Original Research

Nitrogen and Phosphorus Removal from Sewage in Biofilter – Activated Sludge Combined Systems

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Abstract

Our paper analyzes nitrogen and phosphorus removal from sewage in a biofilter. The analysis was based on the multi-variant simulations of the combined system: fixed-film – activated sludge performance. An activated sludge ASIM 2d model related with the model of pollutions' transformations in fixed film was used for the calculations. The results of exploitation analyses performed on the objective treatment plant – average daily rate of wastewater, pH, COD values, total suspended solids, total Kjeldahl nitrogen, nitrate nitrogen, total phosphorus, and alkalinity – were used as input parameters for the calculations. The results indicated that there is a possibility of including fixed-film in the activated sludge technology in order to improve nitrogen and phosphorus removal from the sewage. The nitrification process will be performed in fixed-film, whereas nitrogen and phosphorus removal from the sewage will be performed in anoxic chambers, which operate in the activated sludge technology. Denitrifying the dephosphatation process guarantees the high level of total phosphorus reduction (81%) and the 42% total nitrogen reduction, but only if the whole easily decomposable substrate will be consumed by microorganisms in the anoxic chamber and if enough nitrates will be present in the environment.

Keywords: household sewage, activated sludge, fixed-film, denitrifying dephosphatation, mathematical model

Introduction

According to the requirements of the current Minister of Environment Regulation from 18 November 2014, not all sewage treatment plants achieve the required level of pollution reduction [1]. The only way to adjust these objects to current standards is their complex modernisation. Treatment plant modernisation means liquidation of biofilters. Normally a designer does not see the possibility of including biofilters into a biological dephosphatation scheme coupled with nitrification and denitrification. The possibility of integrating biofilters and activated sludge to intensify biogenic compound removal from the sewage occurred when bacteria capable of denitrifying dephosphatation were identified [2, 3]. Bacteria that accumulate phosphates may be divided into two groups: bacteria that accumulate phosphates from sewage with oxygen as an electron acceptor and with nitrites as electron

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acceptors [4-9]. The first one belongs to a classic anaerobic-aerobic system whereas in the second case phosphorus is removed in anaerobic-anoxic zones. Denitrifying dephosphatation allows for elimination of oxygen chamber. In such a system competition between microorganisms is directed toward the predomination of bacteria capable of dephosphatation in anoxic conditions. By avoiding unnecessary aerobic usage of organic compounds, the denitrifying potential of the system increases and enables effective sewage dephosphatation with low BOD_5/P ratio. Closing dephosphatation in an anaerobic-anoxic cycle allows for separation of nitrification and a dephosphatation system, and conducting it on isolated biofilters or on a separate part of activated sludge [10-12]. Dephosphatation can be also effective when nitrites act as electron acceptors. However, they cannot occur in too high concentrations due to their inhibiting influence on the process of excessive phosphates intake by microorganisms, which continues even after the cessation of NO_2-N dosage into the sludge. According to Huang et al. [13], a critical concentration of nitrite nitrogen in an anoxic chamber should not exceed 5,0-8,0 $mgN-NO_2 \cdot dm^3$. Separation of nitrification beyond the traditional system leads to increasing the percentage of nitrifiers in biomass, thus increasing in productivity of this process [14, 15]. The introduction of nitrification on biofilters into activated sludge systems allows for more effective nitrogen removal in low temperatures without the necessity of increasing the volume of the oxygen chamber [16-19]. Removing a higher amount of organic compounds in anoxic conditions stands for deeper denitrification and in consequence reducing energy consumption for aeration and lower production of excess sludge. The process of denitrifying dephosphatation is possible in flow and cyclically operating systems. Research on denitrifying dephosphatation in an SBR reactor carried out by Styka [20] showed that due to the introduction of an anoxic phase in the middle of the aerobic phase in an anaerobic-aerobic SBR reactor with quick filling, the fraction of denitrifying bacteria phosphate-accumulating organisms (PAO) increased from 15,9 to 44% of the total number.

