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COMPUTER SIMULATION OF WASTEWATER TREATMENT PROCESSES

Dynamic simulation of treatment processes is a very powerful method in wastewater engineering. The existing models are capable of accounting for all major events occurring within the municipal treatment plants. Dynamic nature of the models accounts for unsteady conditions which occur in a plant as a result of continually changing loads. New designs, upgrading as well as analysis of alternative operational strategies and control of existing wastewater treatment plants are greatly facilitated by computer simulation. Many potentially feasible solutions may be evaluated quickly and relatively inexpensively. It allows for eliminating those that are inefficient from either a process or an economic prospect.

1. INTRODUCTION

Wastewater treatment systems have become more complex and difficult to handle due to development in urbanised areas and more stringent quality standards for effluents discharged to the environment. This has rapidly raised the investment, operation and maintenance costs of wastewater treatment plants. The minimisation of costs of treatment processes must be one of the main objectives in wastewater systems planning and management. It is not an easy task as the treatment systems are very complex.

One way of searching feasible solutions is to describe the system by mathematical models. These models are representations of the knowledge we have about the system. They help in decision making by integrating and processing the existing information in such a way that it becomes easier to draw the conclusions needed. If we can build a model, which is a good representation of a real system, we can use it to conduct experiments otherwise prohibitively expensive or even impossible to be carried out. We can "run" the model under conditions that would be harmful or dangerous in a real system. The models are "prototypes" of the systems we need to analyse. Exploring the "prototype" we can gain better understanding of the system itself.

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Development of a mathematical model involves compromises to balance conflicting needs. On the one hand, a model must incorporate the major events occurring within a system in a manner, which is consistent with established knowledge about the system. On the other hand, the model equations must be solvable with a reasonable degree of effort (computational time). Fortunately, the progress observed in computers makes the problem less critical. A model designer should include only those processes, which are essential for a realistic solution. In wastewater engineering, there has been a rapid progress in the development of models for the processes used in a typical municipal treatment plant [1]. Real understanding of the processes expanded sufficiently to enable formulation of mechanistically based models, which seek to account for the major events occurring within the treatment plants. These mechanistic models are powerful tools because they allow extrapolation of the design space beyond that experienced on a physical model [2]. In this way, many potentially feasible solutions may be evaluated quickly and relatively inexpensively, thereby allowing only more promising ones to be selected for actual testing in the physical model. Dynamic nature of the mathematical models allows accounting for unsteady conditions, which occur in the plant as a result of the loads continually changing over time scales that are comparable to the plant residence time. The design of new or modified plants as well as the operation and control of existing wastewater treatment plants can be greatly facilitated by computer simulation. The simulation allows exploration of alternative wastewater treatment system configurations, inputs, and operational strategies. It expands an engineer's experience and increases his decision-making abilities. Once calibrated to a particular wastewater, a model allows an engineer to screen quickly many potential designs and to eliminate those that are inefficient from either a process or an economic prospect. Furthermore, once a system configuration is selected, a model allows individual units to be sized to minimize total system costs. Finally, after a plant is constructed, a model can be used to investigate alternative operational strategies that minimize the impact of new waste loads.

2. PLANT MODEL

Activated sludge plant consists usually of the three main components, namely, a primary settler, an activated sludge bioreactor (BR) and a secondary settling tank (SST). Each of them can be successfully modelled. The submodels of the individual elements together with the model of inputs (influent flow rate, concentrations) comprise a model of the treatment plant. Screens and grit chambers do not contribute much to the inputs modifications, and can be usually neglected in modelling.

2.1. INPUTS MODEL

Concentrations of pollutants in wastewater are structured according to their nature (organics and nitrogen) and transformations they undergo in treatment processes. The organic matter in wastewater can be subdivided into four categories [3]: inert soluble organics (S_I COD), inert particulate organics (X_I COD), readily biodegradable organics (S_S COD) and slowly biodegradable organics (X_S COD). The inert organics (S_I and X_I) do not undergo transformations, and leave the treatment plant unchanged in form. The readily biodegradable material (S_S) consists of relatively simple molecules that can be taken in directly by heterotrophic bacteria and used for growth of new biomass. The slowly biodegradable organics (X_S) consists of relatively complex molecules, and before heterotrophic bacteria can use them they must be hydrolysed extracellularly and converted into readily biodegradable substrate. For the purposes of activated modelling, the X_S fraction is treated as it were particulate.

Nitrogenous matter in wastewater can be divided into five categories: ammonia nitrogen (S_{NH}), biodegradable soluble organic nitrogen (S_{ND}), biodegradable particulate organic nitrogen (X_{ND}), inert soluble organic nitrogen (S_{NI}) and inert particulate organic nitrogen (X_{NI}). A content of the inert nitrogen (S_{NI} and X_{NI}) in wastewater is usually very low and may be excluded from modelling. Proportions of the COD and nitrogen fractions in a given wastewater are characteristic of this wastewater and more or less constant over a time. "Typical" values of unsettled domestic sewage are given in the table.

