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Anatomy of the sequencing batch process for organic carbon removal from sewage with seasonal flow variations

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ABSTRACT

This study evaluated the basic design principles of a sequencing batch reactor (SBR), subject to seasonal wastewater flow fluctuations. Emphasis was placed upon highlighting the role of major process parameters, namely the cycle time, fill volume, number of reactors, the stationary volume, which holds the settled biomass and finally the sludge age in optimizing the necessary SBR configuration, which will effectively serve under these fluctuations. For this purpose, two sites with different wastewater generation schemes were selected in Erbil, a city in northern Iraq. The first one was a residential unit and the second, a luxury hotel with 250 rooms and a full capacity of 500 guests, which was attained in the summer period. The basic approach for SBR design for organic carbon chemical oxygen demand (COD) removal was summarized in the study. While the necessary methodology looks simply, it requires a detailed wastewater characterization involving the assessment of volatile and fixed solids components and COD fractionation. The adopted approach also relies on correlations between major parameters and process kinetics and stoichiometry. System optimization against seasonal fluctuations was essentially based on the utilization of spare reactor volume created under low wastewater flow conditions, without changing the selected parallel reactors, to increase the sludge age to the extent possible, which resulted in minimizing the excess sludge generation.

Keywords: Sequencing batch reactor; Process design; COD removal; Domestic sewage; Flow fluctuations

1. Introduction

The sequencing batch reactor (SBR) is the name assigned to this process in the late seventies [1]. Its name is certainly a misnomer, far from explaining the fundamentals of the process. It is true that SBR is a batch process, consisting of a single tank, serving both as a biological reactor and a settler. It is adjusted to a cyclic operation; where wastewater feeding takes place intermittently during each cycle. Therefore, a better name would be a cyclic batch reactor with intermittent feeding. Biological reactions and settling follow a temporal sequence in the same reactor. Microbial activity is assumed to stop during the settling period for simplicity.

SBR was not conceived in the 1970–1985 period. It was the setup that was used for the development of the activated sludge process in 1914 by Ardern and Lockett [2]; it was also adopted for full-scale operation in many fill and draw plants installed in England and in the US between

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1914–1920 [3]. Then, the practical application turned into "continuous flow" systems. Almost 60 years later, the SBR system was promoted again as a new and much promising biological treatment process for the removal of organic carbon and nutrients, equally applicable to sewage and industrial wastewaters [4–9]. After the major milestone of new modeling for activated sludge process based on chemical oxygen demand (COD) fractionation [10,11], research efforts assumed quite a different character from empirical approaches, focusing on the fundamentals of microbial mechanisms associated with different processes and integrating them with reactor and operating features of SBRs [12–17]. The wide spectrum of papers reflected the remarkable evolution which took place in the conceptual interpretation of the SBR system throughout the years. A comprehensive synthesis of this research effort is presented in an IWA scientific and technical report [18].

Essentially the SBR system is an activated sludge configuration, which is mostly preferred in small communities and tourist resorts, as it offers cheap and simple operation, especially based on its flexibility to adapt itself to places experiencing seasonal wastewater flow fluctuations [19,20]. However, system optimization requires a thorough examination of wastewater character involving a description of solids content in terms of total suspended solids (TSS); volatile suspended solids (VSS) and fixed solids together with COD fractionation [21], in a way to properly utilize system stoichiometry for reliable design. Unfortunately, the practice today mostly relies on empirical experience without benefiting from the guidance of extensive work on the kinetic and stoichiometric description of the SBR system, where it is most needed under seasonal wastewater flow fluctuations.

In this context, the objective of this work was to clarify and evaluate how an SBR system should be designed and operated to cope with such seasonal fluctuations in order to meet effluent requirements for organic carbon (COD). Emphasis was placed upon highlighting the role of major process parameters in optimizing the necessary SBR configuration, which will be illustrated for two different case studies.

2. Methodology

2.1. Conceptual approach

This study will only need appropriate understanding related to the interactions of a few key parameters for system optimization. The first parameter to be selected is the cycle time, T_C; it basically determines the numbers of cycles per day, m, also an important parameter for SBR design and operation:

$$T_c = \frac{1}{m} \tag{1}$$

Each cycle involves two periods, starting with the process phase, T_P, where biological reactions are sustained, and an idle phase T_I, presumably with no biological conversion. The filling of the wastewater into the reactor or the fill phase, T_F, may cover a portion of the process phase, T_P or it may continue throughout this period. The idle phase includes a quiescent phase for settling, T_S, which allows the biomass to settle in the bottom of the reactor and a draw phase, T_D where the treated clear supernatant is decanted and discharged from the reactor. Usually, T_I is selected longer than ($T_S + T_D$) to create additional flexibility to the operation of the system. Fig. 1 gives a schematic display of the cyclic operation of the SBR.

