Time Scale Behaviour of a Biological Wastewater Treatment Facility

MIRELA STOENICA, VASILE LAVRIC[1]*
University Politehnica of Bucharest, Chemical Engineering Department, 1-7 Polizu, 011061, Bucharest, Romania

The effects of recycle and purge ratios (as responsible for the two of the main time scales of the wastewater treatment facility: the residence time of the biological reactors – anoxic and aerobic, and the doubling time of the microorganisms accountable for the biodegradation of substrates), on the performance of a biological treatment process for wastewater are investigated in this study. A modified form of the ASM3 model with two-step nitrification-denitrification (ASM3-2N) [1] was used for the biological process. Three operating time windows with data collected for two weeks: "dry weather", "stormy weather" and "rainy weather" were used to test the system at its largest time scale (http://www.benchmarkwwtp.org). The system under study has two bioreactors in series, followed by a separator, a recycle (through which values the time scale of the bioreactors are modified) and a purge, responsible for the time scale of the activated sludge. Recycle ratios from 0.1 to 0.9 were used and purge ratios from 0.001 to 0.01. The time scale of the bioreactors overcomes the time scale of the biological process, since the latter is, to some extent, determined by the former. This means that the recycle and purge ratios are not independent so, when they are used as command variables to control the process, they should be treated accordingly.

Keywords*: recycle ratio, purge ratio, time scale, wastewater treatment process, bioreactor*

The characteristics of domestic wastewater are highly variable and complex in nature, due to the diversity of the pollutants. The main objective at any biological treatment facility is the reduction or, better elimination of its contamination. Shock loads, high carbon load, presence of toxic and inhibitory organics, solvents and inorganic compounds, variability of the wastewater on both flow and composition diminish the treatment efficiency. The latter depends on the type of the reactors used, their configuration in the treatment system and the associated operating conditions adopted along with the nature and characteristics of wastewater being treated.

The biological treatment of wastewater depends upon the complex, interdependent bacterial community whose structure and composition is highly sensitive to sudden changes in substrate composition, *p*H and temperature and to certain toxic or inhibitory compounds. Basically, bacteria involved in the wastewater treatment belong to two main groups: heterotrophs, whose main target is the carbon based substrates expressed as carbon oxygen demand (COD), and autotrophs, targeting the nitrogen based substrates. The bacteria have small growth rates in general, but smaller for the autotrophs which also have poor yields, meaning slow recovery after toxic shocks or overloading; this requires increased biomass retention in the bioreactors. As in all biological mediated processes, the performance of treatment facility is always a function of the existing number of viable and active cells and a well-balanced biocenosis [2].

The heterotrophic organisms are responsible for COD degradation under both aerobic and anoxic conditions. Under anoxic operating environment some heterotrophic bacteria are stimulated into utilizing nitrates and nitrites (resulted from nitrification) as final electron acceptors for cellular respiration in place of oxygen (complementary process called denitrification) [3,4]. Zhao [5,6] showed that heterotro-phic ammonia oxidation occurs when the C/N ratio is low and the organic carbon loading of acti-vated sludge is high.

Nitrification, the sequential transformation of ammonium to nitrate via nitrite, is typically the result of the activity of two distinct groups of autotrophic bacteria, i.e., the ammonia oxidizing bacteria (AOB) and nitrite oxidizing bacteria (NOB). As oxidation of ammonia to nitrate is a two step reaction in series, nitrite appears only when the ammonia oxidation rate is higher than the nitrite oxidation rate. The decrease of the dissolved oxygen (DO) concentration causes the reduction of both oxidation rates. Nevertheless, NOB are more affected since their value of the oxygen affinity constant is higher than that of AOB. This is the reason for the observed nitrite accumulation for lower DO values [7,8]. AOB become dominant nitrifying bacteria and NOB are inhibited or washout. The NOB are able to utilize both nitrite and organic carbon as energy sources for growth. The influence of organic carbon on the nitrite removal performance and the community structure of NOB and heterotrophic bacteria is complex [9]. Many studies presented the main factors affecting the nitrite buildup [8,10,11], such as higher temperature, short solid residence time (SRT) [11], low DO concentration [12-14] and high free ammonia concentration [15]. Dissimilarities into nitrifying populations are related to niche differentiation concerning ammonium concentrations, system operation, and characteristics of wastewater. Moreover, these communities maintain nitrifying capabilities when conditions change such as sudden increases in ammonium concentrations [16].

In most cases, the mass of nitrifying bacteria is very small compared to the total organic sludge mass due to the relatively low ammonium influent concentration and its low yield coefficient [17]; nitrification is generally a rate-limiting step in a biological nitrogen removal process. A major difficulty is to maintain adequate levels of nitrifiers in the aeration bioreactors. This is achieved using either an internal separation device, like membranes, or a classical external one, sedimentation followed by recycling.

Bacteria concentration increases with both residence time and sludge recycling. Heterotrophs are responsible for the decomposition of dead cells and extracellular polymeric substances (EPS) [18]. When the ecosystem is supplied with organic carbon, the heterotrophs compete with the nitrifiers for ammonia and oxygen and are always

---

* email: Lavric.Vasile@gmail.com

the winner due to their faster growth rate. Consequently, the nitrification efficiency is reduced in most cases [19].

The recycle ratio, α, defined as the ratio between recycle and feeding flows (Q_{rs}/Q_{in}), is a very important parameter, which controls substantially the overall performance of the biological treatment for any substrate, whatever the pending kinetics [20-23]. It affects the microbial ecology, hydraulic regime and characteristics of the operating system by directly influencing the biological system. The effects of recycle on the whole process are difficult to specify beforehand and can be attributed to different time scales (growing characteristics) of the implied species apart from the operational factors. Recycle of treated wastewater which mixes with the influent wastewater provides a method of balancing the hydraulic loading with the carbon loading. A partial effluent recycle increases the reactor performance too. The net effect could be an increase in the efficiency of substrate removal [24].

The purge ratio, β, defined as the ratio between purge and feeding flows (Q_p/Q_{in}), plays a key role in shaping dead cells and overall mass accumulation in the system. Removing a certain amount of sludge doesn't allow the buildup of the particulate materials of any kind, thus lowering the concentration of dead cells and inert solids.

The mathematical model

Various mathematical models for biological wastewater treatment processes have been developed by the International Association on Water Quality (IAWQ), many belonging to the class of activated sludge models (ASM). The first, ASM1, considered as reference for design and assessment of advanced control strategies, includes the carbon oxidation (organic matter consumption) by both heterotrophs and autotrophs, nitrification (ammonia oxidation to nitrite and subsequently to nitrate) and denitrification (nitrate transformation till nitrogen gas) [25].

ASM3 is an extended improved version of ASM1, including the storage of organic substrates as a new process. The lysis process is replaced by an endogenous respiration process [26]. Complete nitrogen removal involves nitrification and denitrification. Nitrite and nitrate produced from nitrification are reduced to gaseous nitrogen by denitrifiers. For ASM3 models nitrification is a single-step process, considering the nitrite as a short-lived intermediate which is easily oxidized to nitrate. However, there are situations where considerable nitrite concentrations may build-up in the system, which requires a two-step nitrification for separate modeling of nitrite and nitrate fate. Such a model is ASM3-2N [1], which will be used subsequently in the overall model of the biological treatment facility. The autotrophic biomass is split into ammonium-oxidizers (Nitrosomonas - AOBs), for the first step of nitrification, and nitrite-oxidizers (*Nitrobacter - NOBs*), for the second step:

Nitrification first step (ammonia oxidation)

$$NH_4^+ + \frac{3}{2}O_2 \xrightarrow{\text{Ammonium oxidizers}} NO_2^- + 2H^+ + H_2O + 66\text{ kcal} \qquad (1)$$

Nitrification second step (nitrite oxidation - ammonia behaves as an inhibitor)

$$NO_2^- + \frac{1}{2}O_2 \xrightarrow{\text{Nitrite oxidizers}} NO_3^- + 18\text{ kcal} \qquad (2)$$

Considering nitrite into ASM3-2N also requires the separate knowledge of the kinetics of ammonia- and nitrite-oxidizing bacteria together with the decay rates of autotrophs, in order to reliably modeling nitrification [27].

The slowly biodegradable substrate in wastewater is first hydrolyzed to readily biodegradable substrate by the heterotrophs. The biomass can use it for simultaneous storage and growth. When the readily biodegradable substrate is depleted (as low as the half saturation concentration for the primary growth [28], the degradation (secondary growth) of the storage polymers takes place [29]. The intracellular storage polymers are taken into consideration, because these components are of a high importance to microbial metabolism, effluent quality, and process dynamics [30].

Denitrification is done by the facultative anaerobe biomass (heterotrophs) that can remove organic carbon through anoxic respiration on nitrite or nitrate, which both serve as electron acceptors in the absence of dissolved oxygen.