Table

"Typical" characteristics of unsettled domestic sewage [4]–[6]

Symbol	Fraction of total COD	Fraction of total nitrogen
S_I	0.05	–
X_I	0.13	–
S_S	0.22	–
X_S	0.60	–
S_{NH}	–	0.60
S_{ND}	–	0.10
X_{ND}	–	0.25
S_{NI}	–	0.01
X_{NI}	–	0.04

2.2. PRIMARY SETTLING TANK MODEL

In the primary clarifier, settleable matter is removed by gravity. It causes the lowering of the load that enters the biological reactor. The nature of particle settling in a primary settling tank is extremely complex and essentially stochastic. Fortunately it has been proved that relatively simple mechanistic models are reliable and give fairly good predictions of pollutant concentrations in the effluent from primary settler [7], [8]. An illustration of predictive power of the model is given in figure 1 [9].

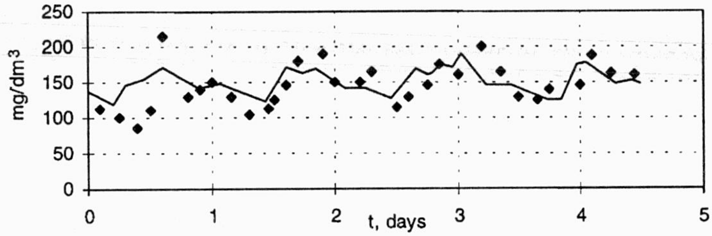

Fig. 1. Comparison of simulation results (solid line) with experimental data (black squares) for a full-scale primary settling tank effluent SS concentration [9]

2.3. ACTIVATED SLUDGE MODEL

In most designs of biological wastewater treatment systems (especially those with nitrogen removal), long solids retention times (SRT) are required. Because of that the differences in effluent soluble biodegradable organics concentration for different system configurations are generally small. Conversely, large differences in activated sludge concentrations and electron acceptor (oxygen or nitrate) requirements are common. Furthermore, good design practice requires supplying a sufficient quantity of electron acceptor in response to diurnal and seasonal changes in demand and capability of final settlers to handle all anticipated concentrations of solids. This means that the models describing a substrate removal should be mostly directed to their impact upon activated sludge concentrations and electron acceptor requirements.

The first good example of such a model was IAWPRC Activated Sludge Model 1 [3], [9]. The model incorporates carbon oxidation, nitrification and denitrification. The changes of the carbonaceous and nitrogenous components of sewage in bioreactors are schematised in the model as shown in figure 2. For the purposes of modelling, the readily biodegradable material (S_S) is treated as it were soluble, whereas the slowly biodegradable material (X_S) is treated as if it were particulate. A portion of the readily biodegradable organics uptaken by heterotrophic bacteria (X_{BH}) is oxidised either with oxygen (oxic process) or nitrates (anoxic process, denitrification) as terminal electron acceptors. The rest of the organic molecules uptaken are incorporated into the biomass. The energy released during the oxidation covers the energetic expenditures of the biomass synthesis. The biomass synthesis is associated with assimilation of some nitrogen and phosphorus.

After entering bioreactor, the slowly biodegradable material is supposed to be quickly enmeshed in the activated sludge floc structure, and then to be acted upon extracellularly (hydrolysed). The hydrolysis is slower than utilisation of readily biodegradable substrate. The extent to which the X_S fraction in the sludge flocs is hydrolysed (before the flocs leave the system) depends mainly on the process temperature and the time designed for the hydrolysis in the system (sludge age). The higher the temperature and the longer the sludge age, the more complete is the hydrolysis.

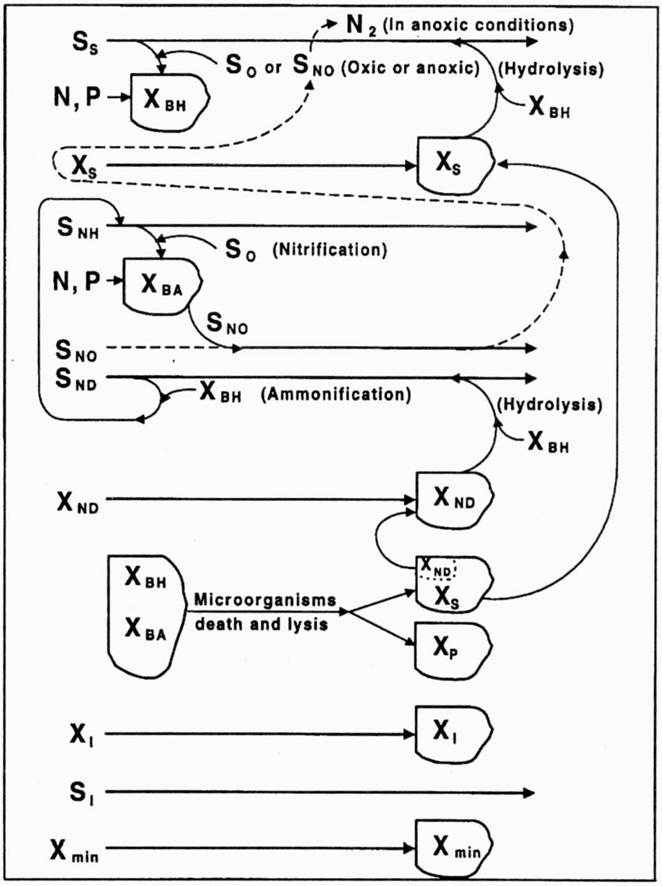

Fig. 2. Scheme of sewage pollutant transformation in activated sludge process

Non-biodegradable organic and mineral matter pass through the activated sludge system unchanged in forms. The inert soluble organic matter (S_I) leaves the system at the same concentration as it enters it. The inert suspended organic mater (X_I) became enmeshed in the activated sludge and is removed from the system through sludge wastage. The same holds for mineral suspended solids (X_{min}).

