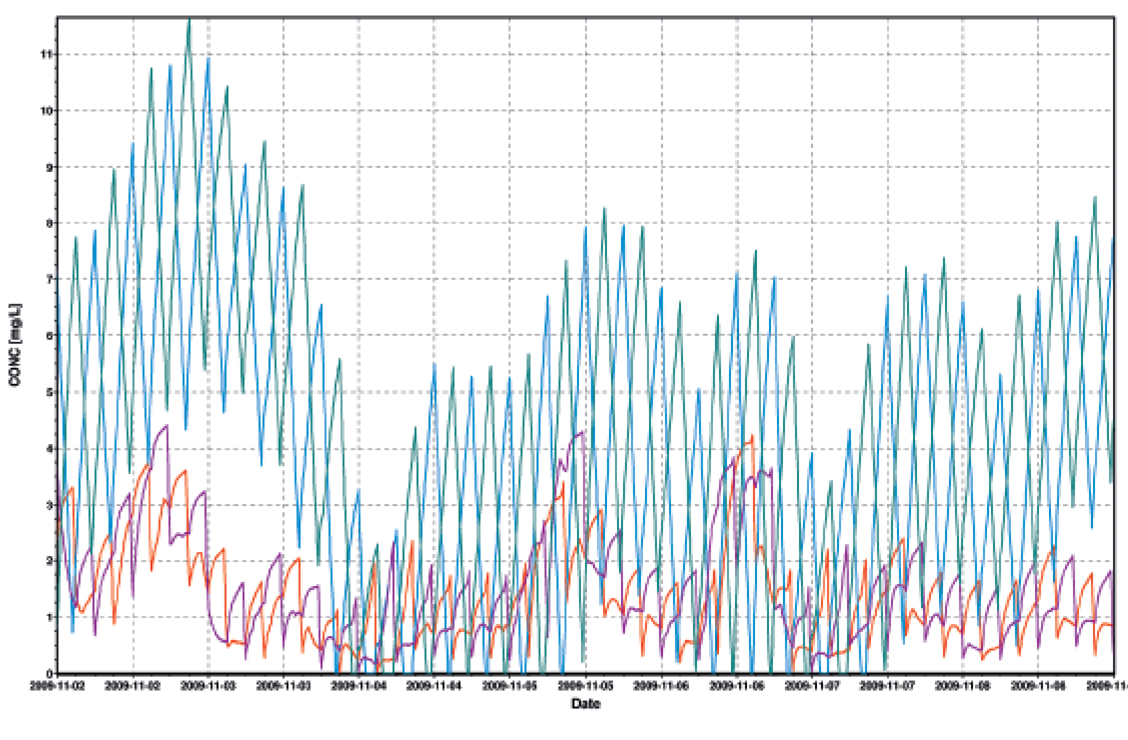

Figure 10.
Concentration changes of nitrates and ammonia in conditions of two cooperating activated sludge chambers (A and B) and dissolved oxygen concentration of 2 mg/l in the six-phase cycle