Anoxic growth (denitrification) on nitrate:

$$\frac{1}{5}NO_3^- + \frac{6}{5}H^+ + e^- \xrightarrow{\text{Heterotrphs}} \frac{1}{10}N_2 + \frac{3}{5}H_2O \qquad (3)$$

Anoxic growth (denitrification) on nitrite:

$$\frac{1}{3}NO_2^- + \frac{4}{3}H^+ + e^- \xrightarrow{\text{Heterotrophs}} \frac{1}{6}N_2 + \frac{2}{3}H_2O \qquad (4)$$

The process generally occurs in two steps: the biological degradation of pollutants, taking place in a series of two biological reactors (the volume of the anoxic tank is 2000 m^3 while the volume of the aerobic tank is 4000 m^3), followed by the separation of the activated sludge in a settling unit (or clarifier), in which the solids settle to the bottom of the unit [31]. Activated sludge, along with mixed liquor, is recycled from the bottom of the clarifier into the anoxic bioreactor. The sketch of the system is given in figure 1, together with the pending notations.

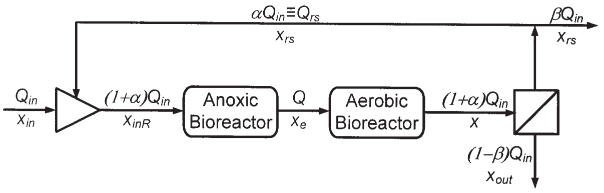

Fig. 1. The sketch of the system, with the main notations

The state variables of the system (table 1) are divided into two categories; soluble components, whose concentrations are denoted by S, assumed to be transported by water, and particulate components, whose concentrations are denoted by X, assumed to be associated with the activated sludge concentrated in the settling tank. According to the ASM general philosophy, the unstructured COD is split into the required partitions [32]: 13% of inert soluble COD (SI), 22% of readily biodegradable COD (SS), 11% of inert particulate COD (XI) and 54% of slowly degradable COD (XS).

The mathematical model is given by the overall and partial mass balances together with the appropriate expressions for the kinetic of different biological processes associated with the degradation of the pollutants.

Assuming perfect mixing, the partial mass balance for the first tank in series, the anoxic bioreactor, reads:

$$\frac{d\overline{x}_e}{dt} = \frac{Q_{in}\cdot\overline{x}_{in} + Q_{rs}\cdot\overline{x}_{rs} - \left(Q_{in} + Q_{rs}\right)\cdot\overline{x}_e}{V_{an}} + \overline{v} \qquad (5)$$

where,

- the vectors x_{in}, x_{rs}, x_e denote the concentrations (kg/m^3) in the influent, Q_{in}, in the recycled sludge, Q_{rs}, and in

Table 1

NOTATIONS USED FOR THE STATE VARIABLES DESCRIBING THE BEHAVIOUR OF THE WHOLE SYSTEM

State variables			M.U.
1	**SO_2**	Dissolved Oxygen	g O_2 / m^3
2	**SS**	Readily biodegradable substrates	g COD / m^3
3	**SN_2g**	Dinitrogen released by denitrification	g N / m^3
4	**SNH_4**	Ammonium	g N / m^3
5	**SNO_2**	Nitrite nitrogen	g N / m^3
6	**SNO_3**	Nitrate nitrogen	g N / m^3
7	**SI**	Soluble inert organics	g COD / m^3
8	**SALK**	Alkalinity	Mol HCO_3^- / m^3
9	**XI**	Inert particulate organics	g COD / m^3
10	**XS**	Slowly biodegradable substrates	g COD / m^3
11	**XH**	Heterotrophic biomass	g COD / m^3
12	**XSTO**	Organics stored by heterotrophs	g COD / m^3
13	**Xns**	Nitrite-oxidizing autotrophs	g COD / m^3
14	**Xnb**	Ammonia-oxidizing autotrophs	g COD / m^3

outlet, $Q_{in}+Q_{rs}$ flows (*m^3/s*) respectively. Their components are: *SO_2, SS, SN_2, SNH_4, SNO_2, SNO_3, SI, SALK, XI, XS, XH, XSTO, Xns, Xnb* (table 1 for details);

- $\overline{v}$ is the vector formed by the reaction rates of each component, kg/m^3 . s

$v_i = \sum_j c_{ji} \cdot \rho_j$, where c_{ji} where c_{ji} is the stoichiometric coefficient of *i^{th}* component in *j^{th}* reaction, according to the stoichiometric matrix from table 2, while ρ_j is the kinetic rate of *j^{th}* reaction, *kg/m^3·s*, as given in t table 3.

- V_{an} is the volume of the anoxic bioreactor (m^3).

The partial mass balance for the second tank in series, the aerobic bioreactor, reads:

$$\frac{d\overline{x}}{dt} = \frac{\overline{x}_e - \overline{x}}{\tau_{ar}} + \overline{v} \tag{6}$$

In equation (6) the notations are the same as in the previous mass balance equation, except for τ_{ar}, which is the residence time, V_{ar} / (Q_{in}+Q_{rs}) of the aerobic bioreactor. In the aeration tank the mass balance for oxygen has an additional term which describes the oxygen mass transfer from the air bubbles fed through the diffusers, kg/m^3 day beside its consumption rate due to the biological process:

$$K_L a \cdot \left(SO2^{sat} - SO2 \right) \tag{7}$$

In equation (7), the notations are:

$K_L a$ - oxygen mass transfer coefficient, *d^{-1}*

SO_2^{sat-} - the saturation concentration of oxygen in the liquid phase, kg/m^3

SO_2- the liquid oxygen concentration, kg/m^3.

The influence of the recycling parameters, α and β, upon the concentrations of the soluble and insoluble species in the inlet of the reactor x_{inR} is expressed in the following equations:

$$\overline{x}_{inR} = \frac{\overline{x}_{in} + \alpha \cdot \overline{x}}{1+\alpha} \tag{8}$$

for the soluble items, and

$$\overline{x}_{inR} = \frac{\alpha \cdot \overline{x}}{\alpha+\beta} + \frac{\overline{x}_{in}}{1+\alpha} \tag{9}$$

for the insoluble species, respectively. In both cases, the dependency upon the system feed is the same, while that upon the recycled concentrations differs because of the effect induced by the presence of the separation unit.

Performance criteria

In order to measure the fitness of the process to the rapid change of the influent, two types of performance criteria were envisaged: an averaging one – the cumulative conversion, taking into account the whole history of the system and an immediate one – the instant conversion, which measures the instantaneous behavior of the system, showing if, for this given particular conditions at this instant of time, a failure appears or not.

The cumulative conversion is defined as the ratio between the amount of species P transformed due to the biological process from the beginning of the time window till present and the amount of species P fed into the system during the same interval:

$$\overline{X} = 1 - \frac{(1-\beta)\int_0^t Q_{in}(t) P_{out}(t)\,dt + \beta \int_0^t Q_{in}(t) P_p(t)\,dt}{\int_0^t Q_{in}(t) P_{in}(t)\,dt} \tag{10}$$

In equation (10), P_{in} stands for the species concentration at inlet, P_{out} stands for the species concentration at outlet, while P_p stands for the species concentration at purge (fig. 1 for the sketch of the system).

The *inst*ant conversion is defined as the ratio between the amount of species P transformed at the moment t and the amount of species P fed into the system at the same time:

$$X_P = 1 - \frac{(1-\beta) P_{out}(t) + \beta P_p(t)}{P_{in}(t)} \tag{11}$$

It must be emphasized that the main difference between the instant and the overall conversions is that the former measure the performance of the system regardless of the load still existing in it, while the latter takes this into account. In other words, there could be cases in which the overall conversion is higher than the instant one, meaning that there is an ongoing accumulation of the *P* species in

Tabel 2

STOICHIOMETRIC MATRIX OF THE ASM3-2N MODEL [1]