The DEPHANOX (ANOXic DEPHosphation) system is an example of practical realisation of nitrification separated on biofilter in a flow system [21-23]. This system reduces general phosphorus by 71% with 7,8 $mgP \cdot gsmo^{-1} \cdot d^{-1}$ of its intake, whereas the efficiency of nitrate nitrogen reduction reached about 60% with 30 $mgNO_3$-$N \cdot gsmo^{-1} \cdot d^{-1}$ speed of the process. The DEPHANOX system also contributed to improvement of sludge sedimentation capacity (sludge index equaled 50 $ml \cdot g^{-1}$).

The objective of our paper is to evaluate possibilities of removal of biogenic compounds using the denitrifying dephosphatation process in a treatment plant with nitrification separated on biofilters. This evaluation was carried out on the basis of data from one municipal sewage treatment plant in Swietokrzyskie voivodeship,

Poland, in which only a trickling filter technology is currently used as a biological component.

Material and Methods

Sewage Treatment Plant Characteristics

Results of municipal sewage treatment obtained in an exploited mechanical-biological sewage treatment plant in a Swietokrzyskie Voivodeship city were the basis for performed calculations. Sewage from about 14,000 citizens runs into the treatment plant. The designed sewage treatment plant capacity is 8620 $m^3 \cdot d^{-1}$. The following objects are included in the technological chain of the analysed treatment plant: horizontal sand separator with manual sand removal, two Imhoff primary settling tanks, two submerged anoxic filters filled with BIOPEX packages (currently out of exploitation), two stage I trickling filters filled
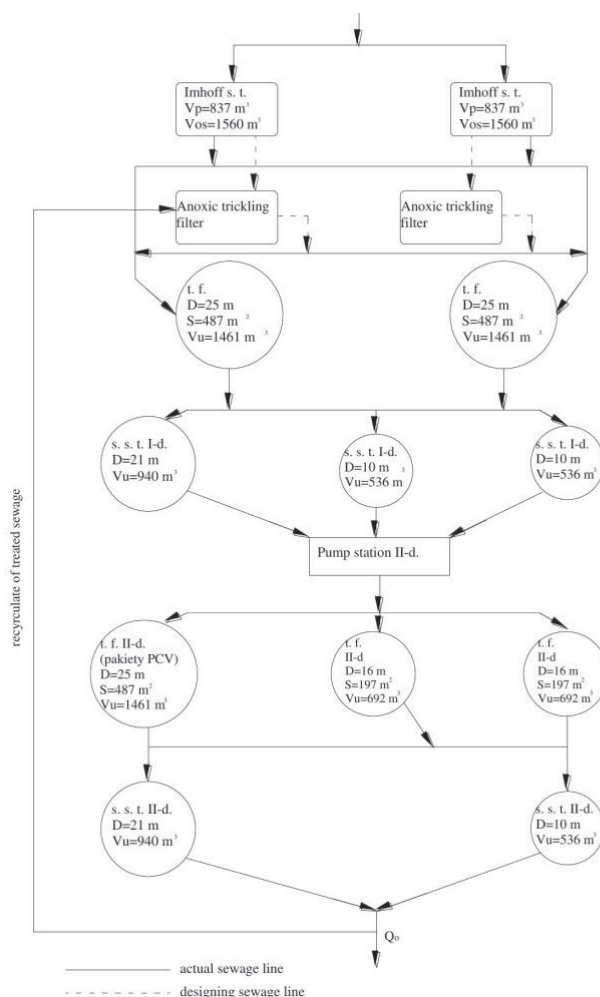