The second key parameter is the fill volume in each cycle, V_F, which is the volume of wastewater that is filled and discharged every cycle. V_F is obviously defined as follows:

$$V_F = QT_C = \frac{Q}{m} \tag{2}$$

where Q is the daily volume of wastewater to be treated. V_F determines part of the total reactor volume, V_T. As shown in Fig. 2, V_T also includes a stationary volume, V_0, which holds the settled biomass. Therefore, the reactor volume reaches its maximum level at the end of the fill phase in each cycle.

The third key parameter is the required number of parallel reactors to accommodate wastewater filling on a continuous basis. A single reactor operation is only possible with an aerated equalization basin before the SBR. The number of parallel reactors, N is obtained as:

$$T_C = N\ T_F \tag{3}$$

The SBR design will also require an appropriate value for V_0, along with other key parameters identified above. The assessment of V_0 depends upon basic relationships of process stoichiometry, which are well covered in related literature. Here, the essential expressions will be provided; additional information may be extracted if needed from a few basic sources [13,21].

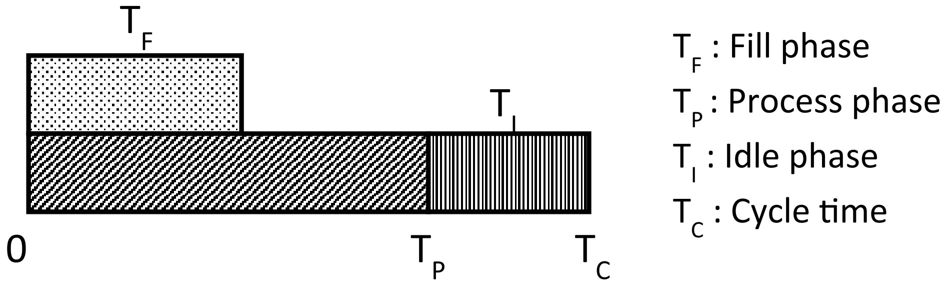


Fig. 1. Schematic representation of SBR cyclic operation.

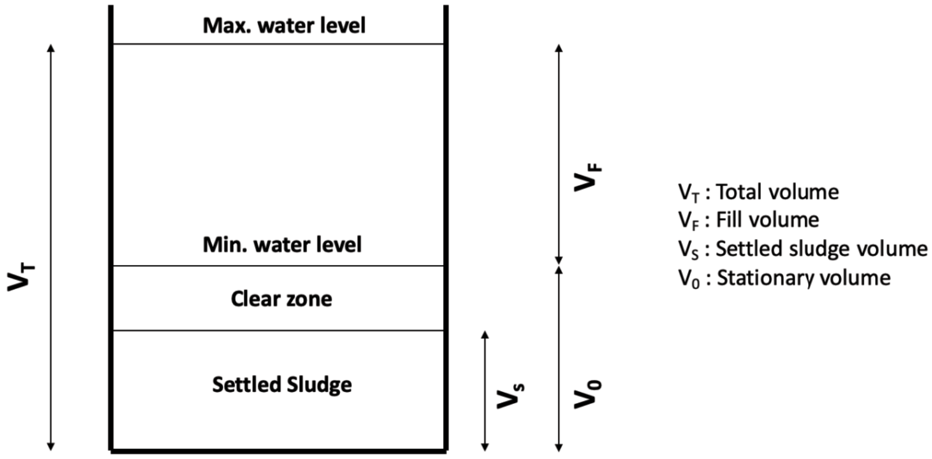


Fig. 2. Schematic display of the SBR volume.