V P	S_{O_2}	S_S	S_{N_2}	S_{NH_4}	S_{NO_2}	S_{NO_3}	S_I	S_{ALK}	X_I	X_S	X_H	X_{STO}	X_{ns}	X_{nb}
1	-	$1-f_{SI}$	-	$-i_{NSS}(1-f_{SI})$ $-(f_{SI}i_{NSI})+i_{NXS}$	-	-	f_{SI}	$\frac{1}{14}\left[\begin{matrix}i_{NXS}-i_{NSS}(1-f_{SI})\\-(f_{SI}i_{NSI})\end{matrix}\right]$	-	-1	-	-	-	-
2	$\frac{1}{Y_{STO,O_2}}$	-1	-	i_{NSS}	-	-	-	$\frac{i_{NSS}}{14}$	-	-	-	Y_{STO,O_2}	-	-
3	-	-1	$\frac{(1-Y_{STO,NO_X})}{2.86}$	i_{NSS}	-	$\frac{\frac{1}{Y_{STO,NO_X}}}{2.86}$	-	$\frac{i_{NSS}+\frac{1-Y_{STO,NO_X}}{2.86}}{14}$	-	-	-	Y_{STO,NO_X}	-	-
4	$1-\frac{1}{Y_{H_2O}}$	-	-	$-i_{NBM}$	-	-	-	$\frac{i_{NBM}}{14}$	-	-	1	$-\frac{1}{Y_{H,O_2}}$	-	-
5	-	-	$\frac{\frac{1}{Y_{H,NO_X}}-1}{1.71}$	$-i_{NBM}$	$\frac{1-\frac{1}{Y_{H.NO_X}}}{1.71}$	-	-	$\frac{-i_{NBM}+\frac{1-Y_{H.NO_X}}{1.71}}{14}$	-	-	1	$-\frac{1}{Y_{H,NO_X}}$	-	-
6	-	-	$\frac{\frac{1}{Y_{H,NO_X}}-1}{2.86}$	$-i_{NBM}$	-	$\frac{1-\frac{1}{Y_{H,NO_X}}}{2.86}$	-	$\frac{-i_{NBM}+\frac{1-Y_{H,NO_X}}{2.86}}{14}$	-	-	1	$-\frac{1}{Y_{H,NO_X}}$	-	-
7	$\frac{1}{f_{XI}}$	-	-	$i_{NBM}-f_{XI}i_{NXI}$	-	-	-	$\frac{i_{NBM}-f_{XI}i_{NXI}}{14}$	f_{XI}	-	-1	-	-	-
8	-	-	$\frac{1-f_{XI}}{2.86}$	$i_{NBM}-f_{XI}i_{NXI}$	-	$\frac{f_{XI}-1}{2.86}$	-	$\frac{(i_{NBM}-f_{XI}i_{NXI})+\frac{1-f_{XI}}{2.86}}{14}$	f_{XI}	-	-1	-	-	-
9	-1	-	-	-	-		-	-	-	-	-	-1	-	-
10	-	-	$\frac{1}{2.86}$	-	-	$-\frac{1}{2.86}$	-	$\frac{1}{2.86\cdot 14}$	-	-	-	-1	-	-
11	$1-\frac{3.43}{Y_{ns}}$	-	-	$-\frac{1}{y_{ns}}-i_{NBM}$	$\frac{1}{Y_{ns}}$	-	-	$\frac{\frac{-1}{7Y_{ns}}-i_{NBM}}{14}$	-	-	-	-	1	-
12	$1-\frac{1.14}{Y_{nb}}$	-	-	$-i_{NBM}$	$-\frac{1}{Y_{nb}}$	$\frac{1}{Y_{nb}}$	-	$-\frac{i_{NBM}}{14}$	-	-	-	-	-	1
13	$\frac{1}{f_{XI}}$	-	-	$i_{NBM}-f_{XI}i_{NXI}$	-	-	-	$\frac{i_{NBM}-f_{XI}i_{NXI}}{14}$	f_{XI}	-	-	-	-1	-
14	$\frac{1}{f_{XI}}$	-	-	$i_{NBM}-f_{XI}i_{NXI}$	-	-	-	$\frac{i_{NBM}-f_{XI}i_{NXI}}{14}$	f_{XI}	-	-	-	-	-1
15	-	-	$\frac{1-f_{XI}}{2.86}$	$i_{NBM}-f_{XI}i_{NXI}$	$\frac{1}{f_{XI}\cdot 2.86}$	-	-	$\frac{i_{NBM}-f_{XI}i_{NXI}+\frac{1-f_{XI}}{2.86}}{14}$	f_{XI}	-	-	-	-1	-
16	-	-	$\frac{1-f_{XI}}{2.86}$	$i_{NBM}-f_{XI}i_{NXI}$	-	$\frac{1}{f_{XI}\cdot 2.86}$	-	$\frac{i_{NBM}-f_{XI}i_{NXI}+\frac{1-f_{XI}}{2.86}}{14}$	f_{XI}	-	-	-	-	-1

V = variable; P = process

the system; conversely, when the overall conversion is smaller than the instant one, the system performs better than it did beforehand, consuming not only the *P* species fed into it, but also a part from the *P* species accumulated so far in the biological reactor. When the system reaches steady state, both conversions should have the same values.

In order to cover the whole spectrum of species this system has to deal with, three components were picked up to compute both criteria for: the readily biodegradable substrate (*SS*), the ammonia (NH_4^+) and the slowly biodegradable substrate (*XS*).

Results and discussions

The benchmark input files referred to as "dry weather", "stormy weather" and "rainy weather" and the process sizing reported in the aforementioned benchmark study (http://www.benchmarkwwtp.org) were used for the operating and initial conditions for an operational window of 14 days (fig. 2 for the variation of the incoming flow which has to be treated in the system). It should be noted that the same variation appears to any inlet concentrations, so the system is intrinsically in a dynamic state. The aeration of aerobic tank is achieved using such mixing and inlet air flowrate so the value of K_{La} is 15 h^{-1}, irrespective of the inflow conditions. This value is high enough so that the process would be on the safe side with respect to the oxygen supply for all situations. It was assumed that process developed at an average temperature of 20°C.

The simulation, based upon the aforementioned mathematical model, was implemented in MATLAB using ode15s integration routine for stiff differential equations.

In the system with recycling of mixed liquor we choose as control parameters the recycle fraction, α, and the purge fraction, β. The performance (cumulative and instant) of system for readily biodegradable substrates (*SS*), slowly biodegradable substrates (*XS*) and ammonium (NH_4^+) were analyzed for the lowest, the middle and highest values of recycle and purge fractions, that is the recycle fraction, α, was 0.1, 0.5 and 1.0, while for the purge fraction, β, was 0.001, 0.005 and 0.01. The first parameter influences the bioreactors' time scales, lowering it from the original values of V_{anox}/Q_{in} and V_{aero}/Q_{in} to the actual values of $V_{anox}/Q_{in}/$

Table 3
KINETIC RATES FOR THE ASM3-2N MODEL [1]

	Process	***Rate equation q_j , $q_j \geq 0$***
1	Hydrolysis	$K_H \cdot \frac{\frac{X_S}{X_H}}{K_X + \frac{X_S}{X_H}} \cdot X_H$
	Heterotrophic organisms, aerobic and denitrifying activity	
2	Aerobic storage of S_S	$K_{STO} \cdot \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_S}{K_S + S_S} \cdot X_H$
3	Anoxic storage of S_S	$K_{STO} \cdot \eta_{NOX} \cdot \frac{K_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{NO_2} + S_{NO_3}}{K_{NOX} + S_{NO_2} + S_{NO_3}} \cdot \frac{S_S}{K_S + S_S} \cdot X_H$
4	Aerobic growth	$\mu_H \cdot \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} \cdot \frac{S_{ALK}}{K_{ALK} + S_{ALK}} \cdot \frac{\frac{X_{STO}}{X_H}}{K_{STO} + \frac{X_{STO}}{X_H}} \cdot X_H$
5	Anoxic growth on nitrite (denitrification on S_{NO2})	$\mu_H \cdot \eta_{NOX} \cdot \frac{K_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{NO_2}}{K_{NO_2} + S_{NO_2}} \cdot \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} \cdot \frac{S_{ALK}}{K_{ALK} + S_{ALK}} \cdot \frac{\frac{X_{STO}}{X_H}}{K_{STO} + \frac{X_{STO}}{X_H}} \cdot X_H$
6	Anoxic growth on nitrate (denitrification on S_{NO3})	$\mu_H \cdot \eta_{NOX} \cdot \frac{K_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{NO_3}}{K_{NO_3} + S_{NO_3}} \cdot \frac{S_{NH_4}}{K_{NH_4} + S_{NH_4}} \cdot \frac{S_{ALK}}{K_{ALK} + S_{ALK}} \cdot \frac{\frac{X_{STO}}{X_H}}{K_{STO} + \frac{X_{STO}}{X_H}} \cdot X_H$
7	Aerobic endogenous respiration	$b_{H,O_2} \cdot \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \cdot X_H$
8	Anoxic endogenous respiration	$b_{H,NOX} \cdot \frac{K_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{NO_2} + S_{NO_3}}{K_{NO_X} + S_{NO_2} + S_{NO_3}} \cdot X_H$
9	Aerobic respiration (oxidation) of X_{STO}	$b_{STO,O_2} \cdot \frac{S_{O_2}}{K_{O_2} + S_{O_2}} \cdot X_{STO}$
10	Anoxic respiration (oxidation) of X_{STO}	$b_{STO,NOX} \cdot \frac{K_{O_2}}{K_{O_2} + S_{O_2}} \cdot \frac{S_{NO_2} + S_{NO_3}}{K_{NO_x} + S_{NO_2} + S_{NO_3}} \cdot X_{STO}$
	Autotrophic organisms, nitrifying activity	
11	Aerobic growth of autotrophs that oxidizing ammonium (*Nitrosomonas*)- nitrification	$\mu_{ns} \frac{S_{O_2}}{K_{A,O_2} + S_{O_2}} \frac{S_{NH_4}}{K_{A,NH_4} + S_{NH_4}} \frac{S_{ALK}}{K_{ALK} + S_{ALK}} \cdot X_{ns}$
12	Aerobic growth of autotrophs that oxidizing ammonium (*Nitrobacter*)- nitrification	$\mu_{nb} \frac{S_{O_2}}{K_{A,O_2} + S_{O_2}} \frac{K_{1,NH_4}}{K_{1,NH_4} + S_{NH_4}} \frac{S_{ALK}}{K_{ALK} + S_{ALK}} \frac{S_{NO_2}}{K_{NO_2} + S_{NO_2}} \cdot X_{nb}$
13	Aerobic endogenous respiration of X_{ns}	$b_{ns,O_2} \cdot \frac{S_{O_2}}{K_{A,O_2} + S_{O_2}} \cdot X_{ns}$
14	Aerobic endogenous respiration of X_{nb}	$b_{nb,O_2} \cdot \frac{S_{O_2}}{K_{A,O_2} + S_{O_2}} \cdot X_{nb}$
15	Anoxic endogenous respiration of X_{ns}	$b_{ns,NO_2} \cdot \frac{K_{A,O_2}}{K_{A,O_2} + S_{O_2}} \cdot \frac{S_{NO_2}}{K_{NO_2} + S_{NO_2}} \cdot X_{ns}$
16	Anoxic endogenous respiration of X_{nb}	$b_{nb,NO_3} \cdot \frac{K_{A,O_2}}{K_{A,O_2} + S_{O_2}} \cdot \frac{S_{NO_3}}{K_{NO_3} + S_{NO_3}} \cdot X_{nb}$

$(1+\alpha)$ and $V_{aero}/Q_{in}/(1+\alpha)$. As the recycle fraction gets higher, the time scale of the bioreactors gets lower, meaning less and less time for the biological process to complete its task. The second parameter has a more subtle but still decisive influence, this time upon the time scale of the biological process, since it is responsible not only for the live vs. dead microorganisms ratio, but for their concentrations as well. As the purge fraction gets lower, living and dead cells concentration gets higher (they accumulate in the system) to values in equilibrium with the bioreactor's substrate concentration. This latter determines the biological process rate and, thus, the doubling time, which is the time scale of the biological process. Keeping the substrate concentration in the feed the same, when the cells concentration increases, the substrate concentration in the bioreactor decreases thus the doubling time increases.