Fig. 1. Technological scheme of the analyzed sewage treatment plant: Imhoff s. t. - Imhoff settling tank; t. f. - trickling filter; s. s. t. I-d. - secondary settling tank first degree; Pump station II-d. - Pump station second degree; t. f. II-d. - trickling filter second degree; s. s. t. II-d. - secondary settling tank second degree
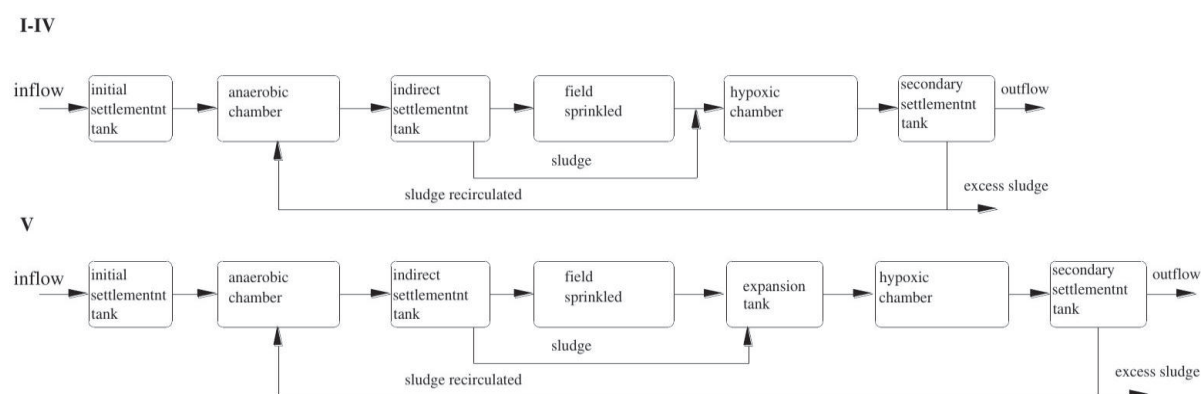
I-IV

V

Fig. 2. Technological variants of the sewage treatment plant facilities included in the variant calculations.

with quartzite break stone of 80 m^2·m^{-3} active surface, three vertical intermediate settling tanks, a stage II sewage pump station, three stage II biofilters (two with quartzite break stone filling and one filled with BIOPEX packages), a coagulant PIX dosing station, and two stage II secondary settling tanks (vertical and radial; Fig. 1).

Technological Variants of the Sewage Treatment Plant in Analysis

In determining the configuration of each variant modernised in the future technological chain of sewage treatment, a principle of maximum use of objects that already exist in the treatment plant and a minimum dosage of chemicals was applied. Calculations were carried out for five technological variants (Fig. 2).

Differences in variants I-V result from adopted values of anoxic chamber volume and oxygen concentration. In general, sewage treatment processes in the discussed variants run as follows: after initial treatment in the primary settling tank sewage goes to an anaerobic chamber where orthophosphates are released by bacteria cells. Energy to obtain and converse substrates (easily decomposable organic carbon) into polyhydroxyalkanoates, mainly poly-β-hydroxybutyrate, accumulated in PAO microorganism cells is derived from hydrolysis of cell polyphosphates. Subsequently, sewage runs into an intermediate settling tank, where residue is separated in the sedimentation process. Supernatant rich in orthophosphates and ammonium nitrogen with a small amount of organic matter is transferred to a trickling filter in which nitrification of ammonium nitrogen occurs. Sediment from the intermediate settling tank with PAO bacteria is transported to an anoxic chamber to which nitrified sewage from the biofilter, rich in nitrates, flows in. In the anoxic chamber with low oxygen concentration and the presence of nitrates as electron acceptors excessive intake of dissolved orthophosphates with simultaneous denitrification of nitrates takes place. The last element of the system is the secondary settling tank in which activated sludge is separated from the treated sewage by sedimentation. Treated sewage runs into the collector and sludge is partially recirculated to the anaerobic chamber, while the remainder is discharged outside the system as excess sludge.

