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Modeling sequencing batch reactor operational conditions depending on oxygen concentration

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Abstract. Sequencing batch reactors (SBR) can be used as a fill-and draw activated sludge system for wastewater treatment with considerable operating flexibility and the possibility to conduct experiments under standard conditions and extreme case scenarios. Mathematical modeling and computer simulations provide an opportunity to implement existing wastewater processes in modeling software and evaluate different modifications at low costs and no disturbances for on-going processes of full scale WWTP. Additionally, the used model can be calibrated and validated against experimental data from laboratory scale devices. The aim of this study was to simulate the processes occurring in laboratory scale SBR under different aeration strategies. The results include the analysis of the adaptation period of the activated sludge biomass in the SBR, as well as the case of breakdown of treatment process due to stoppage of raw wastewater inflow and the interruption of the aeration and/or mixing. As a result, it can be stated that the oxygen transfer rate should be incorporated in the calibration of biological nutrient removal model in order to effectively visualize the individual contributions of each process.

1. Introduction

Sequencing batch reactors (SBRs) are a type of activated sludge process for wastewater treatment [1,2]. These are usually characterized by the five sequential stages of filling, reacting, settling, decanting and idling, allowing considerable flexibility for the design and operation of different biological wastewater treatments [3-8]. This versatility allows to carry out experiments under standard and/or variable conditions at full and laboratory scale, with the possibility for implementing new methods of measurement, technological solutions or exploitation strategies as well as to test extreme conditions during different treatment processes (e.g. failure of a reactor component) [9-18]. Additionally, SBR reactors at large scale, usually require a higher level of sophistication than conventional systems, with complex timing units and controls to achieve optimized management of performance over time [19-22]. Thus, properly set experiments allow to address questions on how to respond to different factors affecting wastewater treatment process in the short time.

The design of SBR bioreactors for nutrient removal, including nitrogen and phosphorus, is based on the selection of parameters such as sludge age, volume exchange ratio, cycle time and sludge volume index, as described for instance, in the ATV guidelines [23]. In reality, the resulting wastewater treatment plants (WWTPs) are mostly oversized to sustain efficient carbon and nutrient removal under varying environmental and operating conditions. Nowadays, the achievement of this goal can be aided



by computer softwares using mathematical models, e.g. IWA's ASM, which reflect the kinetics and stoichiometry of wastewater treatment processes [24-26]. Mathematical modelling and computer simulations of the projected or existing WWTP provide an opportunity to study current treatment and evaluate potential modifications at little financial costs and no disturbances of the on-going processes [27,28]. However, although the system might be designed with safety margins, attention should be paid to the operating conditions, which may positively or negatively affect the overall system performance. The optimization of operating parameters, e.g. aeration control, can be an asset to benefit from simultaneous nitrogen removal coupled with enhanced biological phosphorus removal (EBPR) [29]. Moreover, computer modelling can help establish optimal procedures in case of system failure in the treatment or can help predict problems with the quantity or quality of inflowing wastewater. The models used for simulations can also be calibrated and validated using data obtained from experiments carried out at the laboratory scale [30,31]. This approach has the advantage of testing for hypotheses and collecting data that otherwise would not be implementable or achievable at the full-scale WWTP.

The aim of this study was to simulate processes occurring in an laboratory scale SBR used for nutrients removal under different aeration strategies. Here we present the model used for the SBR operation along with the results of the simulations. The results were used to evaluate the adaptation period of the biomass and biological wastewater treatment processes in SBRs, as well as the period of breakdown of treatment process caused by the stoppage of raw wastewater inflow and interruption of the aeration and/or mixing system.