Similar to all activated sludge configurations, the starting point of the design approach will be to select an appropriate value for the sludge age, θ_X, which commands all microbial mechanisms in the reactor. It continues with the evaluation of the daily sludge production rate, P_{XT}:

$$P_{XT} = i_{TSS,COD}\left(Y_{NH,e}QC_{S1} + QX_{I1}\right) + QX_{FS1} \quad (4)$$

where $i_{TSS,COD}$ is the coefficient to convert COD into TSS; X_{FS1} is the influent fixed (inorganic) solids concentration which can be determined as the difference between influent TSS and VSS; X_{I1} is the influent particulate inert solids concentration, Q is the flowrate, C_{S1} is the influent total biodegradable COD and Y_{NH} is the net yield coefficient accounting both for heterotrophic growth and endogenous respiration:

$$Y_{NH,e} = \left(1 + f_E b_H \theta_{XE}\right)\left(\frac{Y_H}{\left(1 + b_H \theta_{XE}\right)}\right) \quad (5)$$

where f_E is the inert particulate residue of endogenous respiration, b_H is the endogenous decay coefficient and θ_{XE} is the effective sludge age.

Then, the amount of biomass sustained in the SBR, M_{XT} can be computed as follows:

$$M_{XT} = V_T X_T = P_{XT}\theta_X = P_{XT}\theta_{XE}\left(\frac{T_C}{\left(T_C - T_I\right)}\right) \quad (6)$$

where V_T is the total volume of the reactor. These stoichiometric expressions lead to the calculation of V_0:

$$V_0 = \text{SF}\, P_{XT}\,\theta_X\,\text{SVI}\,10^{-6} \quad (7)$$

where SF is the safety factor.

This expression shows that smaller V_0 levels can be obtained with higher settled biomass concentrations, X_R. The maximum achievable value for X_R is a function of settling characteristics of sludge, which can be estimated by the value of the sludge volume index (SVI) that can be sustained during SBR operation. A realistic value for SVI (mL/g) needs to be estimated for system design:

$$X_R\left(\text{g/m}^3\right) = 10^6/\text{SVI} \quad (8)$$

Essentially, the design and optimization of SBR systems under variable conditions may be accomplished by the selection of suitable values of key parameters and proper use of the above stoichiometric expressions.

2.2. Selected sites for SBR optimization

Two sites with different characters in terms of wastewater generation were selected in Erbil, a city in northern Iraq. The first one is a residential unit, called "The Italian Residential Compound" including 500 separate houses with a total population of 2,500. It is fully occupied in winter; the occupancy rate decreases to 80% due to summer vacations and travels. The unit wastewater generation rate, q_W is assessed as 180 L/ca.d with a total wastewater flow, q_W of 450 m^3/d in winter and 360 m^3/d in summer. The total COD in wastewater was observed to change in the narrow range of 470–530 mg/L averaging 490 mg/L adopted as a design parameter for both seasons.

The second site is a luxury hotel with 250 rooms and a full capacity of 500 guests, which is attained in the summer period. The unit wastewater generation rate, q_W reaches a high level of 400 L/bed d in this period amounting to a total wastewater flow rate, Q_S of 200 m^3/d. The total design COD, C_{TS} is confirmed as 350 mg/L. In the winter period, the guest capacity drops to 80%, together with the applicable unit wastewater flow, q_{WW} of 250 L/bed.d, due to the absence of water consumption at the swimming pool and showers, raising the total COD in the wastewater C_{TW} to 400 mg/L.

COD measurements were carried out in accordance with the dichromate reflux method as defined in International Standard ISO 6060 [22].

2.3. COD fractionation and process stoichiometry

Nowadays, COD fractionation is accepted as an indispensable asset for the accurate design of activated sludge systems. Since this information is not available for the selected sites, default values suggested for domestic sewage were adopted [23,24]. Accordingly, the ratio of the biodegradable COD, C_S to total COD, C_T, C_S/C_T was accepted as 0.85; similarly, the initial inert particulate COD, X_I was calculated from the X_I/C_T ratio of 0.10. The mass balance equations for excess sludge P_{XT} also include the amount of inorganic solids, X_{FS}, which was selected as 30 mg/L for the residential compound and negligible for the hotel.

Similar default values were also adopted for the necessary stoichiometric and kinetic coefficients, namely, the heterotrophic yield coefficient, Y_H of 0.64 g cell COD/g COD; the TSS equivalent of COD, $i_{TSS,COD}$ of 0.9 g TSS/g COD; the particulate fraction of endogenous residue, f_E of 0.2 and the endogenous decay rate coefficient, b_H of 0.15 1/d [25].