Table 1 compares technical parameters of devices included in the analyzed variants. Equipment from the mechanical part of the sewage treatment plant, stage II of the biofilter with BIOPEX packages filling, and intermediate and secondary settling tanks from the previously exploited technological chain were left for operation, but stage I and II filters filled with quartzite break stone will be eliminated. Two existing chambers with submerged beds, which currently are not exploited, will be adapted as an anaerobic chamber. In proposed variants the anoxic chamber will be a new object created within modernization efforts. Although it was assumed that in the anoxic chamber denitrifying dephosphatation will occur, dissolved oxygen concentration was accepted to range from 0,5 to 1,0 mgO$_2$·dm^{-3} for additional intake of phosphates remaining in the sewage by microorganisms.

Experimental Procedure

Calculations of pollution removal capacity in analyzed variants of the technological chain were based on commonly used mathematical models of pollutant transformation in bioreactors with activated sludge and biofilters. In recent years such an attitude is more and more common in the simulation of exploited treatment plants as well as in designing new technological systems of treatment. Processes related to wastewater treatment can be predicted using artificial neural networks (ANN), where the number of input variables can be separated by cluster analysis [24-26] or by principal component analysis [27, 28]. Activated sludge simulation models (ASIM) widely discussed in literature (e.g., by Gujer and Henze [29], Gujer and Larsena [30], Gujer et al. [31], Gujer et al. [32], Henze et al. [33], Snip et al. [34], and Wu et al. [35]) are leading in the modelling issues of operating systems with activated sludge. In the present paper calculations of activated sludge chambers

Table 1. Technical characteristics of devices included in the analyzed variants.

Device	Device characteristics				
Variant	I	II	III	IV	V
Primary settling tank	Settling tank volume V = 837m^3; Depth of the flow part H = 2,5m; Amount of sludge/sewage = 0,20; hydraulic load O_h = 13,44 m^3·m^2·d^{-1}				
Anaerobic chamber	Oxygen concentration O_2 = 0,0 mg·dm^3; Chamber volume V = 100 m^3; Retention time T_h = 0,4 h.				
Intermediate settling tank	Amount of sludge/sewage = 0,60				
Trickling filter	BIOPEX packages; Specific surface A = 150 m^2·m^3, Filter volume V = 1460 m^3, Oxygen concentration O_2 = 2,0 mg·dm^3				
Anoxic chamber	Volume V = 400 m^3; Oxygen concentration O_2 = 0,8 mg·dm^3; Depth H = 4,0 m	Volume V = 400 m^3; Oxygen concentration O_2 = 0,5 mg·dm^3; Depth H = 4,0 m	Volume V = 1000 m^3; Oxygen concentration O_2 = 0,8 mg·dm^3; Depth H = 4,0 m	Volume V = 1000 m^3; Oxygen concentration O_2 = 0,5 mg·dm^3; Depth H = 4,0 m	Volume V = 600 m^3; Oxygen concentration O_2 = 1,0 mg·dm^3; Depth H = 4,0 m
Secondary settling tank	Volume V = 1880 m^3; Depth H= 4,0 m; Hydraulic load O_h = 9,74 m^3·m^2·d^{-1}; Sediment load O_o = 4,77 kg·m^{-2}·d^{-1}; Amount of sludge/sewage = 0,20; Reactive settling tank				

were based on the ASIM 2d model, which represents continuation of the previous version called ASIM 2 [36-38]. This takes into account dissolved substance, which consists of fermentation products, sewage alkalinity, very easily and easily decomposable organic matter, nitrogen dioxide as denitrification product, ammonium and ammonium nitrogen, nitrite and nitrate nitrogen, dissolved oxygen, and inorganic phosphates. This model also includes non-dissolved substances such as nitrifying organisms, heterotrophic aerobic and facultative anaerobic organisms, indecomposable molecular organic substance, salts and metal hydroxides (included in processes of chemical phosphorus precipitation), PAO phosphate-accumulating bacteria, cell components of bacteria (e.g., poly-β-hydroxybutyrates, polyphosphates, and slowly decomposable hydrolysed organic substances), and general suspended solids [39].