2. Material and methods

2.1. Laboratory experiments

The experimental setup consisted of three SBRs with an active and total volume of 8 and 10 liters, respectively. In the first part of the study, in order to simulate a conventional biological wastewater treatment process, a standard schedule was applied. The reactor operating cycle consisted of six consecutive phases: filling (30 min), mixing (120 min), aeration (420 min), sedimentation (90 min), decantation (50 min) and idle (10 min). The simulation was based on an analysis of the system assuming similar parameter concentrations for the wastewater flow during each cycle. Aeration (7 hours) was carried out at constant dissolved oxygen and controlled by an on/off aeration valve. Oxygen was kept at around 2 mg/L with an on/off controller and a 0.5 mg/L dead band. Electrodes for pH, DO (dissolved oxygen) and temperature measurements, were installed and connected to each individual SBR system. Experimental data were collected and the status and fluctuations of the reactor were constantly monitored. Time series of the electrode signals were stored in a data log-file. The temperature during the whole experiment was kept at 20-21°C. The Hach test-in-tube Hach DR2800 spectrophotometer was used to determine the concentrations of phosphorus, total nitrogen, ammonia as well as nitrites, nitrates, COD, BOD₅ and TSS. These were systematically measured at the beginning and at the end of each SBR cycle (each cycle lasted 12 hours). The WTW CelloX® 325 DO sensor was used to measure DO concentration and to establish set point for each SBR.

In order to simulate operational challenges of limiting substrates inflow, during the second stage of the experiment, the SBR was challenged with different operational strategies:

- SBR1, Aeration: SBR1 was constantly aerated and maintained a high DO;
- SBR2, Mixing: SBR2 used only mechanical mixing with a final DO level around 0.5 mg/L;
- SBR3, Control: SBR3 was used as a control reactor and neither aeration nor mixing was used.

Described laboratory SBRs and conducted experiments gives the data for build computer model and introduce parameters characterizing realized processes, activated sludge and treated wastewater. The rest of the paper presents the results of computer simulations.

2.2. Model layout

A computer model was developed and simulations were carried out using the modelling platform GPS-X v.7.0.1 (Hydromantis, Canada). A schematic of the laboratory SBR based on the GPS-X modeling

platform can be found in Figure 1. In order to describe the processes involving activated sludge, the ASM2d model was applied. The general model calibration of laboratory scale SBR with nutrient removing processes under standard conditions as well as limiting substrates inflow, limiting aeration and mixing were applied. Based on process measurements in SBR and influent wastewater characterization, the ASM2d model input data were verified by Influent Advisor module linked to the GPS-x program. Other parameters used to build the model for simulations are presented in detail in Table 1.

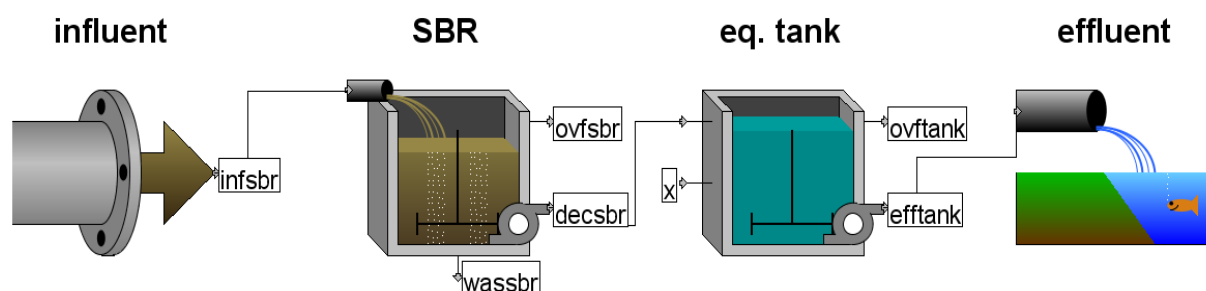


Figure 1. Schema of the laboratory SBR based on the GPS-X modelling platform.

Table 1. List of data used in GPS-X.

Type of data	Description
Library	CNPlib (Carbon-Nitrogen-Phosphorus library)
Model components	Influent, SBR (Advanced), Equalization tank, Discharge (Figure 1)
Sub-models used	Influent – COD fractions, Advanced SBR – ASM2d, Equalization tank – No react, Discharge – Default
Influent quality parameters	COD, TKN (Total Kjeldahl Nitrogen), Phosphorus (Total Phosphorus, Orthophosphates), Nitrogen (Total Nitrogen, Nitrate & Nitrite, Ammonia), TSS
Number of cycles per day	2 cycles, 12 hours each
Duration of phases	Variable and based on schedule
Influent characteristics	Influent Advisor – GPS-X accompanying application

3. Results

Sample results of the simulations in GPS-X during the first stage of experiment are presented in Figure 2. The concentration profiles of nitrite, ammonia nitrogen and total nitrogen were analysed (Figure 2a). Additionally, profiles of biological and chemical oxygen demand (BOD₅, COD) as well as TSS are presented in Figure 2b. A general stability of the treated wastewater leaving the equalization tank can be remarked.