Under aerobic conditions ammonia nitrogen (S_{NH}) is the energy source for the autotrophic nitrifying bacteria (X_{BA}) which oxidize it to the nitrate nitrogen (S_{NO}), (nitrification). The nitrate formed may serve as terminal electron acceptor for heterotrophic bacteria under anoxic conditions, yielding nitrogen gas. Usually the nitrate nitrogen content in raw municipal wastewater is nearly zero.

The soluble biodegradable organic nitrogen (S_{ND}) is converted by heterotrophic bacteria into ammonia nitrogen (ammonification). The biodegradable particulate organic nitrogen (X_{ND}) is enmeshed in the sludge flocs and hydrolysed by heterotrophic bacteria to soluble organic nitrogen (S_{ND}) in parallel with hydrolysis of slowly biodegradable organics (X_S).

Due to both heterotrophic and autotrophic bacteria decay a slowly biodegradable matter (X_S) is released, then it reenters the cycle and is further hydrolysed, and non-biodegradable particulate organic matter (X_P) remains enmeshed in the sludge flocs and leaves the system with sludge wastage. The nitrogen present in the X_S fraction (X_{ND}) undergoes hydrolysis in parallel. The longer the sludge age, the more decay products are released.

The model can predict the sludge composition and its production in a given system as a function of sludge age and pollutants concentration in the wastewater treated. Suspended (sludge) as well as soluble organics and nitrogen concentrations can be calculated in steady state and under dynamic conditions in each reactor of variously configured systems. The same holds for spatially and temporally changing oxygen uptake rate. An illustration of the predictive power of the model under dynamic conditions is given in figure 3. The results are collected for unsettled municipal wastewater treated in a single completely mixed aerobic reactor under daily cyclic square wave flow and load conditions (12 hours feed /12 hours no feed) [10].

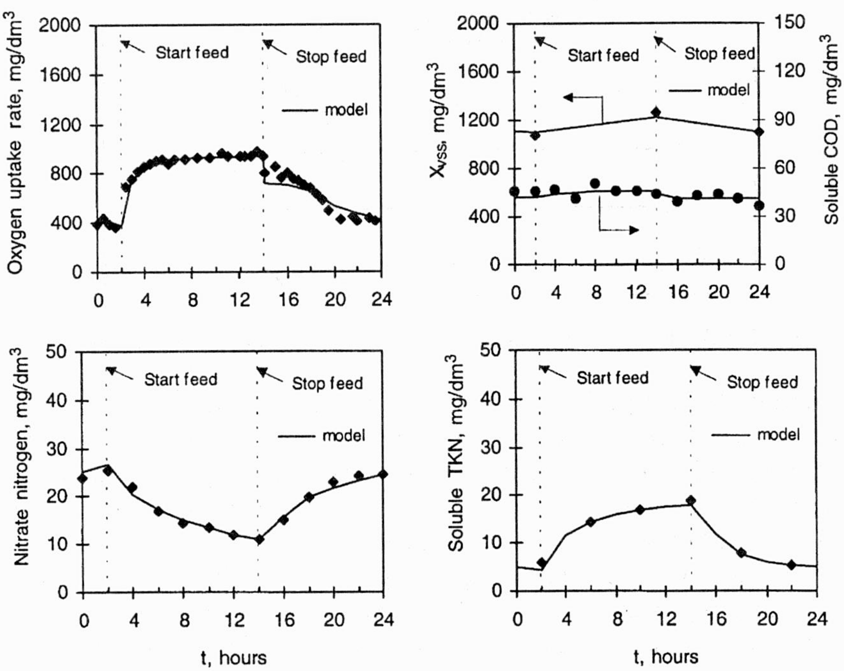

Fig. 3. Comparison of experimental results and the activated sludge model predictions under daily wave loading conditions [10]

2.4. MODEL OF SECONDARY CLARIFIER

The overall efficiency of the activated sludge process is highly dependent on the satisfactory performance of the secondary clarifier. The unit operates as a thickener (to concentrate biological solids which must be recycled to sustain the processes in bioreactors) and clarifier (to keep the final concentration of effluent suspended solids as low as possible). A good settler model should be able to predict the concentration of solids in the underflow (return sludge concentration), solids blanket height, solids concentration profile in the settler and the concentration of suspended solids in the overflow [9], [11], [12].

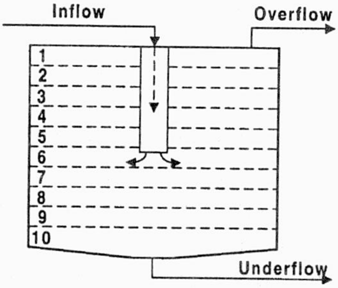

Fig. 4. Layered final settler model

Model of the settler divides the sludge blanket into several completely mixed layers (figure 4), and allows the description of the solids transport between the layers in terms of the limiting flux theory. The models can predict behaviour of the sludge blanket under different loading conditions. The example is given in figure 5, which is for the full-scale final settler under high-loading conditions [11].