One of the objectives of the present study is to emphasize which of the two control parameters has greater influence upon the process. Because of their complex behavior, activated sludge processes are very difficult to control, due to the composite interactions among species, on one hand, and to different time scales, on the other.

Irrespective of the weather, the first eight days are the same, with respect to the incoming flow (fig. 2). The next three days the incoming flow changes according to the weather type changing decisively the further evolution of the system; thus a particular attention will be addressed to the last six days, in order to see how the time scales of the biological process and of the bioreactors cope with this rupture in the confined dynamics of the system. We will consider, during this analysis, an ideal situation where the

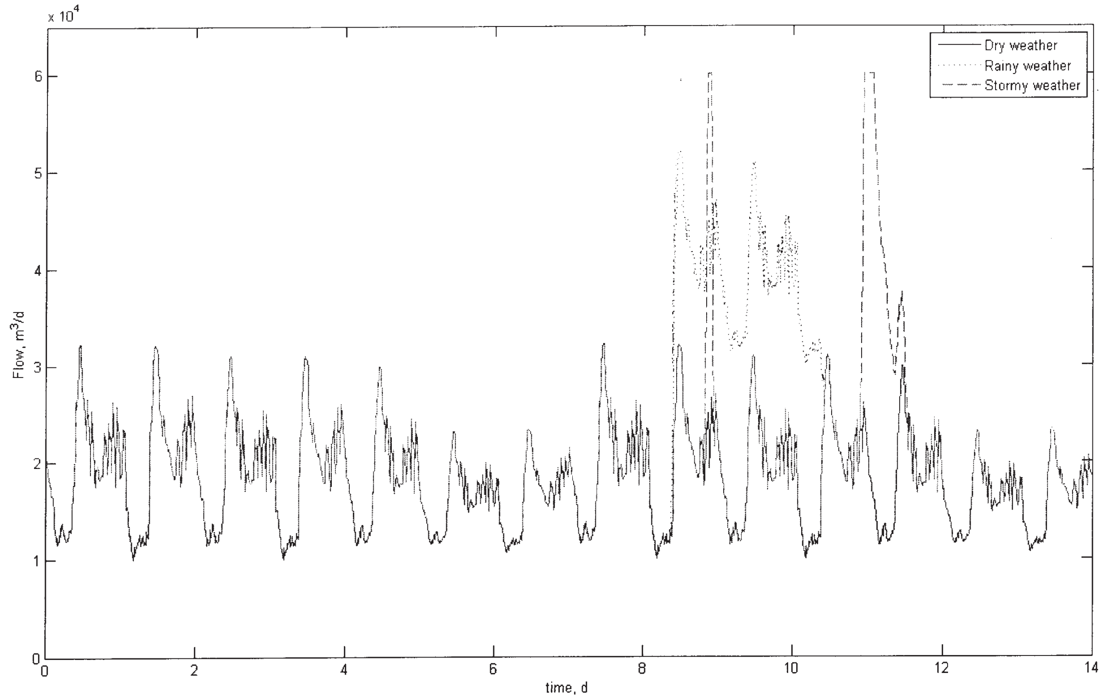

Fig. 2. The inflow characteristics for the benchmark, corresponding to the dry, rainy and stormy weather

recycling and purge flows will be, continuously, adapted to the actual values – the question of "how the system would respond if the recycle and the purge would have been fixed" will be addressed in another study. Another simplifying assumption is the biological process shifts instantaneously according to the external substrate concentrations, no adaptation lag being taken into consideration.

According to figure 2, the system is forced into a dynamic state; the crucial problem at hand is "could the system fail?" and, if so, "when and for what combination of operating parameters?" In subsidiary, there is another question: "does the system reach a steady state for the average values of the inflow conditions?"

We consider the following time averaging formula as a convenient relationship:

$$y_{ave} = \frac{\int_0^{t_f} y(t)\cdot dt}{t_f} \qquad (12)$$

Applying equation (12) for the "dry weather" conditions (since the other two are exceptions, they cannot be considered as candidates to establish the average conditions), the calculated common values for the considered period are: Q_{in}=18445 m^3/day, COD_{in}=398.72 g/m^{3}and NH_{4in}=31.556 g/m^3. With this constant input and for α=0.5 and β=0.005 (chosen as the middle values of the proposed ranges), the system reached a steady state characterized by the following conversions: of the readily biodegradable substrates (*SS*) X_{SS} = 0.999 of the slowly biodegradable substrates (*XS*) X_{XS}=0.065 and of the ammonium (NH_4^+)X_{SNH4}=0.983. The rest of the steady state values are presented in table 4.

The cumulative and instant performance criteria of the system converged rapidly to the same value, characteristic for the steady state. Due to the cascade system adopted for the two reactors (anoxic and aerobic), the values of the parameters corresponding to steady state do not differ as much as expected, although for the most sensitive the differences are conclusive (table 4). While the system performs excellent for the readily biodegradable substrates and the ammonium, consuming them almost entirely, the conversion of the slowly biodegradable substrates is very low. This means that a large part is disposed to the environment.

An interesting development would be to study the behaviour of a slightly changed system, with a settler and recycling after each reactor, which would permit to the activated sludge from each reactor to adapt itself better to its particular operating conditions, but this is left for another study.

In figure 3, we present the time behaviour of the readily biodegradable substrates for the three weather conditions under three different pairs of parameters α and β: middle, lowest and highest. The system is in a confined dynamic, meaning that its performance varies according to the inlet changes between some finite boundaries; both conversions are high, slightly under the pseudo-steady state performance obtained with the averaged inlet data (fig. 3A, dry case). The ascending trend of the conversions is due to the slowly increase in heterotrophs concentration, which increases the total amount of readily biodegradable substrate processed. This has as effect higher instant conversions than cumulative ones for the last part of the time window. For the rainy case, there is a significant drop in performance starting from the eighth day, due to the increase in the influent, which increases the recycled flow and the purge flow. This affects negatively the process, reducing the time scale of the biological reactor. More, the increase in both throughput and purge flows diminishes the concentration of the biomass in the bioreactors, thus decreasing the amount of processed substrates. After the shock ends, the instant conversion regains its behavior (fig. 3A, dry and rainy cases after the tenth day), although with a slight delay. The same is valid for the cumulative conversion, but due to the substrate accumulations in the system, it has lower values for the same time window. The stormy case is characterized by two sudden increases of inlet flows, much larger than in the rainy case, but for shorter periods (fig. 3A, stormy case). Consequently, the system behaves badly during these periods, worse that in the previous case, but it recovers faster, due to the less accumulation of substrates in the biological reactors this time.

Table 4
THE STEADY STATE VALUES OF THE STATE VARIABLES FOR THE TWO BIOREACTORS CORRESPONDING TO THE PSEUDO-INLET CONDITIONS RESULTED FROM AVERAGING THE DRY WEATHER BENCHMARK INPUT

Parameter	Values, g/m^3	
	anoxic	aerobic
organic substrate easy biodegradable, SS	8.79	0.08
soluble inert organic materials, SI	48.1	
slowly biodegradable substrate, XS	255.95	201.34
particulate inert material, XI	4296.1	
ammonium nitrogen, NH_4	23.92	0.54
gaseous organic nitrogen, N_2	8.57	
nitrite, NO_2	0.02	0.11
nitrate, NO_3	7.26	29.75
dissolved oxygen, O_2	1.57	4.7
HET (heterotrophs)	4406	4449
AOB (*Nitrosomonas*)	135.6	137
NOB (*Nitrobacter*)	181.6	183.6

Working at very low recycling and purge ratios affects slightly the behavior of the system, decreasing the overall performance. But, since the heterotrophs concentration is high enough, the conversion varies between almost the same values (fig. 3B, dry case – see the overall performance, compared to the previous case). The shocks induced by the weather change (rainy or stormy – fig. 3B) is a little bit higher, but still the conversions are very good,