ASIM 2d model considers 21 unitary processes qualified into 5 groups: hydrolysis, processes with heterotrophic bacteria, processes with autotrophic bacteria, polyphosphate-accumulating bacteria, and chemical processes. A mathematical description of denitrification processes with polyphosphate-accumulating bacteria [40] was included in this model. The simulative calculation of activated sludge chambers was realised using BioWin 2 software. To realise the objective of the research, a model of pollutants' transformation on biofilter, described in Rauch's et al. paper [41], was also included in the ASIM 2d model, which consists of the following assumptions: biological membrane is of homogenous structure and density throughout the depth, microorganisms are uniformly distributed in the biological membrane, reactions occur with first-order kinetics, and dissolved substances are immediately diffused by biological membrane. The transformation of organic matter and nitrification of ammonium nitrogen in biological membrane were calculated according to the scheme given by Henze et al. [42].

Results of exploitation research on the objective treatment plant (which included average daily sewage inflow, pH reaction, COD values (total and dissolved), total suspended solids, Kiejdahl's general nitrogen, nitrate nitrogen, general phosphorus, and alkalinity) were adopted as input parameters for calculations. Sewage composition was determined by referential methods stated by Polish standards, as at work [43]. The description of shares of each organic fraction of pollutants in raw sewage has particular meaning in modelling of sewage treatment processes. In order to do this, analyses of total and dissolved COD content (after filtering through a filter of 0,45 μm pore size) in raw sewage were performed, and then a share of each fraction was defined according to methods described by Barnad and Oleszkiewicz [44]. The age of sludge at 10 d and constant temperature at T = 20ºC were adopted for calculations. Constants of reaction kinetics were adopted from the range given by Henze et al. [33], Rauch et al. [41], and Henze et al. [42]; therefore, the obtained results can only illustrate the potential possibility of adaptating the existing biofilters into the chain with activated sludge. All simulations were performed in set conditions.

Results and Discussion

Reducing Wastewater Pollutants

The main reason why variant calculations of technological chains of the sewage treatment plant were undertaken was because the treated sewage did not meet conditions from water law permission for the objective treatment plant for general nitrogen and general

Table 2. Share of each COD fraction in sewage running into the treatment plant .

COD fraction	Value, mg/dm^3
Dissolved decomposable S_{BS}	110,53
Dissolved indecomposable S_{US}	34,54
Molecular decomposable S_{BP}	456,92
Molecular indecomposable S_{UP}	89,81

phosphorus concentrations, which was confirmed by the statistical analysis of the obtained results. The calculations showed that, concerning BOD_5 values, the treatment plant operates correctly for 66,2% of year, for COD 99,4%, for total suspended solids 98,6%, for general nitrogen 3,0%, and for general phosphorus 89,8% [42]. Considering the insufficient capacity of sewage treatment concerning the removal of biogenic compounds, variant deliberations were carried out to search for the optimal solution of a technological chain that would guarantee reliable operation of the object regarding nitrogen and phosphorus removal from the sewage while enabling maximum usage of the existing objects. As shown by Bugajski and Woźniak-Vecchie [43] and Bugajski [44], there is a need to modify classical technological systems with activated sludge in order to intensify the process of biogenic compound removal.

Experimental Procedure Results

Table 2 presents average values of each COD fraction in raw sewage that were used for modeling.

Research showed that dissolved COD fraction constituted less than 21% of total COD, whereas the share of decomposable (dissolved and molecular) organic substances equaled 82% in total COD. This suggests that the analyzed sewage is susceptible to biochemical decomposition. Table 3 shows average

values of the analyzed pollution indexes in the treated sewage obtained in performed calculations compared to values gained from the exploitation of the existing technological chain.