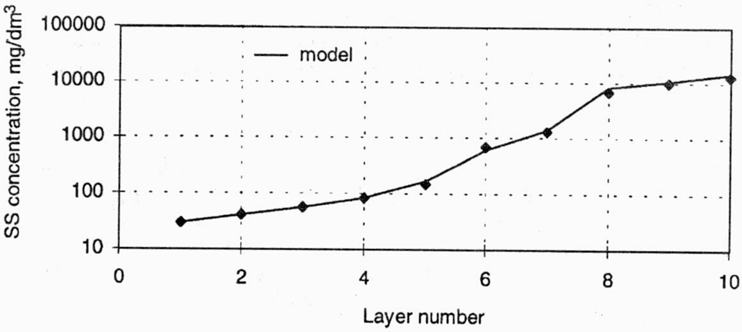

Fig. 5. Comparison of the observed and simulated SS concentration profiles in a full-scale secondary settling tank [11]

3. APPLICATIONS OF THE PLANT MODEL

The dynamic models of the activated sludge treatment plant are very convenient tools for designers and operators. On the following pages an example of possible model applications is given. The example is related to the analysis of how a nitrifying activated sludge system can be upgraded to enable biological nitrogen removal. The objective is to obtain average effluent concentrations not exceeding the following limits: $BOD_5 \leq 30$ mg/dm^3, $SS \leq 50$ mg/dm^3, $N_{total} \leq 30$ mg/dm^3, $N\text{–}NO_3 \leq 30$ mg/dm^3, $N\text{–}NH_4 \leq 6$ mg/dm^3.

A hypothetical treatment plant, which is the object of the analysis, is shown in figure 6. The average influent flow rate to the plant is 10 000 m^3/d, $BOD_5 = 280$ mg/dm^3, SS = 250 mg/dm^3 and TKN = 60 mg/dm^3. The analysis has been carried out for constant or diurnal loading conditions. The assumed input time series of the BOD_5 and TKN are shown in figure 7. The first day of a series is for a constant loading, the days from 1 to 4 for a diurnal loading, and the next 16 days for a diurnal loading plus the first-order autoregressive stochastic component [9]. By adding the stochastic component one can account for a noise associated with real inputs when they are stationary. The outputs simulated for the system operated at sludge age (solids retention time – SRT) of 6 days, the reactor temperature 15 °C and under loading conditions given in figure 7 are shown in figure 8. One can notice that the system nitrifies, but the resultant total effluent nitrogen is too high ($N_{total} \geq 30$ mg/dm^3, N–$NO_3 \geq 30$ mg/dm^3) compared with the objective defined. It is obvious that denitrification of nitrates is necessary.

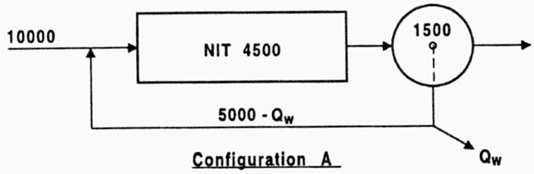

Fig. 6. Configuration of the treatment plant to be upgraded. The numbers inside the shapes relate to the volumes (in m^3) of the respective units, while those along the arrows relate to the respective flow rates (in m^3/d)

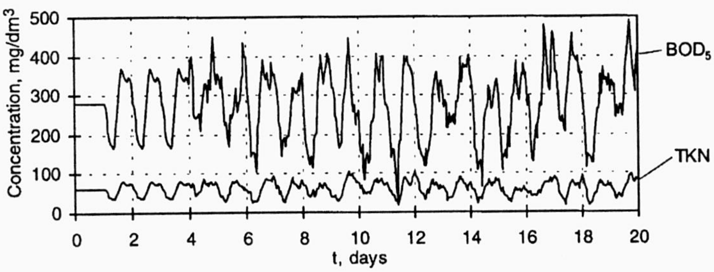

Fig. 7. Influent BOD_5 and TKN time series

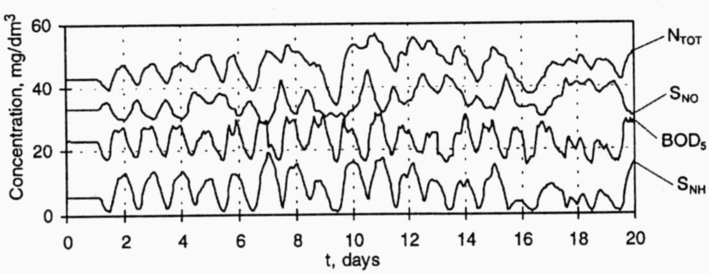

Fig. 8. Effluent concentrations for the configuration A. ($V_{NIT} = 4500$ m^3, SRT = 6 d, temperature = 15 °C, resultant $MLSS_A \approx 3000$ mg SS/dm^3)

As a first trial solution to the problem a reconfiguration of the plant was proposed as shown in figure 9. The configuration B consisted in assigning one third of the aeration tank to the anoxic reactor. Feasibility of the configuration was checked by simulation. It was assumed that inputs to the plant were constant and equal to the mean values. The initial conditions for the simulation were the steady state values for the configuration A.