3. SBR design and optimization results

The system design was first considered for the period where selected sites reflected full capacity. Then, the operation characteristics of the design parameters were optimized to best adjust for periods of low capacity. The sludge age, θ_X for full capacity was chosen as a conservative value of 10 d for safe operation that would secure the desired effluent quality. It should be noted that an SBR system requires a minimum of two parallel tanks (N = 2) unless the reactor is preceded with an equalization tank. This was avoided to better illustrate the inherent flexibility of SBR operation. All design steps followed the sequence of mass balance equations given in the conceptual approach section.

3.1. Residential compound

3.1.1. Winter period

The SBR system will be designed for a wastewater flow of 450 m^3/d, with a total COD of 490 mg/L for this period. A cycle time T_C of 8 h, with a process phase, T_P of 6 h and an idle phase, T_I of 2 h was adopted mainly to minimize to the extent possible the fill phase, T_F in each cycle. For two parallel reactors, the fill phase, T_F may be calculated as 4 h, as indicated in the schematic cyclic system operation as illustrated in Fig. 3. A shorter T_C value would also reduce the process phase, T_P to a level that would not be safe to ensure the desired effluent quality. In this configuration, the wastewater flow of 450 m^3/d will be split between the two parallel reactors and the fill volume in reach cycle, V_{FN} is calculated as 75 m^3.

The total excess sludge, P_{XT} generated through the SBR operation is computed as 96 kg TSS/d, which corresponds to total biomass, M_{XT} of 960 kg TSS to be held in the two reactors, which means M_{XN} of 480 kg TSS in one reactor. The assumption of an SVI value of 120 mL/g and a safety factor, SF of 1.2 yields a value of 8.3 kg TSS/m^3 for the concentration of settled biomass during the idle phase. Then, the total stationary volume V_{0T} for the two reactors will be 140 m^3, will be equally divided between the parallel reactor, that is, the stationary volume in each reactor, V_{0N} = 70 m^3. This way, the reactor design is completed, with a total volume of 145 m^3, as schematically indicated in Fig. 4a. The major design parameters for this period are outlined in Table 1.

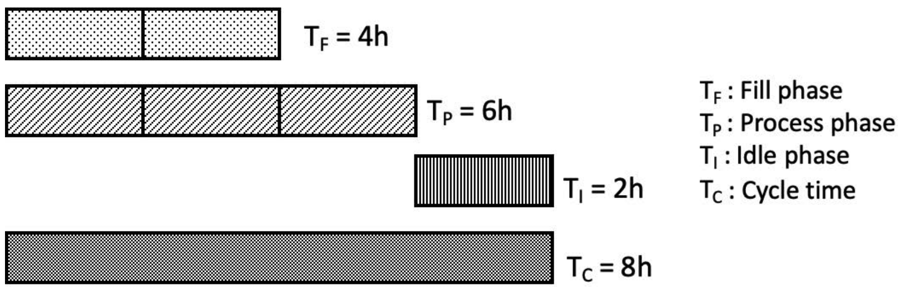


Fig. 3. Schematic cyclic operation was selected for the SBR system.

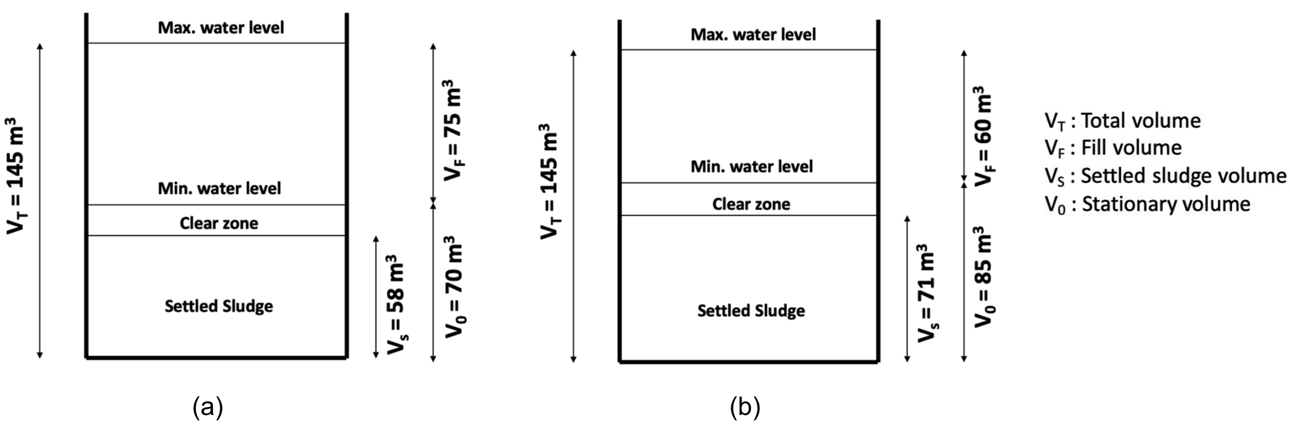


Fig. 4. Schematic representation of each SBR volume for residential compound during (a) winter period and (b) summer period.