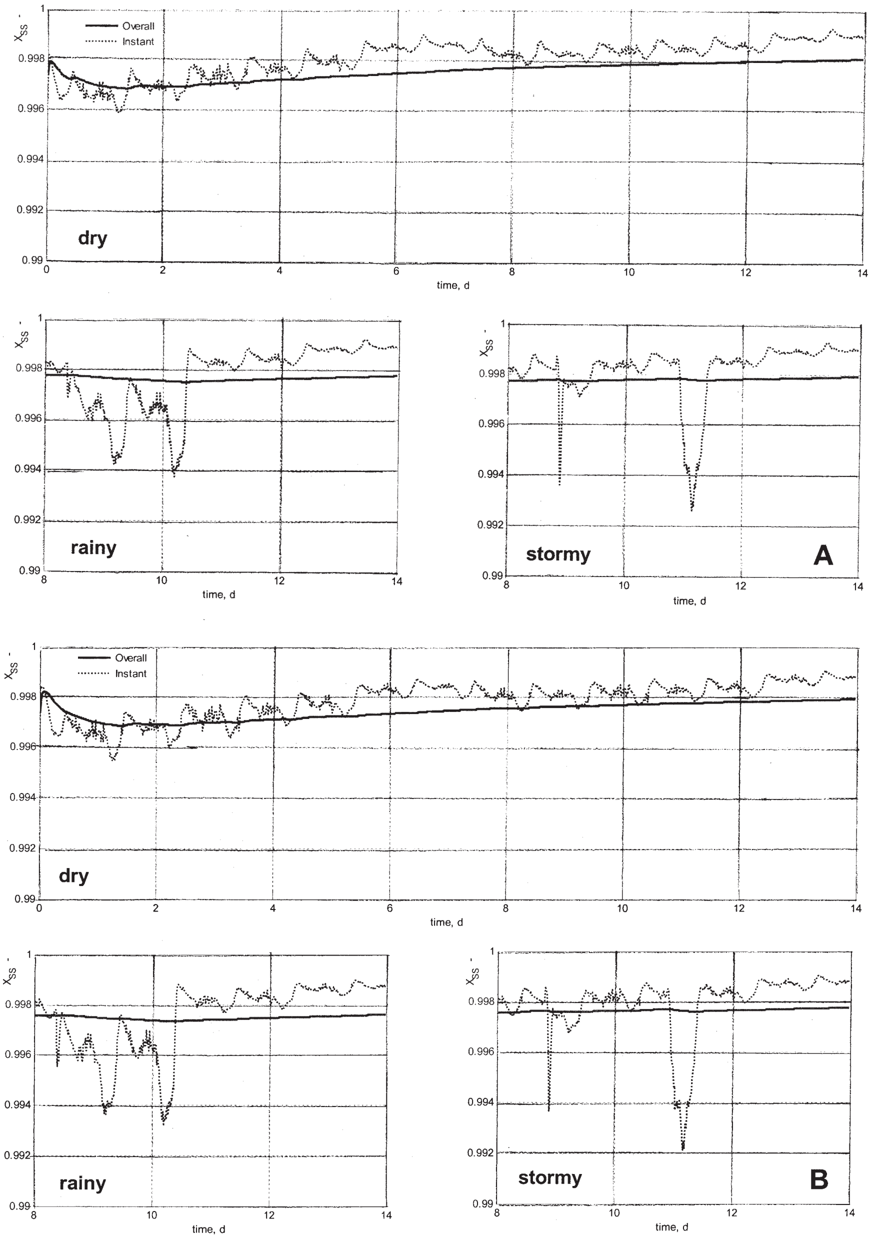

Fig. 3AB. Performance of readily biodegradable substrates, expressed as cumulative and instant conversions, for different time scales and weather conditions A) base case of α=0.5 and β=0.005; B) lowest operating parameters values of α=0.1 and β=0.001;

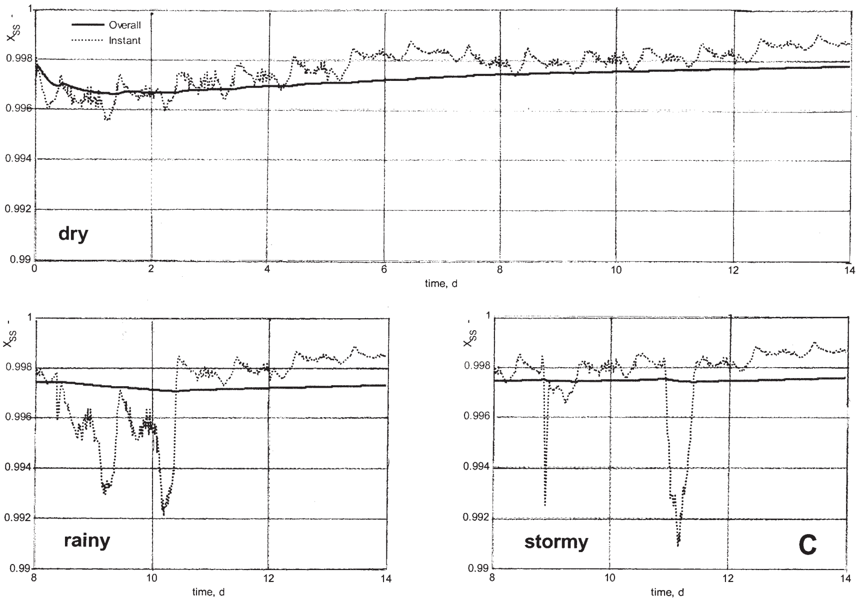

Fig. 3C. Performance of readily biodegradable substrates, expressed as cumulative and instant conversions, for different time scales and weather conditions C) highest operating parameters values of $\alpha=1.0$ and $\beta=0.01$

meaning that the system performs well even with these values of α and β.

Increasing both ratios to their maximum values worsens the behaviour of the system, but not to a great extent (fig. 3C, dry, rainy and stormy profiles, compared to the base case profiles). Working at high values of the recycle ratios decreases the time scale of the bioreactor significantly, especially when shocks arrive (see the overall and instant conversions for the rainy and stormy periods – fig. 3C). On the other hand, higher values for the purge ratio decrease the concentration of the living cells, which are withdrawn from the system through the purge. This way, the processed amount of soluble substrates diminishes although their concentrations remain the same (the purge fraction affects only the concentration of the suspended particles, like microorganisms or any other solids which are present in the system).

A similar behaviour of the system could be seen with respect to the slowly biodegradable substrate consumption, as depicted in figure 4, where the profiles of its conversion are presented, for all three aforementioned scenarios. Even for the virtual steady state conditions expressed as the averaged values for the inlet variables, the system in its actual configuration well behaved , ensuring a high conversion, of 0.98. Actually, this means that almost all the slowly biodegradable substrate entering the system , defined as the sum of fragments of heterotrophic biomass resulting from decay by endogenous respiration, and slowly hydrolysible substrate, was transformed, a small amount was removed by purge. For any of the confined dynamics scenarios (dry, rainy or stormy weather), the cumulative conversion has positive values for the whole time window. Nonetheless, working at the lowest possible values for α and β seems beneficial, the cumulative conversion of the

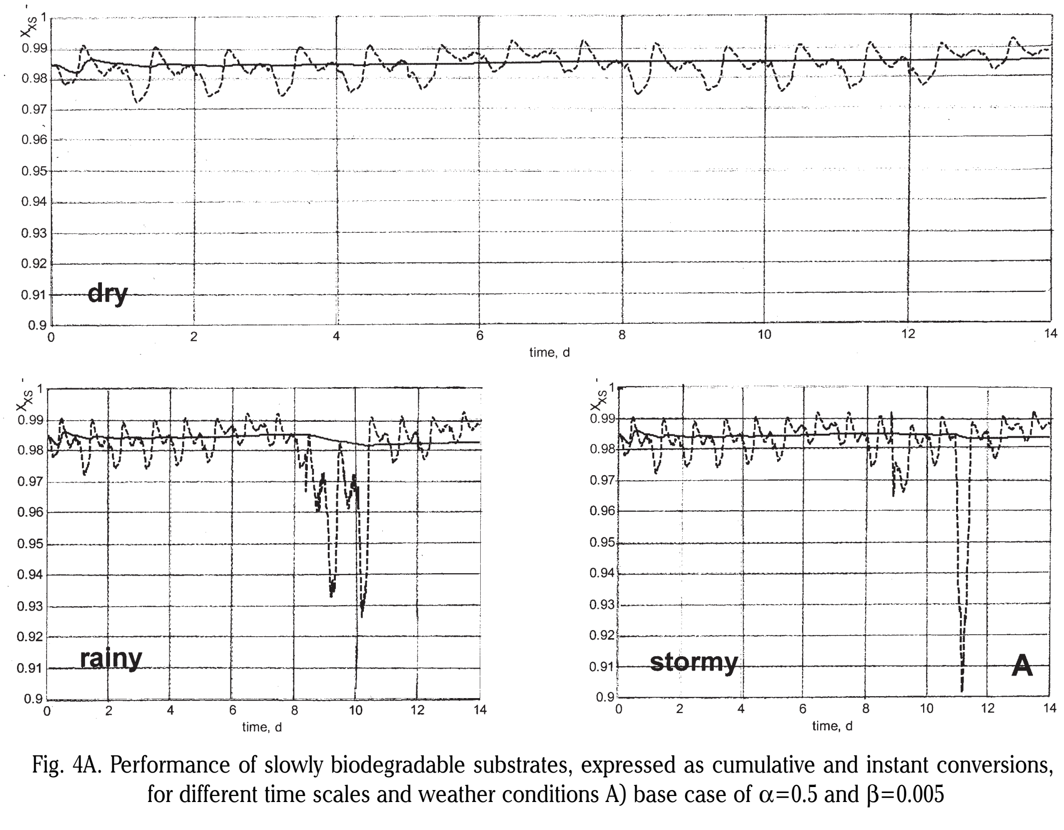

Fig. 4A. Performance of slowly biodegradable substrates, expressed as cumulative and instant conversions, for different time scales and weather conditions A) base case of $\alpha=0.5$ and $\beta=0.005$