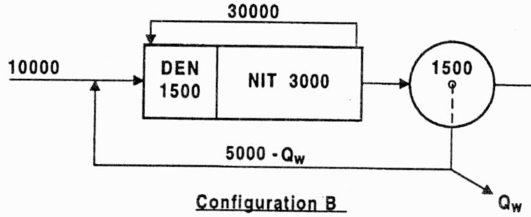

Fig. 9. Configuration B of the upgraded plant

The simulation results for 19 days after starting the configuration B are shown in figure 10. It can be seen that the configuration B did not give satisfactory results. The most spectacular effect was the cessation of nitrification. It was so because the SRT (6 d) applied appeared to be too short to sustain the nitrifiers in the activated sludge (at SRT = 6 d the effective aerobic solids retention time in the system is much shorter, i.e. $SRT_{AER} = (3000/4500) \cdot 6 = 4$ d).

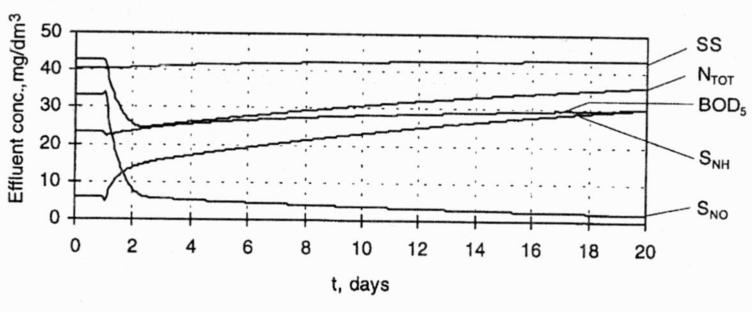

Fig. 10. Transition from the configuration A ($V_{NIT} = 4500$ m^3, MLSS$_A \approx 3000$ mg SS/dm^3, SRT = 6 d) to the configuration B ($V_{NIT} = 3000$ m^3, $V_{DEN} = 1500$ m^3, SRT = 6 d). Temperature = 15 °C, resultant MLSS$_B \approx 3200$ mg SS/dm^3

In order to prolong the time for nitrifiers to grow in the system, the SRT was increased to 9 d. The simulation results are shown in figure 11. As can be seen the sludge age is still too short to assure satisfactory nitrification results. Further trial to increase the SRT to 12 d did not bring about any success, as can be seen from the simulation results shown in figure 12. On the 12th day (11 days after switching to the configuration B) the MLSS concentration reached 4500 mg/dm^3. At this concentration the thickening function of the secondary settling tank was overloaded. Since then on the mass of the MLSS in the bioreactors could not be increased above ~20 tons. All the rest, which was not removed as the excess sludge, built up in the secondary settler. Under these conditions the effective SRT of the sludge in the bioreactors could not be longer than ~9.6 d, and this did not guarantee the needed degree of nitrification. If the settler overloading lasts, the sludge building up in the settler finally reaches the overflow weirs and is massively discharged to the effluent.

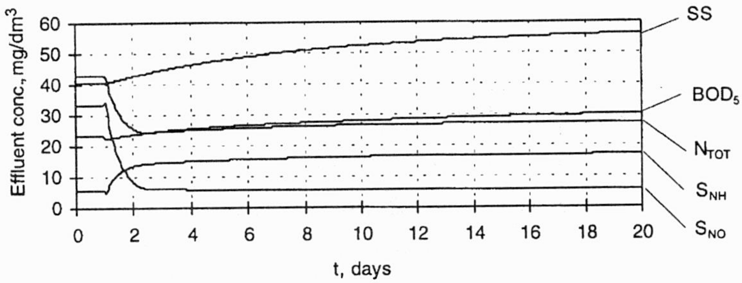

Fig. 11. Transition from the configuration A (V_{NIT} = 4500 m^3, MLSS$_A$ ≈ 3000 mg SS/dm^3, SRT = 6 d) to the configuration B (V_{NIT} = 3000 m^3, V$_{DEN}$ = 1500 m^3, SRT = 9 d). Temperature = 15 °C, resultant MLSS$_B$ ≈ 4100 mg SS/dm^3

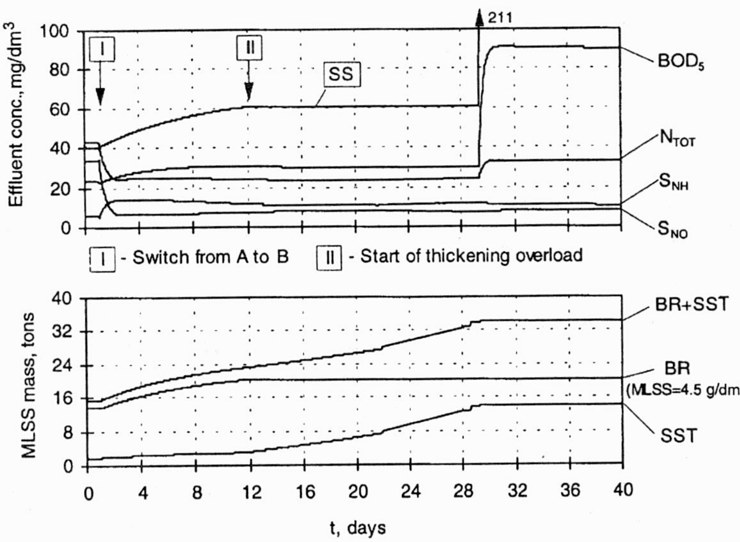

Fig. 12. Transition from the configuration A (V_{NIT} = 4500 m^3, MLSS$_A$ ≈ 3000 mg SS/dm^3, SRT = 6 d) to the configuration B (V_{NIT} = 3000 m^3, V_{DEN} = 1500 m^3, target SRT = 12 d). Temperature = 15 °C