Table 1
Major design characteristics of the SBR system for the residential compound

Parameters	Residential area	
	Winter	Summer
Q (m³/d)	450	360
C_T (kg COD/m³)	0.49	0.49
C_{S1} (kg COD/m³)	0.42	0.42
X_{I1} (kg COD/m³)	0.049	0.049
X_{FS1} (kg TSS/m³)	0.03	0.03
Cycle time (h)	8	8
Process time (h)	6	6
N	2	2
θ_X (d)	10	17
θ_{XE} (d)	7.5	12.75
$Y_{NH,e}$ (g cell COD/g COD)	0.37	0.30
P_{XT} (kg TSS/d)	96	68
p_x (kg TSS/m³)	0.21	0.19
M_{XT} (kg TSS)	961	1,156
M_{XN} (kg TSS)	481	578
V_{SN} (m³)	58	71
V_{ST} (m³)	116	142
V_{0N} (m³)	70	85
V_{0T} (m³)	140	170
V_{FN} (m³)	75	60
V_{FT} (m³)	150	120
V_{TN} (m³)	145	145
V_{TT} (m³)	290	290
θ_h (d)	0.32	0.40

3.1.2. Summer period

The operation of the SBR system needs to be adjusted to the reduced wastewater flow rate of 360 m³/d. Maintaining the 3 cycles/d operation (T_C = 8 h), the fill volume in each cycle, V_{FN} drops to 60 m³. Then, the available stationary volume in each reactor is increased to 85 m³, and the net sludge holding volume, V_{SN} to 71 m³. Taking the same settled biomass concentration of 8.3 kg TSS/m³, the volume corresponds to an available biomass holding capacity, M_{XN} of 590 kg TSS, which can be contained in each reactor. The increased biomass capacity will enable us to achieve a significant reduction in the excess sludge production, that is, sludge minimization, simply by increasing the sludge age level associated with the SBR operation. As shown in Fig. 5, θ_X level may be raised up to 17 d, where the M_{XN} reaches only 578 kg TSS, still below the available M_{XT}. This mode of system operation reduces the daily excess sludge rate down to 68 kg TSS, 70% lower than the level in the winter period. The modified volume of the SBR for the summer period is displayed in Fig. 4b. The major design parameters for this period are outlined in Table 1.

3.2. Luxury hotel

3.2.1. Summer period

For this period, the design parameters will be a daily wastewater flow of 200 m³ and a total COD concentration of 300 mg/L. The design will involve similar characteristics as the previous residential compound, that is, two parallel reactors, a cycle time, T_C of 8 h, and a sludge age, θ_X of 10 d. The same design approach yields a fill volume in each cycle, V_{FN} of 33 m³, a stationary volume V_{0N} of 19 m³, corresponding to a total volume for each reactor, V_{TN} of 52 m³ as schematically given in Fig. 6a. The excess sludge, P_{XT} generation through this type of an SBR operation is calculated as