According to simulations during the first part of the experiment, the adaptation of activated sludge and stabilization of process parameters were achieved after 20 cycles (10 days) of SBR work. This adaptation period is generally coherent with literature data [32,33] and experiments carried out in our laboratory [3].

The second stage of the scenario started after the initial adaptation period. In order to determine the process efficiency, key parameters such as total COD, total carbonaceous BOD₅ and TSS were analysed (Figure 2b).

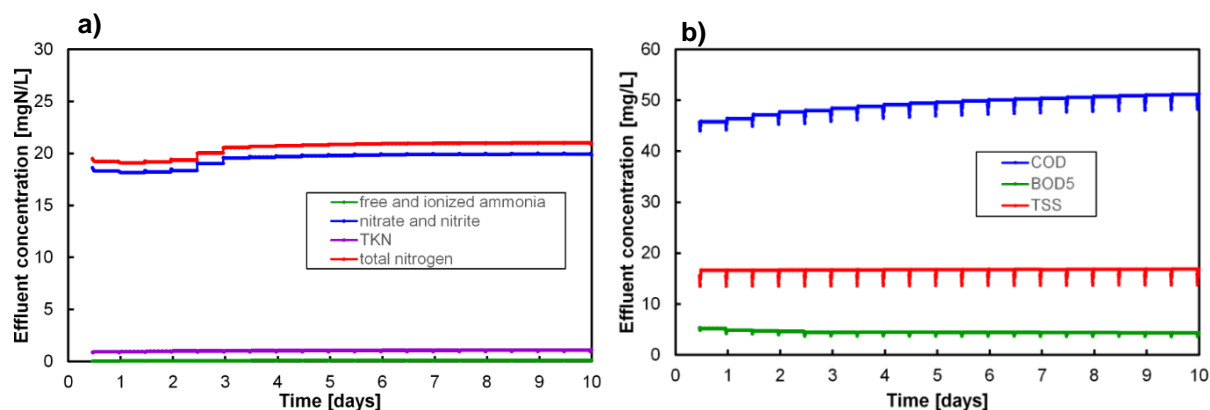


Figure 2. Simulated effluent concentrations of (a) nitrogen species and (b) effluent COD, BOD₅ and TSS.

Figure 3 shows the results of simulation concerning situation in SBR1 where after stopping of substrates inflow continuous aeration was conducted. Under aerobic conditions and the lack of an external carbon source, during the first three days, the accumulation of nitrates and nitrites can be observed. Moreover, due to loss of alkalinity, a lower rate of nitrification with an increase of free and ionized ammonia was observed (Figure 3a). At the same time a high depletion of heterotrophic biomass was observed along with a lower decrease of autotrophic and P-accumulating organisms. This situation appear in aerobic condition regardless level of DO, but it was more pronounced at higher oxygen concentration (6 – 7 mg/L) rather than at standard oxygen concentration (2 mg/L).

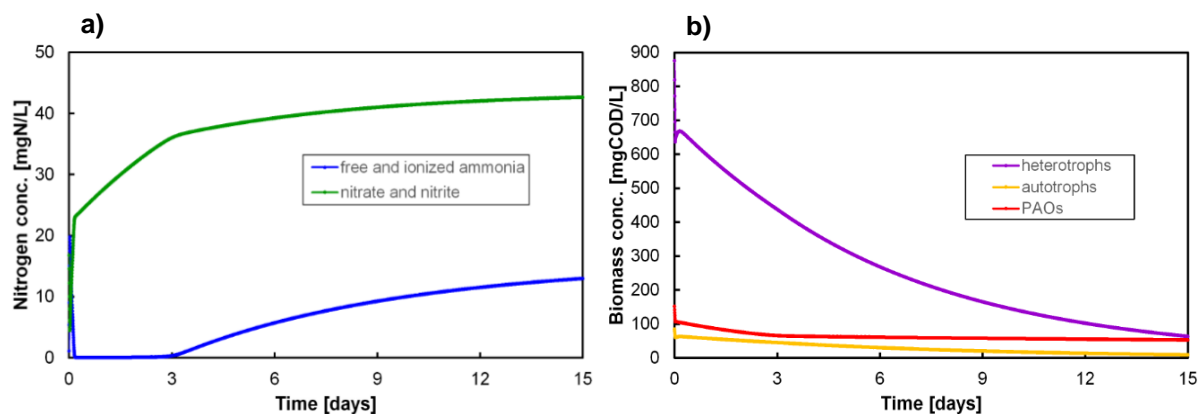


Figure 3. Concentrations of (a) nitrogen species and (b) biomass in SBR1.