Based on the above simulations one concludes that upgrading of the plant requires extension of the bioreactor and/or the final clarifier and/or building a primary clarifier. Following the conclusion, configuration C (figure 13) consisting in enlargement of the bioreactor was checked. The simulation results are shown in figure 14. As can be seen the BOD and nitrogen removals are satisfactory, but the SS exceeds the limit of 50 mg/dm^3. It is so because the high MLSS (~4300 mg SS/dm^3) causing high solid load to the clarifier results in the high effluent SS.

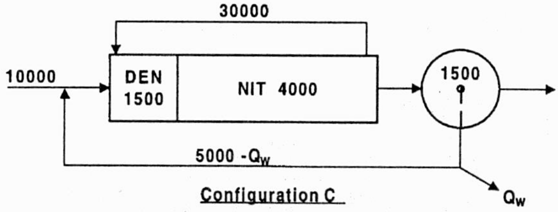

Fig. 13. Configuration C of the upgraded plant

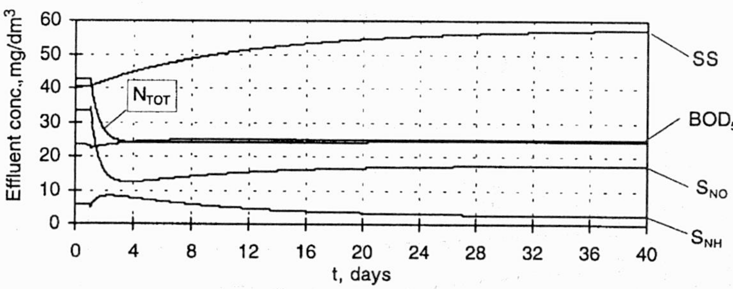

Fig. 14. Transition from the configuration A ($V_{NIT} = 4500$ m^3, MLSS$_A \approx 3000$ mg SS/dm^3, SRT = 6 d) to the configuration C ($V_{NIT} = 4000$ m^3, $V_{DEN} = 1500$ m^3, SRT = 12 d). Temperature = 15 °C, resultant MLSS$_C \approx 4300$ mg SS/dm^3

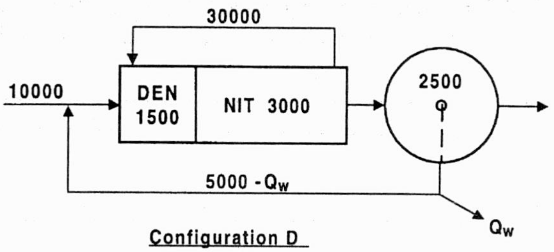

Fig. 15. Configuration D of the upgraded plant

Instead of increasing the bioreactor volume it seems reasonable to try increasing the final clarifier volume (configuration D in figure 15) or building a primary clarifier (configuration E in figure 16). The simulation analysis for the two options has been carried out. The construction costs involved in each option are more or less the same, because of the same additional volumes assumed. The simulation results are shown in figures 17 and 18. In both cases the results appear satisfactory, but in some respects they are different. If there is no primary clarifier in the system the resultant MLSS is very high (~5000 mg SS/dm^3).

This can make the final settler in the system prone to overloading at peak flows and/or in periods of poor sludge settleability. The presence of the primary clarifier results in much lower MLSS (~3200 mg SS/dm^3), but at the same time brings about poorer denitrification as a result of lower BOD/TKN ratio in the primary effluent.

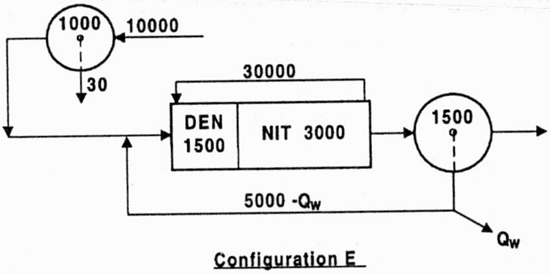

Fig. 16. Configuration E of the upgraded plant

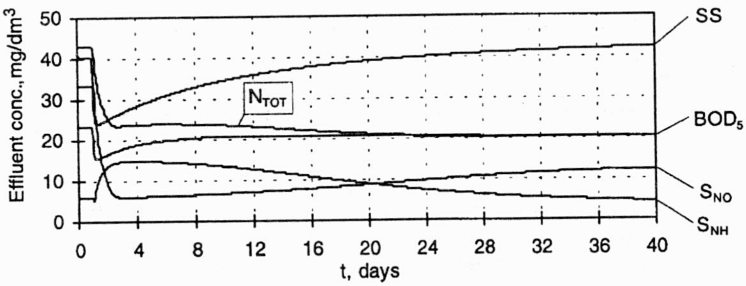

Fig. 17. Transition from the configuration A (V_{NIT} = 4500 m^3, MLSS$_A$ ≈ 3000 mg SS/dm^3, V_{SST} = 1500 m^3, SRT = 6 d) to the configuration D (V_{NIT} = 3000 m^3, V_{DEN} = 1500 m^3, V_{SST} = 2500 m^3, SRT = 12 d). Temperature = 15 °C, resultant MLSS$_D$ ≈ 5000 mg SS/dm^3