Calculations proved that in variants I–IV a lower treatment capacity was obtained for organic matter in comparison to the existing object. BOD_5 values were significantly higher than the admissible level of 15 $mgO_2 \cdot dm^{-3}$. However, we observed that an increase in anoxic chamber volume from 400 to 1000 m^3 and an increase of oxygen concentration from 0,5 to 0,8 $mgO_2 \cdot dm^{-3}$ causes an increase of organic pollutants' reduction. This results from the fact that although nitrified sewage after biofilter with low amount of organic pollutants flows into the anoxic chamber, it is still overloaded with organic matter from the residue after the intermediate settling tank. Calculations showed that the average BOD_5 value in the sludge was 1117,9 $mgO_2 \cdot dm^{-3}$, and COD 2550, 3 $mgO_2 \cdot dm^{-3}$. The high load of sludge with organic substances causes an increase of oxygen demand. Keeping low oxygen concentration in the anoxic chamber causes substrate to be only partially mineralised, which results in low BOD_5 and COD production. It also results from low activity of activated sludge in the anoxic chamber – the calculated respiration speed for variants I and II ranged from 0,12 to 1,25 $mgO_2 \cdot gsm^{-1} \cdot h^{-1}$, and for variants III and IV 7,54 and 9,67 $mgO_2 \cdot gsm^{-1} \cdot h^{-1}$, respectively. For total suspended solids a higher reduction obviously is observed in variants I-IV in comparison to the one obtained in the existing object. In each variant, concentrations of total suspended solids in the outflow were lower than the admissible value of 35 $mg \cdot dm^{-3}$.

Introducing the anoxic chamber after nitrifying filters contributes to an increase of removal of general phosphorus from sewage. This is mainly caused by significant ammonium nitrogen reduction in the sewage in the nitrifying filter and its slight increase in the anoxic chamber. On the other hand, clear nitrate nitrogen reduction resulting from classic dissimilative denitrification is not observed (Fig. 3).

Table 3. Capacity of selected pollution indexes observed in exploited technological chain and calculated for analyzed variants.

Pollution index	Raw sewage	Sewage treated in the exploited treatment plant	Calculation variant				
			I	II	III	IV	V
BOD_5, $mgO_2 \cdot dm^{-3}$	267,01	13,14* 95,1**	46,31 82,6	49,35 81,5	29,16 89,1	31,77 88,1	10,14 96,2
COD, $mgO_2 \cdot dm^{-3}$	690,83	55,25 92,0	77,24 88,8	80,89 88,2	52,33 92,4	58,52 91,5	35,9 94,8
Total suspended solids $mg \cdot dm^{-3}$	209,23	18,51 91,1	2,84 98,6	0,98 99,5	1,05 99,5	1,21 99,4	4,49 97,8
General nitrogen $mg \cdot dm^{-3}$	62,37	25,93 58,4	18,64 70,1	18,49 70,3	17,44 72,0	16,82 73,0	36,44 41,6
General phosphorus $mg \cdot dm^{-3}$	9,03	3,39 62,4	3,13 65,3	3,14 65,2	3,07 66,0	2,9 67,9	1,74 80,7

*average concentration
** reduction, %

In variants I-IV, general nitrogen concentration in the outflow is significantly lower than the one obtained in the real object; however, in each case the admissible value of 15 mg·dm^{-3} is exceeded. In variants I-IV significant improvement of phosphorus removal in comparison to the existing treatment plant is not observed. Average concentrations of general phosphorus obtained from the calculations are slightly lower than the real values for the analyzed object and exceed the admissible value of 2,0 mg·dm^{-3}.

It is worth noting that phosphorus is removed only biologically in the analyzed variants, whereas in the existing treatment plant it is removed by chemical precipitation with PIX coagulant, dosed at the inflow to the stage II secondary settling tank. Therefore, possible modernization of the technological chain carried out accordingly to the discussed variants would contribute to lowering the costs of sewage treatment. Together

with an increase of anoxic chamber volume and a decrease of dissolved oxygen concentration from 0,8 to 0,5 mgO$_2$·dm^{-3}, an increase of consumed phosphates can be noticed (Fig. 4). Considering the fact that in an anoxic chamber nitrate nitrogen occurred in a concentration of about 9,0 mgN-NO$_3$·dm^{-3}, there was a possibility of denitrifying dephopsphatation, because N-NO$_3$ was the electron acceptor for PAO bacteria. On the other hand, the speed of phosphorus intake in the anoxic chamber could have been limited by insufficient nitrate nitrogen concentration and too short time of sewage retention.