Figure 4 shows the case scenario where SBR2 did not receive any sewage inflow and the only parameter used was mixing. Since mixing allowed some oxygen transfer, this was also considered as a simulation scenario. When the oxygen concentration reached 0.4 – 0.6 mg/L, the nitrate and nitrite levels stabilized after around seven days, and a small increase in ammonia was also observed (Figure 4a). The change in biomass concentration (Figure 4b) showed similar trends to the case scenario with constant aeration (Figure 3b). However, when mixing and a “zero” oxygen concentration was imposed, the results showed only an increase in ammonia without accumulation of nitrite and nitrate within reactor (Figure 4c). This scenario showed a much faster decrease of heterotrophic biomass with a slower decrease of P-accumulating (Figure 4d).

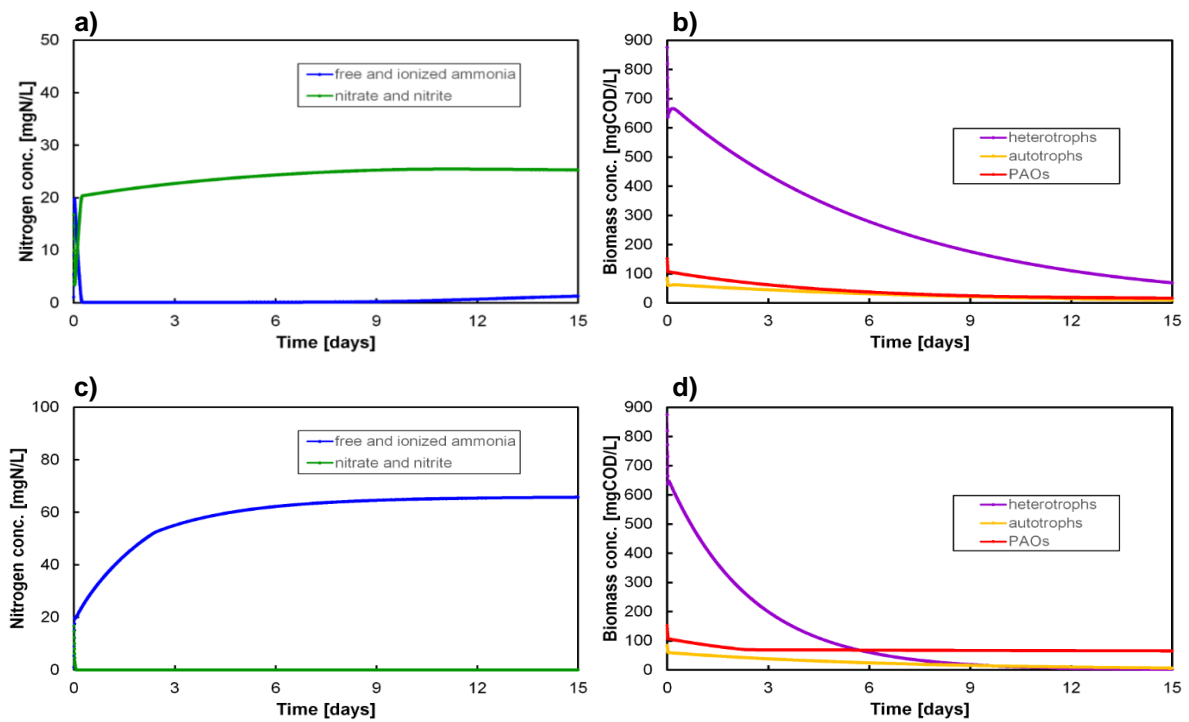


Figure 4. Nitrogen concentrations in SBR2 in presence of (a) low DO and (c) zero DO. Biomass concentrations in SBR2 in presence of (b) low DO and (d) zero DO.