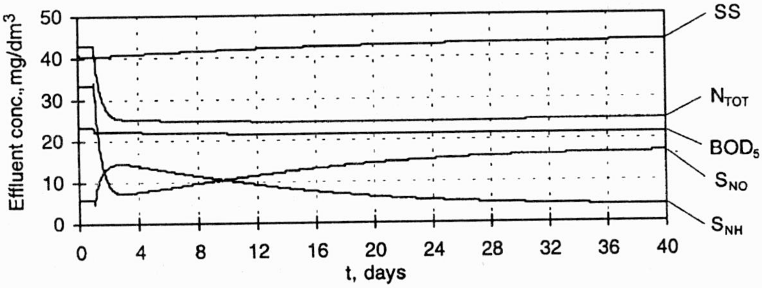

Fig. 18. Transition from the configuration A (V_{NIT} = 4500 m^3, MLSS$_A$ ≈ 3000 mg SS/dm^3, V_{SST} = 1500 m^3, SRT = 6 d) to the configuration E (V_{NIT} = 3000 m^3, V_{DEN} = 1500 m^3, V_{SST} = 1500 m^3, V_{PST} = 1000 m^3, SRT = 12 d). Temperature = 15 °C, resultant MLSS$_E$ ≈ 3200 mg SS/dm^3

Performance of the plant E has been analysed under diurnal loading with periods of poor sludge settleability (SVI = 150 cm^3/dm^3) and wet weather conditions (150% Q) sustained for 9 days. The results obtained are shown in figure 19. The first day series are representative of the E plant at steady state, while the days from 1 to 4 – of the plant under diurnal loading conditions. It is visible that the plant operates well in this period. The same holds for the next three days when the activated sludge settleability deteriorates (SVI rises from 100 to 150 cm^3/g). The days from 7 to 16 represent wet whether conditions (flow rate rises by 50%) together with the poor sludge settleability. As can be seen the increase in hydraulic load causes the secondary settler thickening function overloading. Solids accumulate in the settler resulting in the rise of