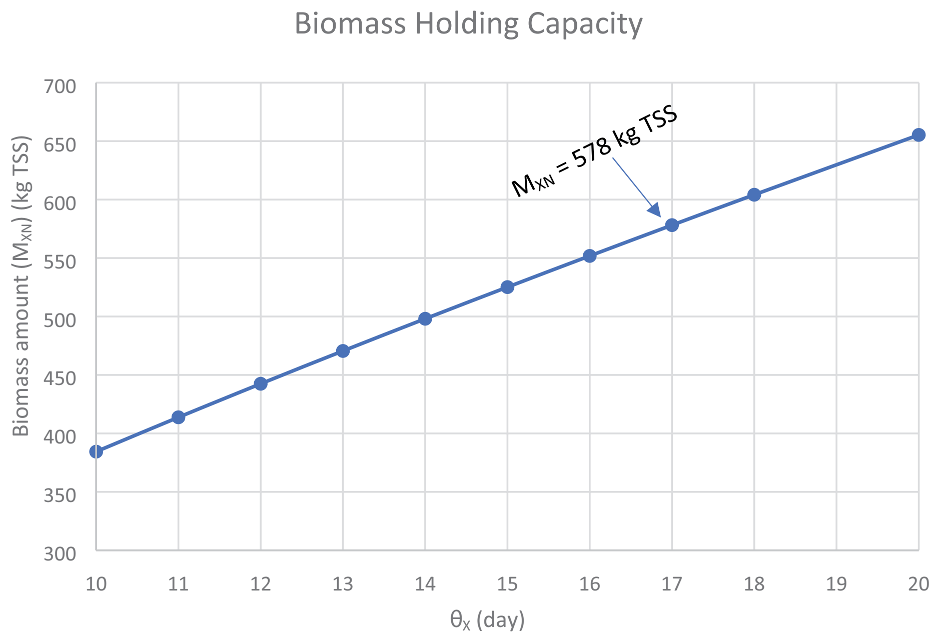


Fig. 5. Variation of the biomass holding capacity with the sludge age during summer period-residential compound.

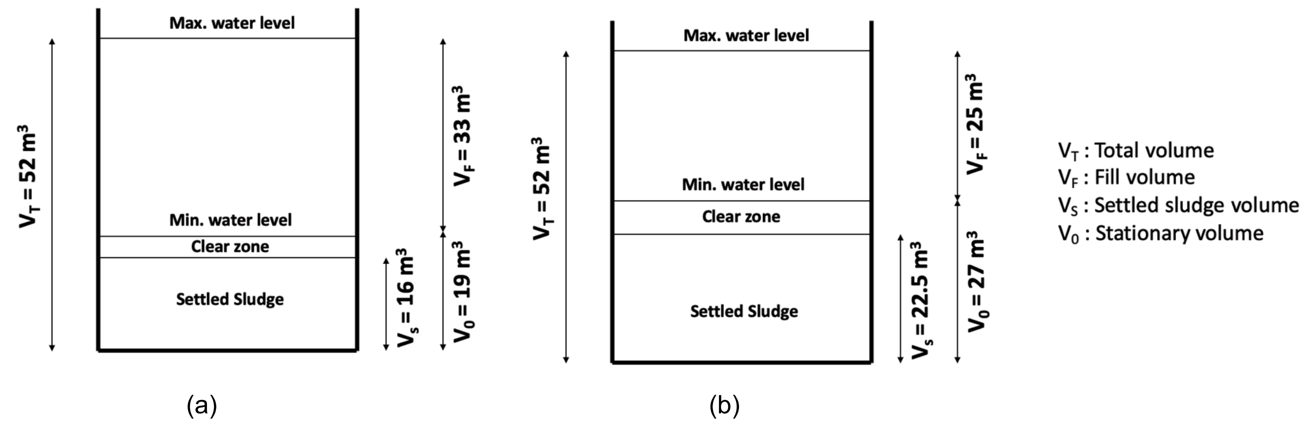


Fig. 6. Schematic representation of each SBR volume for the luxury hotel during (a) the summer period and (b) winter period.

26 kg TSS/d. Major design parameters for the summer period are outlined in Table 2.