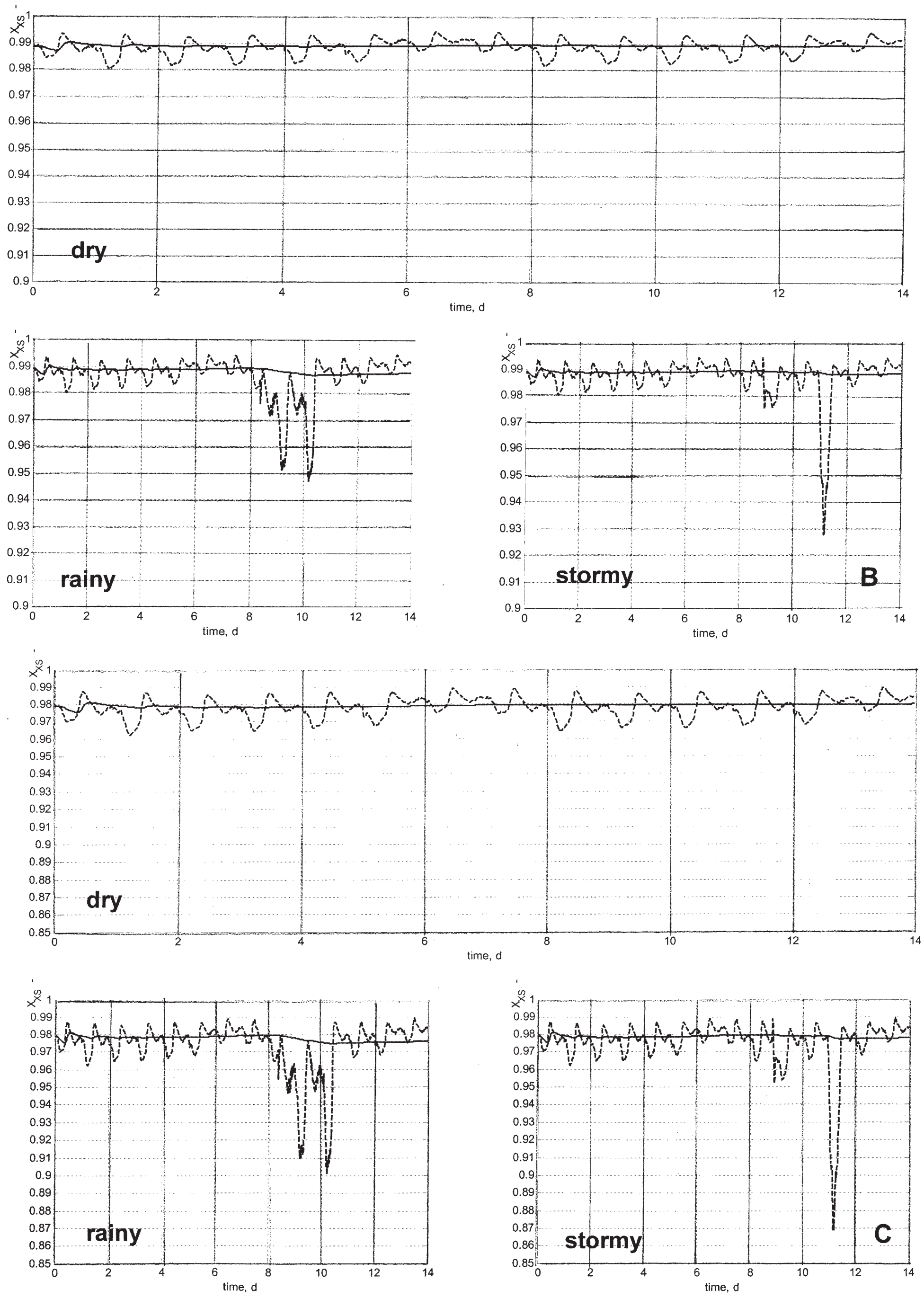

Fig. 4BC. Performance of slowly biodegradable substrates, expressed as cumulative and instant conversions, for different time scales and weather conditions B) lowest operating parameters values of $\alpha=0.1$ and $\beta=0.001$; C) highest operating parameters values of $\alpha=1.0$ and $\beta=0.01$

slowly biodegradable substrate has most values, 0.99. At these low values of the operating parameters, the time scale of the bioreactors is the highest and so is the concentration of the microorganisms responsible for the consumption of the slowly biodegradable substrate. Thus, the microorganisms, which are in a higher concentration, have a longer time to process this substrate, which increases its conversion (fig. 4B). For the highest values of the operating parameters α and β (fig. 4C), the system behaves worst; the time scale of the bioreactors decreases dramatically diminishing the time the microorganisms act upon the substrate, and so does their concentration. Less substrate processed is a consequence of a smaller amount of bacteria, despite the slight increase in the process rate due to the raise in the concentration of this substrate.

The behavior of the system, with respect to the ammonium, is presented in figure 5 for all the operating conditions at hand (A – dry weather, B – rainy weather and C – stormy weather). The system behaves worse than for the previous substrates (readly biodegradable substrate and slowly biodegradable substrate), although the confined dynamics has as inferior margin 0.75 which could be seen acceptable for such daily fluctuations of the inlet flow and concentrations. Although the steady state conversion of the system subject to the averaged inlet conditions is rather close to the conversion of the readily biodegradable substrates, the amplitude of the variations are higher since the class of the microorganisms responsible or ammonium conversion is different, namely AOBs. These microorganisms have a much lower concentration in the system, so a comparable percentage of their variation compared to the heterotrophs would imply a more pronounced effect upon the quantity of the processed substrate than for heterotrophs. That is why keeping a high concentration of AOBs and a longer residence time (lowest values for α and β) is beneficial (fig. 5B), while the highest values for these operating parameters have detrimental effects (fig. 5C). The changes in the weather conditions only increase the lower spikes for the instant conversion (fig. 5, the first three days period corresponding to the rainy

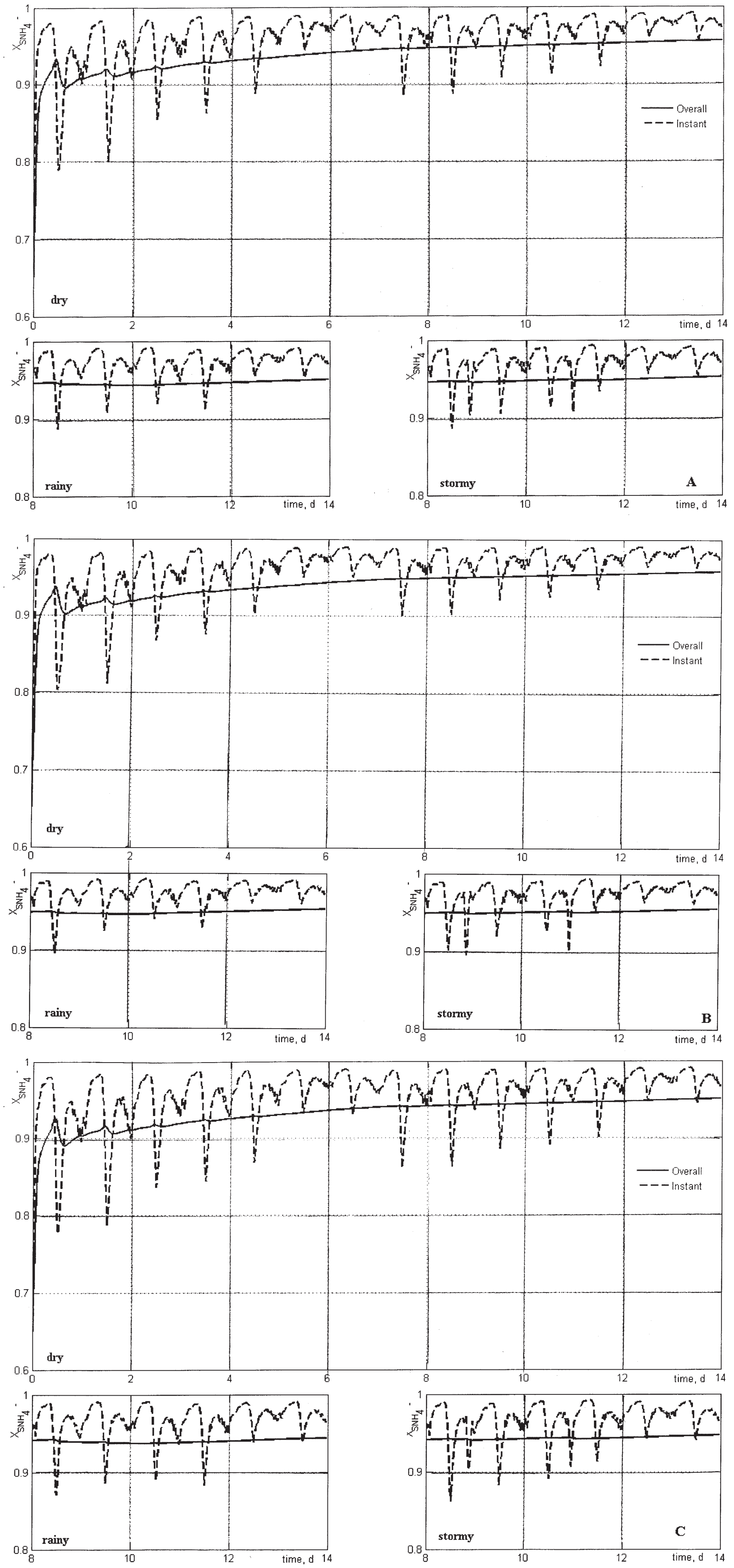

Fig. 5. Performance of ammonium substrate, expressed as cumulative and instant conversions, for different time scales and weather conditions A) base case of $\alpha=0.5$ and $\beta=0.005$; B) lowest operating parameters values of $\alpha=0.1$ and $\beta=0.001$; C) highest operating parameters values of $\alpha=1.0$ and $\beta=0.01$