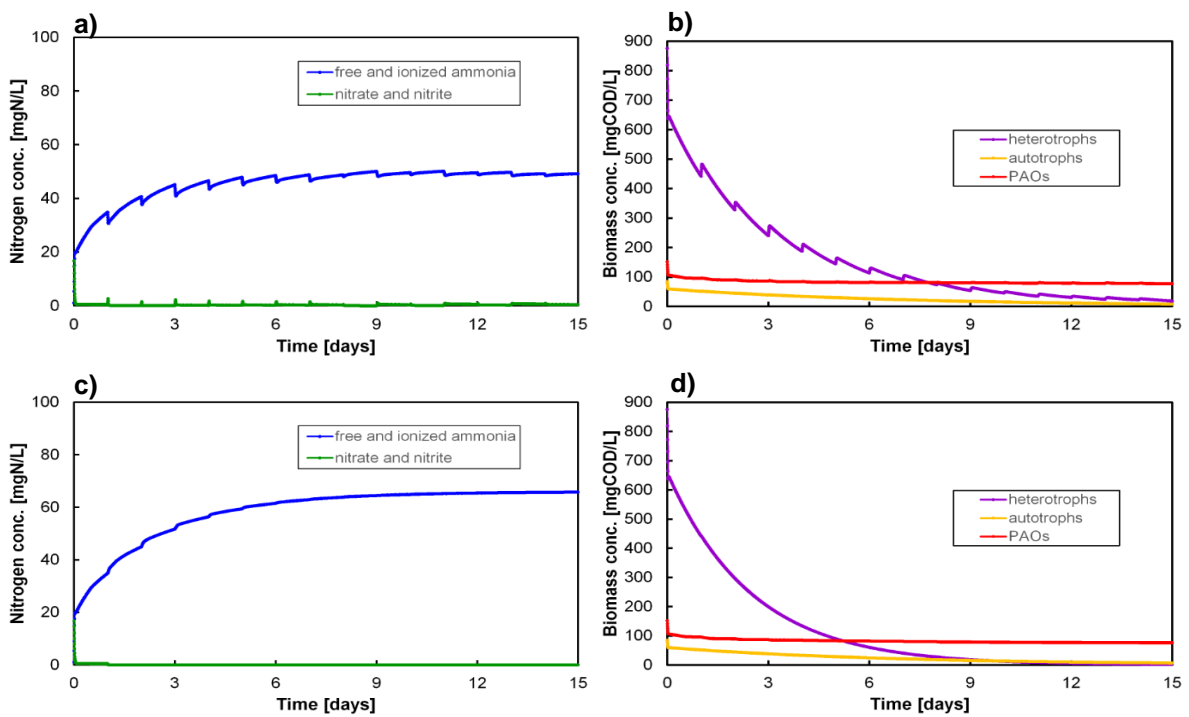


Figure 5. Nitrogen concentrations in SBR3 (a) low DO, (c) zero DO. Biomass concentrations in SBR3 (b) low DO and (d) zero DO.

The most interesting results are based on the simulation of the reactor with no continuous aeration or mixing. The first scenario shows more realistic conditions where complete mixing of the reactor occurs once a day before activated sludge and sewage were sampled for analysis (Figure 5a, b). In this case, a transient (15 min) low DO concentration (0.4 – 0.6 mg/L) characterized this phase with subsequent short drops of the ammonia concentration, increase of nitrite and nitrate concentration as well as an overall decrease of biomass amount. The second scenario was based on applying only mixing with no oxygen in the reactor. In this case, a greater increase of ammonia concentration occurred along with no formation of nitrite and nitrate and a faster loss of biomass from the reactor (Figure 5c, d).

The processes that occurred in SBR3 (with predominant sedimentation) as well as in reactors with aeration and mixing were presented with the data averaged for 10 modelled layers of SBR. In this circumstances it is worth to mention in case of SBR3. The results for the 4th layer (near the middle of the cross section of the reactor), where in mixing scenario whole volume of reactor is homogenised once for day (Figure 6a and b) – then in 4th layer appear also biomass, before sediment at the bottom (Figure 6b). The same layer without mixing only showed dissolved compounds – e.g. free and ionised ammonia nitrogen (Figure 6c and d). This confirms that in computer simulation time and place of sampling is very important for proper data analysis.