3.2.2. Winter period

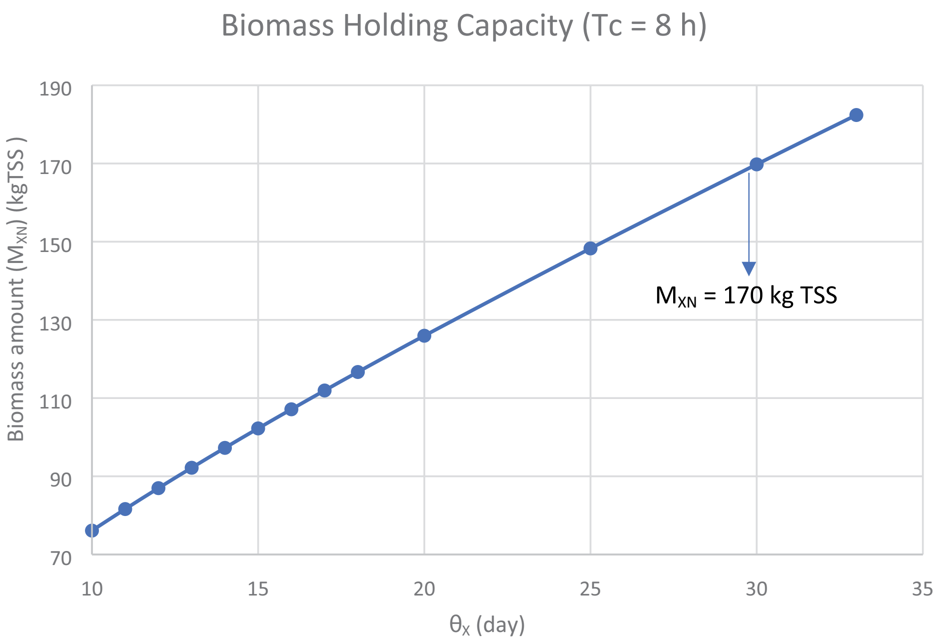
In this period, the wastewater flow rate exhibits a significant drop down to 100 m^3/d as the COD concentration appears to be increased to 400 mg/L, due to the absence of dilution by slightly polluted streams associated with summer activities. Maintaining the same cycle time, T_C of 8 h set for the summer period, the fill volume in each cycle, V_{FN} drops to 17 m^3. Then, the available stationary volume in each reactor is increased to 35 m^3, and the net sludge holding volume, V_{SN} to 30 m^3. Assuming that the same SVI value of 120 mL/g can be also maintained during the winter period, the modified V_{SN} volume can now accommodate a biomass holding capacity of 250 kg TSS. At this point, optimization of SBR performance may involve two options (i) the first option would consist of maintaining the same cyclic operation with 3 cycles per day (T_C = 8 h) and increase the sludge age in order to achieve sludge minimization. As shown in Fig. 7a, this alternative does not yield a satisfactory result. Even when the sludge age is increased to 30 d, the resulting reactor biomass only reaches 170 kg TSS, significantly lower than the available holding capacity of 250 kg TSS, leaving a portion of the reactor operation inactive during cyclic operation. (ii) The second option would consist of adopting a more relaxed operation of two cycles per day (T_C = 12 h), which will increase the fill volume in each cycle, V_{FN} to 25 m^3 and to limit V_{0N} and V_{SN} to 27 and 22.5 m^3, respectively. This way, the available biomass holding capacity M_{XN} could be reduced to 187 kg TSS. As shown in Fig. 7b, at a θ_X level of 30 d, M_{XN} reaches 165 kg TSS, only slightly below the available M_{XN}. This mode of system operation reduces the daily excess sludge rate down to 11 kg TSS, 42% of 26 kg TSS obtained for the summer period. The modified volume of the SBR for the summer period is displayed in Fig. 6b. The major design parameters for this period are outlined in Table 2.

4. Discussion

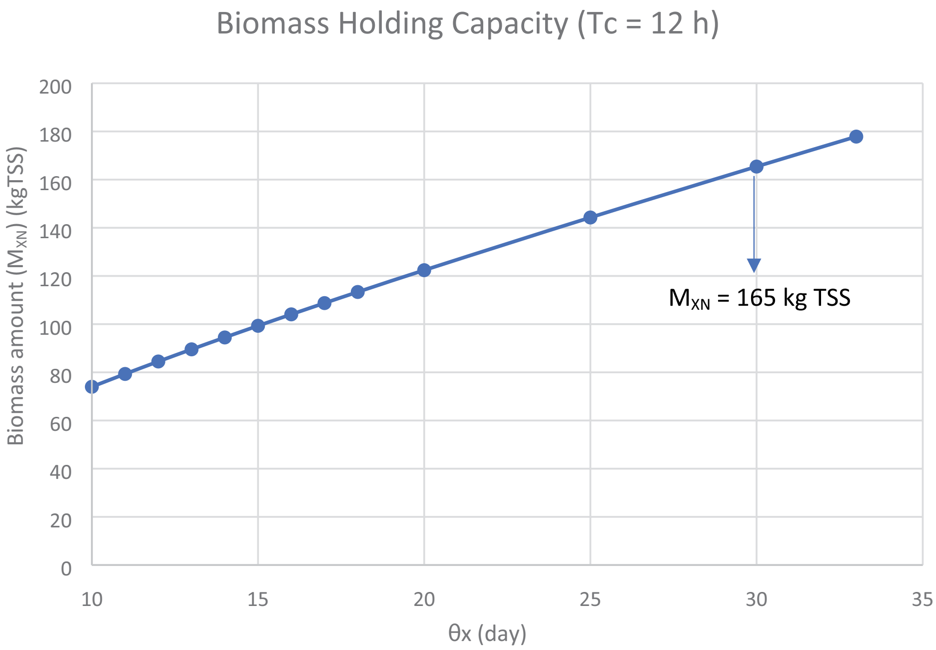
This study involved domestic wastewater from different sources, maintaining its basic characteristics over the years, as can be visualized through the inspection of selected reports [26,27]. It is now almost a common trend for papers in the literature to serve as waste backyards of information useless for the content and conduct of related studies. Here, the opposite was adopted just to show how limited information is really needed to fulfill the objectives of the study. Based on the information provided, optimization