and stormy weather respectively), consequently affecting the cumulative conversion too.

Analyzing the profiles presented in figures 3-5, we observe that except the three days period when the weather changed in the rainy and stormy periods, it is rather difficult to seize the differences between them for the last three days, even if it is obvious that they exist. Measuring the distance between the perturbed trajectory of a process

Table 5a
THE GENERATED ENTROPIES OF THE PERTURBED TRAJECTORIES, AS RESULTED FROM THE WEATHER CHANGE, FOR THE SAME VALUES OF THE OPERATING PARAMETERS α AND β (C STANDS FOR CUMULATIVE

		Dry-Rainy			Dry-Stormy		
		X_{SS}	X_{XS}	X_{NH_4}	X_{SS}	X_{XS}	X_{NH_4}
$\alpha = 0.5$ $\beta = 0.005$	C	0.088	0.187	0.006	0.033	0.082	0.003
	I	0.038	0.031	0.002	0.017	0.015	0.002
$\alpha = 0.1$ $\beta = 0.001$	C	0.078	0.191	0.005	0.03	0.081	0.003
	I	0.039	0.031	0.002	0.017	0.015	0.002
$\alpha = 1.0$ $\beta = 0.01$	C	0.119	0.184	0.007	0.043	0.082	0.003
	I	0.038	0.03	0.004	0.017	0.014	0.001

Table 5b
THE GENERATED ENTROPIES OF THE PERTURBED TRAJECTORIES, AS RESULTED FROM THE OPERATING PARAMETERS α AND β CHANGE, FOR THE SAME WEATHER CONDITIONS (C STANDS FOR CUMULATIVE CONVERSION, I STANDS FOR INSTANT CONVERSION)

		Dry		
		X_{SS}	X_{XS}	X_{NH_4}
$\alpha = 0.5, \beta = 0.005$ $\alpha = 0.1, \beta = 0.001$	C	0.051	0.108	0.003
	I	0.051	0.023	0.003
$\alpha = 0.5, \beta = 0.005$ $\alpha = 1.0, \beta = 0.01$	C	0.145	0.078	0.006
	I	0.072	0.016	0.005
		Rainy		
$\alpha = 0.5, \beta = 0.005$ $\alpha = 0.1, \beta = 0.001$	C	0.049	0.095	0.003
	I	0.014	0.007	0.003
$\alpha = 0.5, \beta = 0.005$ $\alpha = 1.0, \beta = 0.01$	C	0.168	0.067	0.008
	I	0.028	0.005	0.005
		Stormy		
$\alpha = 0.5, \beta = 0.005$ $\alpha = 0.1, \beta = 0.001$	C	0.05	0.108	0.003
	I	0.029	0.004	0.005
$\alpha = 0.5, \beta = 0.005$ $\alpha = 1.0, \beta = 0.01$	C	0.16	0.078	0.007
	I	0.016	0.003	0.005

and the nominal one is not trivial, since the process could behave differently immediately after the perturbation occurred or after a rather long period. To quantitatively characterize the departure of the state trajectory given by any kind of perturbations from the original, non-perturbed one, we will use an intensive measure, derived from the notion of Shannon entropy, the generated entropy of a perturbed trajectory, as defined in [33,34]. Since in the present analysis the accent is made more upon the existence and magnitude of the variations and less upon the direction of them, this measure is a reliable measuring tool. The sensitivity of the bioreactor to some parameter should imply larger generated entropies for some if not all the state variables, for small changes in the former. When more than one parameter has to be analyzed simultaneously, care should be taken to adequately decouple their mutual influence upon the process.

Applying the relationship presented in [33,34], we obtained the values of the generated entropy of the perturbed trajectory for the aforementioned cases, which are summarized in Table 5a and b. Analyzing the figures from table 5, we observe that we can express in a quantitative manner the observations made so far for the influence of the operating parameters α and β upon the process, coupled with weather changes. According to the type of substrate under scrutiny, lowering α and β could be beneficial or detrimental. For example, the generated entropy for the cumulative conversion of the readily biodegradable substrates, X_{SS}, is high for the highest values of the operating parameters and low for the lowest values, irrespective of the weather change (table 5a, S column, for both Dry-Rainy and Dry-Stormy cases). This means that the system has the tendency of amplifying any departure from the normal confined dynamics. The same is true for the ammonium substrate, although the figures are one order of magnitude lower, which is in agreement with the concentrations of the responsible species (table 5a, N column, for both Dry-Rainy and Dry-Stormy cases together with table 4, HET and AOB concentrations). The highest effect of weather change, although in the opposite direction, is for the slowly biodegradable substrates, X_{XS}, where the generated entropy is almost double than for the readily biodegradable substrates (table 5a, X column).

The influence of the operating parameters change upon the process is affected by the weather conditions, as can be seen from table 5b. For the dry period, which is considered as the base case in this study, as the system works at higher values of the operating parameters, it will be more affected by any of their change (table 5b) for the reasons aforementioned, proper to each type of substrate.

Conclusions

The study at hand presents the time scale behaviour of a wastewater treatment facility subject to environmental stress, such as weather changes. Two of the time scales are addressed here, the residence time of the biological reactors (aerobic and anoxic) which is mainly influenced by the recycling ratio α, and the doubling time of the biological process, corroborated with the concentration of the microorganisms, which is mainly influenced by the purge fraction β. In order to quantitatively measure the performance of the system, two types of conversions were used, a cumulative one, as introduced by equation (10), and an instant one, equation (11). The former, being of integral type, stands for the average processing performance of the system, considering its time-history as captured by the time window under scrutiny, while the latter gives the actual performance, with respect to the inlet and outlet. While the former is valuable for describing the long term performances, the latter shows when and to what extent the system fails punctually and harms the environment. To quantify the time scale influences upon the system, generated entropy of a perturbed trajectory concept was used, not only showing that lower time-scales are detrimental for slowly degradable substrates, but also to what extent.

Notations

ASM - Activated Sludge Model
AOB - ammonia oxidizing bacteria
$b_{A,NOX}$ - Anoxic endogenous respiration rate of XA (d^{-1})
$b_{H,NOX}$-Anoxic endogenous respiration rate of X_H(d^{-1})
$b_{H,O2}$ - Aerobic endogenous respiration rate of X_H (d^{-1})
$b_{nb,NO3}$- Aerobic endogenous respiration rate of Xnb (d^{-1})
$b_{nb,O2}$ - Aerobic endogenous respiration rate of Xnb (d^{-1})
b_{nsNO2} - Aerobic endogenous respiration rate of Xns (d^{-1})
$b_{ns,U2}$ - Aerobic endogenous respiration rate of Xns (d^{-1})
$b_{STO,NOX}$- Anoxic respiration rate of XSTO (d^{-1})
$b_{STO,O2}$- Aerobic respiration rate of XSTO (d^{-1})
COD - Chemical Oxygen Demand (g O_2 /m^3)
C/N - Carbon to Nitrogen ratio