The research carried out by Sorm et al. [14] showed that phosphates were partially consumed by PAO bacteria when initial concentration of N-NO$_3$ equaled 25 mgN-NO$_3$·dm^{-3}, whereas practically total phosphate intake occurred with initial N-NO$_3$ concentration of 60 mgN-NO$_3$·dm^{-3} and lasted until their complete
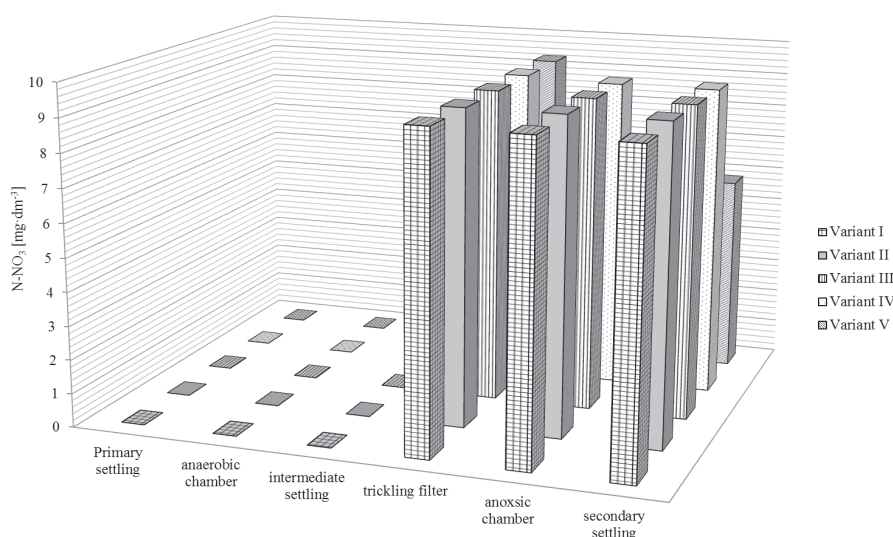

Fig. 3. Profile of concentration values of nitrate nitrogen for analyzed calculation variants.
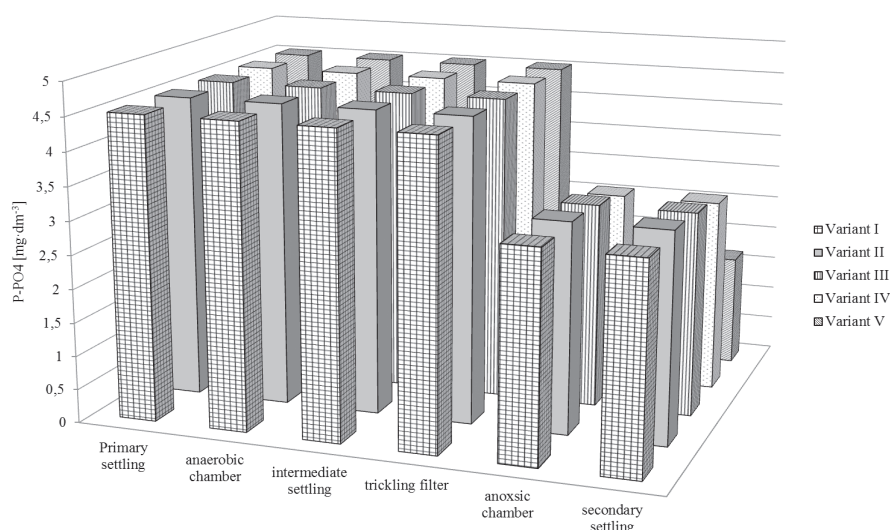

Fig. 4. Profile of concentration values of phosphates for analyzed calculation variants.

depletion. COD/N ratio confirms nitrate deficiency for denitrifying dephosphatation. As given by Kuba et al. [45], Chen et al. [49], and Meng et al. [50], optimum value of this ratio should amount to 3,5 gCOD/gN. With a ratio higher than the given one (in the analyzed sewage it was 11,1), incomplete phosphorus removal occurs as caused by a deficiency of nitrates.