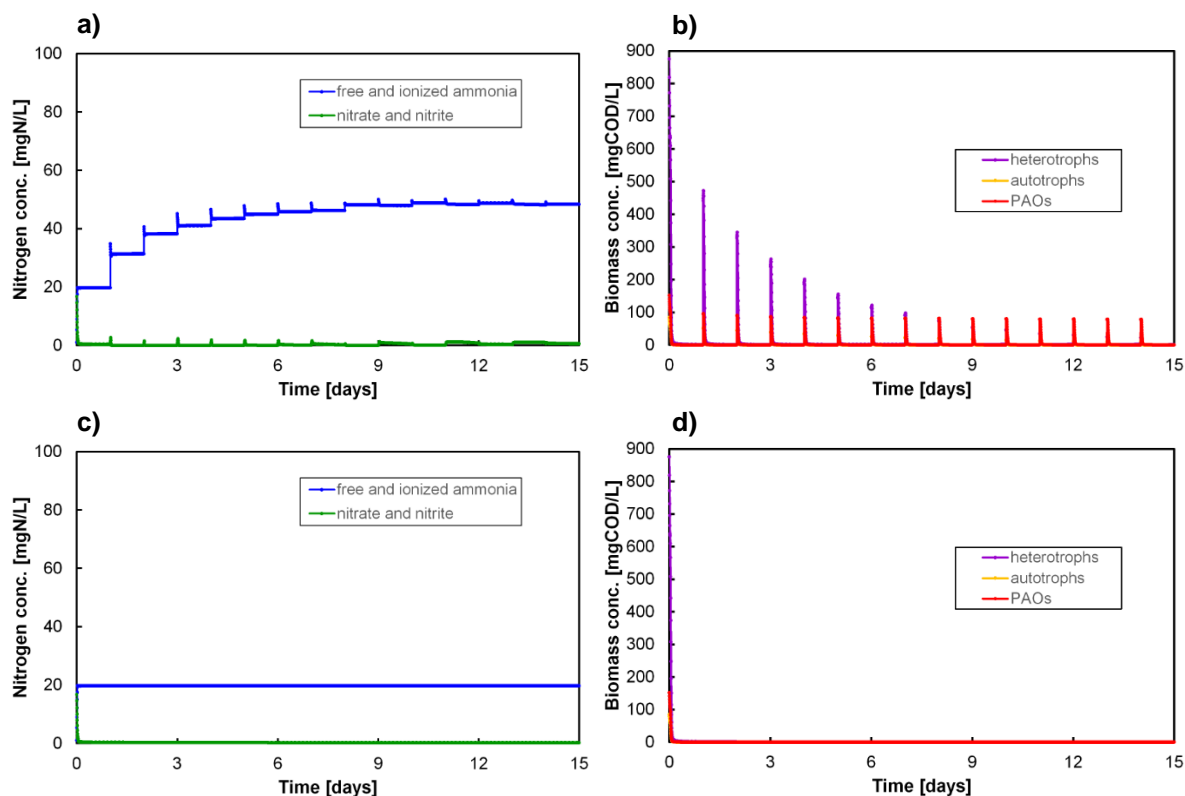


Figure 6. Nitrogen concentrations in 4th layer of the SBR3 - with mixing (a), without mixing (c) and biomass concentration in the SBR3 with mixing (b), without mixing (d).

4. Conclusions

From this study, the following conclusions can be derived:

- GPS-X allowed to carry out different simulations and evaluate the adaptation period of the SBR with the cycle of scheduled sequential phases and also within the scenario where different aeration/mixing conditions were applied.
- Modeling SBRs, where it is difficult to achieve steady state operation, requires accurate setting of the initial conditions. This will significantly affect the simulation results.

- A general model calibration methodology was applied using data from a laboratory scale SBR. Simulations showed a simultaneous nitrification-denitrification process together with biological phosphorus removal. However, here we mainly focused on the nitrogen compounds.
- The biological processes described in the model were found to occur simultaneously under limiting aeration conditions. A low oxygen transfer inherently differentiates the SBR behaviour from systems under traditional design calculations.
- After a general calibration of the model the best compatibility between simulation results and measurements in laboratory was achieved for concentration of free and ionized ammonia. This was particularly accurate for SBR3, in scenario where mixing was applied once per day.
- Computer simulations conducted with model calibrated using data from laboratory experiment show, that in case of inflow interruption, the biomass is at the highest concentration during aeration. A fast biomass depletion occurs when activated sludge settled at the bottom of reactor.

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