Table 2
Major design characteristics of the SBR system for the luxury hotel

Parameters	Luxury hotel	
	Summer	Winter
Q (m^3/d)	200	100
C_T (kg COD/m^3)	0.35	0.4
C_{S1} (kg COD/m^3)	0.3	0.35
X_{I1} (kg COD/m^3)	0.035	0.04
X_{FS1} (kg TSS/m^3)	0	0
Cycle time (h)	8	10
Process time (h)	6	12
N	2	2
θ_X (d)	10	30
θ_{XE} (d)	7.5	8.3
$Y_{NH,e}$ (g cell COD/g COD)	0.37	0.36
P_{XT} (kg TSS/d)	26	11
p_x (kg TSS/m^3)	0.13	0.11
M_{XT} (kg TSS)	262	374
M_{XN} (kg TSS)	131	187
V_{SN} (m^3)	16	22.5
V_{ST} (m^3)	32	45
V_{0N} (m^3)	19	27
V_{0T} (m^3)	38	54
V_{FN} (m^3)	33	25
V_{FT} (m^3)	66	50
V_{TN} (m^3)	52	52
V_{TT} (m^3)	104	104
θ_h (d)	0.26	0.52



(a)



(b)

Fig. 7. Variation of the biomass holding capacity with the sludge age for the luxury hotel during the winter period for (a) $T_C = 8$ h and (b) $T_C = 12$ h.

of SBR systems, both in terms of design and operation, should account for to minimize several important factors such as plant footprint; mechanical equipment; generated sludge and operation and maintenance.

The extent of sludge generation in biological treatment systems is one of the major concerns, mainly due to the cost of its treatment and disposal [3,25]. For small systems, such as the SBR systems designed in this study, managed with a limited budget, sludge minimization becomes a major target. For given wastewater, the magnitude of sludge is strictly dependent on the sludge age selected for system operation. The sludge age exerts a dual impact on the sludge balance of the system, which seems to contradict one another (i) higher sludge age levels impose higher biomass holding capacity in the reactor, that is, larger reactor volumes, as a function of the θ_X/θ_h ratio [28]. (ii) At the same time, it also reduces the amount of generated excess sludge. Thus, in order to reduce the excess sludge, a larger reactor volume is needed. In the study, this was adopted as the highlight of the optimization scheme of SBR operation facing seasonal wastewater flow fluctuations. The excess reactor volume created during the low season was used to increase the sludge age and consequently, the biomass holding capacity without changing the SBR total volume. This way, significant sludge minimization levels could be achieved.

Smaller SBR footprint can only be achieved with a minimum number of parallel reactors, which was limited with two parallel units in the study. A higher number of parallel units would not only increase the overall footprint but also it would necessitate significantly higher mechanical equipment and increase the initial and operation/maintenance cost of the plant. The operation scheme devised during the low season for the luxury hotel, involving a transition from three cycles per day to two cycles per day operation, sets as a vivid and practical example of how the operation and maintenance load could be reduced and optimized when the SBR system works under lower wastewater flow conditions.

5. Conclusions

The key messages of this study may be summarized as follows:

- Simplicity and the flexibility of the SBR process makes it a perfect activated sludge configuration to cope with seasonal fluctuations in the quantity and the quality of wastewaters from small residential communities and resorts.
- System design is simple and may be quite accurate if correlations between major parameters and process kinetics and stoichiometry are well established and utilized. This principle constituted the basis of the novel approach set forth in the study for system optimization, to combine relevant wastewater characteristics and major parameters with process kinetics and stoichiometry inherently defining SBR systems.
- System optimization against seasonal fluctuations targeted minimum treatment footprint, that is, reactor number and volume, and sludge minimization; it essentially relied on the utilization of spare reactor volume created under low wastewater flow conditions, to increase the sludge age to the extent possible, which resulted in minimizing the excess sludge generation.

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