In variant V the volume of anoxic chamber was decreased to 600 m^3 and oxygen concentration was increased to 1,0 mgO$_2$·dm^{-3}. As a result, significant improvement in organic pollutant removal was observed in comparison to variants I-IV. Average BOD$_5$ and COD values at the outflow from the secondary settling tank were lower than the admissible value defined in the water-law permission. The concentration of total suspended solids slightly increased at the outflow in comparison to previously analyzed variants. General nitrogen reduction was significantly worse and its average concentration at the outflow reached 36,44 mg·dm^{-3} and clearly exceeded value obtained in the existing object and admissible value from the water law permission. This situation is mainly caused by a significant increase of N-NH$_4$ concentration in anoxic chamber to the level of 26,14 mgN-NH$_4$·dm^{-3}. Increasing oxygen concentration in the anoxic chamber caused a decrease of the denitrification process, which in turn caused an increase in general nitrogen concentration at the outflow of the treatment plant. At the same time, such actions caused an increase of phosphorus consumed by PAO bacteria (general phosphorus concentration at the outflow of the settling tank was 1,74 mgP$_{og}$·dm^{-3} and does not exceed the admissible value). In the anoxic chamber bacteria do not have organic acids at their disposal so only organisms capable of using stored, easily decomposable substrates exclusively in the presence of nitrates as an electron acceptor are promoted [51].

Conclusions

As a result of the performed calculations, the following conclusions may be formulated:
1. It is possible to significantly remove organic pollutants (BOD$_5$, COD) and total suspended solids from the sewage in a treatment plant with biofilters as biological stage devices. General phosphorus may be removed only by chemical precipitation.
2. There is a possibility of including biofilters into activated sludge technology in order to improve nitrogen and phosphorus removal from the sewage. The nitrification process will be carried out on biofilters, whereas in anaerobic and anoxic chambers operating in activated sludge technology the process of nitrogen and phosphorus removal will take place. Separating nitrifiers from heterotrophic organisms causes lack of competition between these organisms and higher stability of the nitrifier population. In systems with nitrification in the so-called "side

sequence," a denitrifying dephosphatation process will be possible.
3. Using the denitrifying dephosphatation process reduces energy consumption of the system related to decreased oxygen need. Calculations showed that even with oxygen concentration of 1,0 mgO$_2$·dm^{-3in} in an anoxic chamber, denitrification as well as orthophosphate intake were carried out by microorganisms.
4. The denitrifying dephosphatation process guarantees high general phosphorus removal at 81%, provided that total easily decomposable substrate will be consumed by microorganisms in an anaerobic chamber and that a sufficient amount of phosphates will be available.
5. Calculations showed that integration of biofilters with activated sludge in a flow system allows for high reduction of organic pollutants, total suspended solids, and biogenic compounds from sewage. Considering general nitrogen reduction, the most favourable variant was the system with an anoxic chamber 1000 m^3 in volume and oxygen concentration equal to 0,5 mgO$_2$·dm^{-3}, whereas phosphorus removal featured a solution with anoxic chamber 600 m^3 in volume and oxygen concentration of 1,0 mgO$_2$·dm^{-3}.
6. The ASIM 2d model seems to be an extremely useful tool for designing and simulating sewage treatment plant operation. It follows from the fact that it enables the simulation of most processes occurring in a bioreactor with activated sludge.

Conflict of Interest

The authors declare no conflict of interest

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