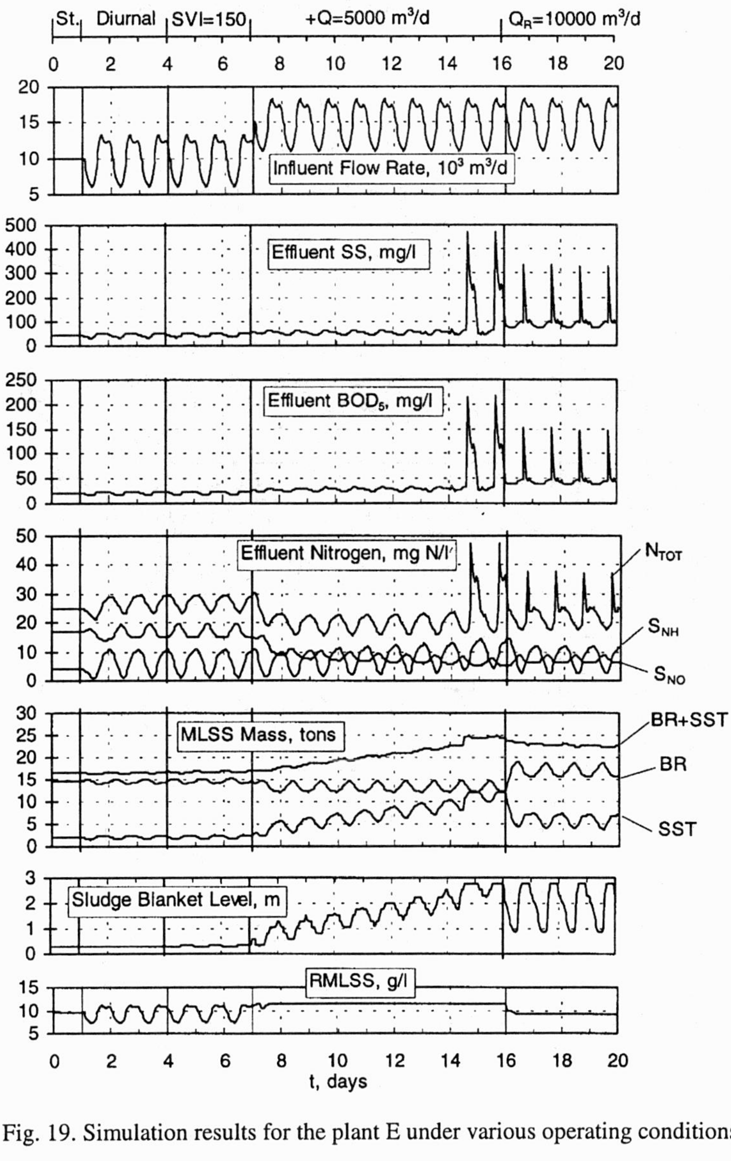

Fig. 19. Simulation results for the plant E under various operating conditions

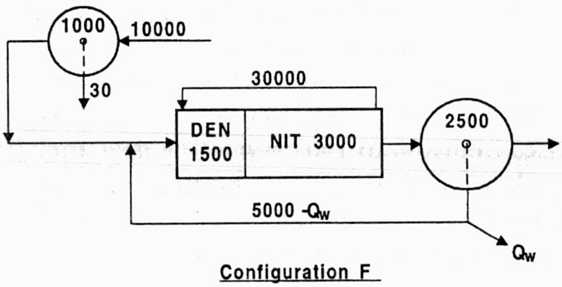

Fig. 20. Configuration F of the upgraded plant

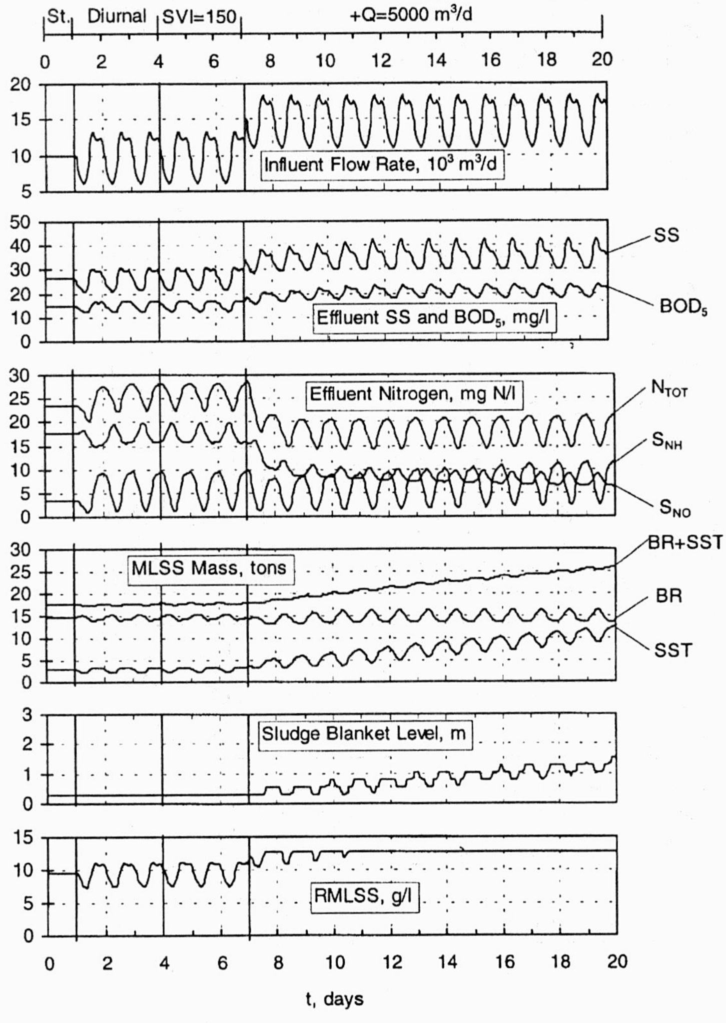

Fig. 21. Simulation results for the plant F under various operating conditions

sludge blanket level (SBL). In terms of the effluent quality the results of the overloading are not dramatic for about one week. One would observe only a slight increase in the effluent SS and BOD_5, and even a noticeable decrease in the total nitrogen concentration (but not load). Symptoms of severe overloading can be noticed only if the SBL is being monitored. Otherwise the plant operator could be even unaware of the problems awaiting him soon. If the overloading lasted for more than one week the plant would collapse as a result of a massive solids discharge. The massive solids discharge starts after the accumulating sludge blanket reaches the final clarifier overflow weirs.

The results for the last four days (from 16 to 20) relate to a remedial action possibly performed by an operator. The action consists in doubling the sludge recirculation ratio (from 5000 to 10000 m^3/d) to shift the sludge from the settler to the bioreactor. As can be seen the action proves not to be a success.

To make the system less sensitive to the overload, the configuration F (figure 20) has been tried out. The configuration consists in enlargement of the secondary settler, which appeared to be a bottleneck of the configuration E. The simulations results for the plant F under the same loading conditions as assumed for the plant E are shown in figure 21. It is visible that owing to the enlargement of the final settler the system can successfully sustain the imposed overload for more than two weeks without violating the effluent limits.

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SYMULACJA KOMPUTEROWA PROCESÓW OCZYSZCZANIA ŚCIEKÓW

Symulacja dynamiczna jest bardzo przydatna w inżynierii oczyszczania ścieków. Istniejące modele matematyczne właściwie odzwierciedlają przebieg głównych procesów wykorzystywanych w komunalnych oczyszczalniach ścieków. Dynamiczny charakter modeli pozwala analizować warunki nieustalone, które są rezultatem ciągłych zmian dopływających ładunków zanieczyszczeń. Symulacja komputerowa istotnie wspomaga projektowanie nowych i modernizację istniejących obiektów oraz analizę alternatywnych strategii sterowania procesami. Symulacja komputerowa daje możliwości szybkiej i stosunkowo taniej analizy wielu potencjalnych rozwiązań technologicznych. Umożliwia to racjonalną eliminację rozwiązań nieefektywnych z technologicznego lub ekonomicznego punktu widzenia.