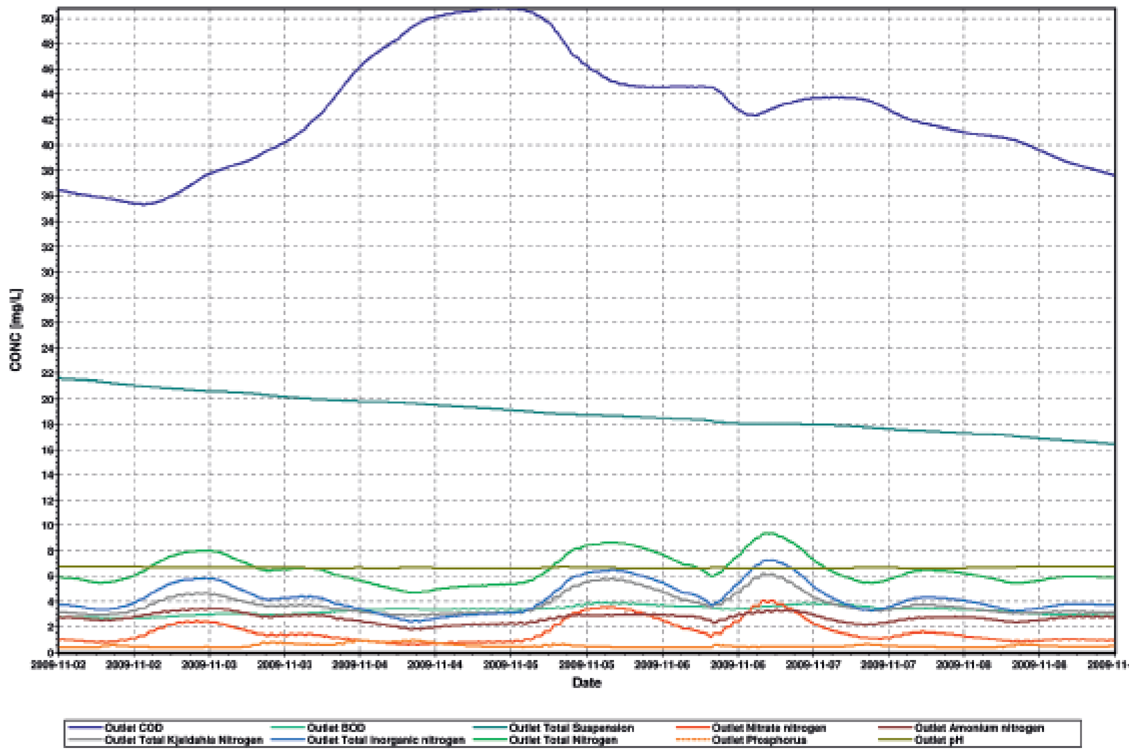

Figure 11.
Parameters of wastewater treated in a four-phase cycle

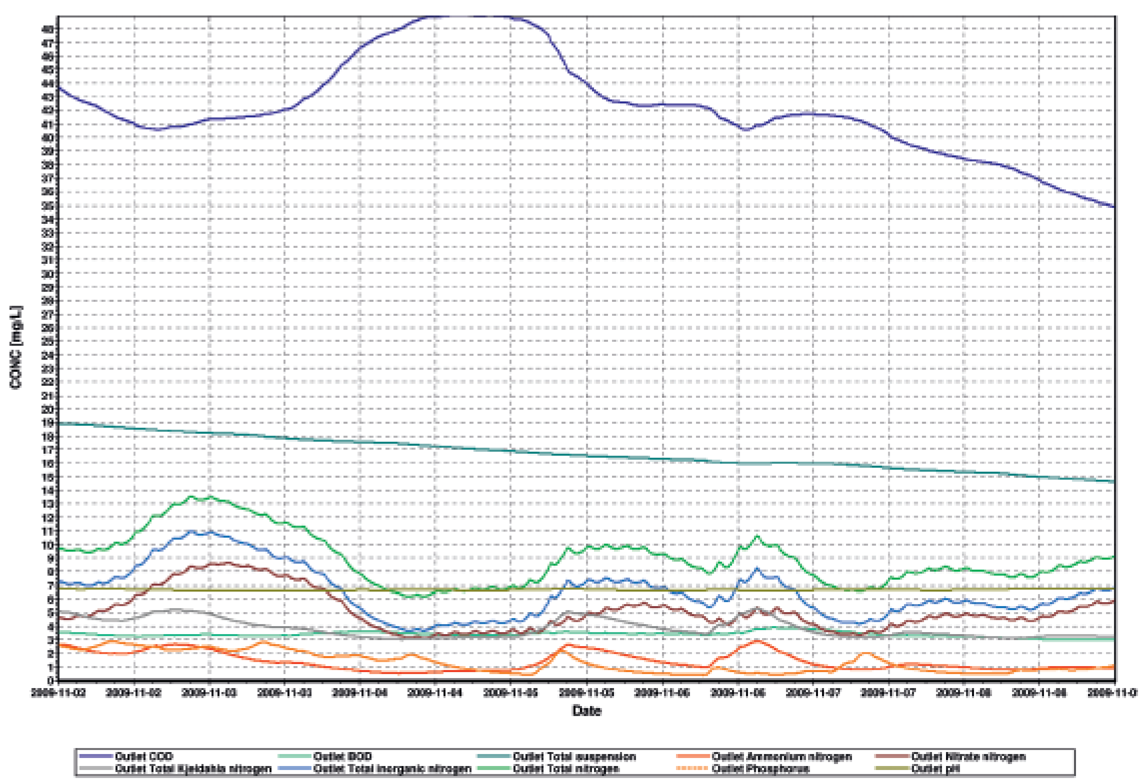

Figure 12.
Parameters of wastewater treated in a six-phase cycle

7. SUMMARY

The elaboration of a computer model requires carrying out a detailed technological system of the wastewater treatment plant and taking into consideration the characteristic variables for particular devices (working time, frequency trigger, cubic capacity, inflow distribution, distribution of wastewater/sludge acceptance etc.). The essential for the analysis of the technological system and then the elaboration of a computer model is the information acquired from a user of a wastewater treatment plant. The settings and the working time of particular technological objects differ from the values accepted in an instruction manual for functioning of a wastewater treatment plant many times.

It results from the changes introduced during conducting the process of wastewater treatment. To determine the local parameters that dominate in particular objects, i.e. in the activated sludge chambers, the dephosphatation chamber, the primary settling tanks, the initial and recycled sludge as well as the distribution of the flow of wastewater, require conducting additional laboratory and testing studies, in order to make the conditions of the computer model more similar to the technological system. When these parameters are described properly, they influence the results of the calibration.

A model prepared in such a way, with the local parameters introduced (typical of this installation), was an object for the calibration. The results of this process were parameters of treated wastewater, received through in the object studied in reference to the results obtained from the simulation.

On the basis of the modelling results, the following conclusions were reached. They apply to the operation standards and the ways of optimization of the technological parameters and the parameters of the process:

1. The amount of oxygen of 2 mg/l in the chambers is correct at the time of peak inflow of wastewater load, while at the time when the inflow of wastewater load decreases, the amount of oxygen can be reduced to 0.5-1.5 mg/l.
2. The concentration of dissolved oxygen, amounting to 1 mg/l, is an insufficient value for the process of nitrification to be correctly carried out with an increased inflow of a wastewater load to biological chambers. But this concentration is sufficient to oxygenate the ammonia at the non-peak-time hours, i.e. when the wastewater load is reduced.

Summing up, it can be found that the dynamic modelling of each of the wastewater treatment plants, requires the reproduction of an existing process-technology system describing conditions and relations existing in a specific wastewater treatment system. Such a model allows for the studies of the system response to different values of the process-technology parameters to which it is subjected.

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