DO - dissolved oxygen
EPS - extracellular polymeric substances
f_{SI} - Production of SI in hydrolysis
f_{XI} - Production of XI in endogenous respiration
HET – heterotrophic bacteria
i_{NSS} - % amount of N in SS (g-N/g-COD)
i_{NXI} - % amount of N in XI (g-N/g-COD)
i_{NBM} - % amount of N in biomass (g-N/g-COD)
i_{NSI} - % amount of N in SI (g-N/g-COD)
i_{NXS} - % amount of N in XS (g-N/g-COD)
$K_{A,ALK}$ - Saturation constant for alkalinity for autotrophs (mol HCO_3/m^3)
K_{ALK} - Saturation constant for alkalinity for X_H (mol HCO_3/ m^3)
$K_{A,NH4}$ - Saturation constant for S_{NH4} for autotrophs (g N / m^3)
$K_{A,NOX}$ - Saturation constant for SNOX for autotrophs (g NOx / m^3)
$K_{A,NO2}$ - Saturation constant for SNO2 for autotrophs (g NO_2 / m^3)
$K_{A,NO3}$ - Saturation constant for SNO3 for autotrophs (g NO_3 / m^3)
$K_{A,O2}$ - Saturation constant for SO2 for autotrophs (g O_2 / m^3)
$K_{1,NE4}$ - Ammonia inhibition of nitrite oxidation (g NH_4/ m^3)
K_H - Hydrolysis rate constant
K_X - Hydrolysis saturation constant
K_La - Oxygen mass transfer coefficient (h^{-1})
K_{NH4} - Saturation constant for S_{NH4} (g N / m^3)
K_{NO2} - Saturation constant for S_{NO2} of Xns (g NO2/ m^3)
K_{NO3} - Saturation constant for S_{NO3} of Xnb (g NO3/ m^3)
K_{NOX} - Saturation constant for S_{NOX} (g NO3/ m^3)
K_{O2} - Saturation constant for S_{O2} (g O_2/ m^3)
K_S - Saturation constant for S_S (g COD S_S / m^3)
K_{STO} - Saturation constant for X_{STO} (g COD X_{STO} / g COD X_H)
k_{STO} - Storage rate constant (d^{-1})
NOB - nitrite oxidizing bacteria
Q_{in} – feeding flow
Q_{rs} - recycle flow
SRT - short solid residence time
S_{ALK} - Alkalinity [mol HCO_3/m^3]
S_I - Soluble inert organics (g COD /m^3)
S_{N2g} - Dinitrogen released by denitrification (g N / m^3)
S_{NH4} - Ammonium (g N / m^3)
S_{NOX} - Total oxidized nitrogen in the ASM3 model (g N / m^3)
S_{NO2} - Nitrite nitrogen (g N / m^3)
S_{NO3} - Nitrate nitrogen (g N / m^3)
S_{O2} - Dissolved oxygen (g O2 / m^3)
S_S - Readily biodegradable substrates (g COD / m^3)
V_{aero} – volume of aerobic reactor
V_{anox} – volume of anoxic reactor
X_H - Heterotrophic biomass (g COD / m^3)
X_I - Inert particulate organics (g COD / m^3)
X_{nb} - Nitrite-oxidizing autotrophs (g COD / m^3)
X_{ns} - Ammonia-oxidizing autotrophs (g COD / m^3)
X_S - Slowly biodegradable substrates (g COD / m^3)
X_{STO} - Organics stored by heterotrophs (g COD / m^3)
Y_A - Aerobic yield of X_A (g COD X_A / g N NOX)
$Y_{H,NOX}$ - Anoxic yield of heterotrophic biomass (g COD X_H / g COD X_{STO})
$Y_{H,O2}$ - Aerobic yield of heterotrophic biomass (g COD X_H / g COD X_{STO})
Y_{nb} - Aerobic yield of Xnb (g COD Xnb / g N NO_3)
Y_{ns} - Aerobic yield of Xns (g COD Xns / g N NO_2)
$Y_{STO,O2}$ - Aerobic yield of stored product for SS (g COD X_{STO} / g COD S_S)
$Y_{STO,NOX}$ - Anoxic yield of stored product for S_S (g COD X_{STO} / g COD S_S)
α - recycle ratio
β - purge ratio
η_{NOX} - Anoxic reduction factor
μ_A - Autotrophic max. growth rate of X_A (d^{-1})
μ_H - Heterotrophic max. growth rate of X_H (d^{-1})
μ_{nb} - Max. growth rate of Xnb (d^{-1})
μ_{ns} - Max. growth rate of Xns (d^{-1})

Acknowledgements; This work was supported at University Politehnica of Bucharest by UEFISCSU project No 175/1.10.2007 - Complex behavior of mixed microbial populations induced by time scales and segregation. Case study: wastewater biological treatment process.

References

1. IACOPOZZI, I.; INNOCENTI, V.; MARSILI-LIBELLI, S.; GIUSTI, E. Environmental Modelling & Software, **22**(6),2007**,** p. 847
2. MERKEL, W.; MANZ, W.; SZEWZYK, U.; KRAUTH, K. Water Research, **33**(10),1999**,** p. 2392
3. MOUSSA, M.S.; HOOIJMANS, C.M.; LUBBERDING, H.J.; GIJZEN, H.J.; VAN LOOSDRECHT, M.C.M. Water Research, **39**(20),2005**,** p. 5080
4. CHUANG, S.-H.; OUYANG, C.-F. Water Research, **34**(8),2000**,** p. 2283
5. ZHAO, H.W.; MAVINIC, D.S.; OLDHAM, W.K.; KOCH, F.A. Water Research, **33**(4),1999**,** p. 961
6. HU, J.; LI, D.; LIU, Q.; TAO, Y.; HE, X.; WANG, X.; LI, X.; GAO, P. Journal of Environmental Sciences, **21**(3),2009**,** p. 387
7. CAMPOS, J.L.; GARRIDO, J.M.; MOSQUERA-CORRAL, A.; MENDEZ, R. Biochemical Engineering Journal, **35**(1),2007**,** p. 87
8. PLÓSZ, B.G.; JOBBÁGY, A.; GRADY, C.P.L. Water Research, **37**(4),2003**,** p. 853
9. JIE, H.; DAPING, L. Current Microbiology, **57**(4),2008**,** p. 287
10. KIM, D.-J.; LEE, D.-I.; KELLER, J. Bioresource Technology, **97**(3),2006**,** p. 459
11. KIM, J.-H.; GUO, X.; PARK, H.-S. Process Biochemistry, **43**(2),2008**,** p. 154
12. KIM, D.-J.; AHN, D.; LEE, D.-I. Korean Journal of Chemical Engineering, **22**(1),2005**,** p. 85
13. CANZIANI, R.; EMONDI, V.; GARAVAGLIA, M.; MALPEI, F.; PASINETTI, E.; BUTTIGLIERI, G. Journal of Membrane Science, **286**(1-2),2006**,** p. 202
14. XUE, Y.; YANG, F.; LIU, S.; FU, Z. Bioresource Technology, **100**(3),2009**,** p. 1055
15. PAMBRUN, V.; PAUL, E.; SPÉRANDIO, M. Chemical Engineering and Processing: Process Intensification, **47**(3),2008**,** p. 323
16. WHANG, L.-M.; CHIEN, I.C.; YUAN, S.-L.; WU, Y.-J. Chemosphere, **75**(2),2009**,** p. 234
17. CERVANTES, F.J.; PAVLOSTATHIS, S.G.; VAN HAANDEL, A.C. Advanced biological treatment processes for industrial wastewaters: principles and applications, 2006.
18. GAO, M.; YANG, M.; LI, H.; YANG, Q.; ZHANG, Y. Journal of Biotechnology, **108**(3),2004**,** p. 265
19. MICHAUD, L.; BLANCHETON, J.P.; BRUNI, V.; PIEDRAHITA, R. Aquacultural Engineering, **34**(3),2006**,** p. 224
20. WANG, H.; LI, Q.; WANG, Y.; HE, N.; SUN, D. Journal of Hazardous Materials, **168**(1),2009**,** p. 203
21. RIVAS, J.; GIMENO, O., BELTRÁN, F. Chemosphere, **74**(6),2009**,** p. 854
22. RAMAKRISHNAN, A., GUPTA, S.K. Bioresource Technology, **99**(9),2008**,** p. 3745
23. HAO, R.-X.; ZHOU, Y.-W.; CHENG, S.-Y.; LI, J.-B.; ZHAO, M.; CHEN, X.; YAO, N. Chemosphere, **70**(5),2008**,** p. 783
24. YOOCHATCHAVAL, W.; OHASHI, A.; HARADA, H.; YAMAGUCHI, T.; SYUTSUBO, K. International Journal of Environmental Research, **2**(3),2008**,** p. 231
25. TOMITA, R.K.; PARK, S.W.; SOTOMAYOR, O.A.Z. Chemical Engineering Journal, **90**(3),2002**,** p. 283
26. GUJER, W.; HENZE, M.; MINO, T.; VAN LOOSDRECHT, M. Water Science and Technology, **39**(1),1999**,** p. 183
27. MANSER, R.; GUJER, W.; SIEGRIST, H. Water Research, **40**(12),2006**,** p. 2416
28. SIRIPONG, S.; RITTMANN, B.E. Water Research, **41**(5),2007**,** p. 1110
29. NI, B.-J.; YU, H.-Q. Chemical Engineering Journal, **140**(1-3),2008**,** p. 101
30. NI, B.-J., YU, H.-Q. Chemical Engineering Science, **63**(10),2008**,** p. 2785
31. ILIE, M.; ROBESCU, D.N.; GHITA, G. Rev. Chim. (Bucharest), **60**, no. 5, 2009**,** p. 529
32. HENZE, M.; GUJER, W.; MINO, T. Activated sludge models ASM1, ASM2, ASM2d and ASM3. IWA Scientific and Technical Report no. 9, 2000
33. LAVRIC, V.; OFITERU, I.D.; WOINAROSCHY, A. Biotechnology and Applied Biochemistry, **41**(2005**,** p. 89
34.OFITERU, I.D.; LAVRIC, V.; WOINAROSCHY, A. Chemical Engineering Transactions, **3**(3),2003**,** p. 1845

Manuscript received: 17.07.2009