Design of SBR systems for nutrient removal from wastewaters subject to seasonal fluctuations

N. Artan, D. Orhon and R. Tasli
Environmental Engineering Department, Istanbul Technical University, I.T.U. İnşaat Fakültesi, 80626, Maslak, İstanbul, Turkey

Abstract Designing SBR systems for simultaneous biological nitrogen and phosphorus removal is evaluated and defined for wastewaters from small coastal areas subject to seasonal fluctuations in quantity and quality. A design procedure is developed using basic process stoichiometry and significant operating parameters. A stepwise approach was utilized to secure full nitrification, available nitrate limitation for denitrification, a mixed phase with enough anaerobic fraction for P removal. A fundamental relationship between the effective sludge age, the recycle ratio and the cycle time was developed and used for the determination of physical design parameters.

Keywords Activated sludge; design; nutrient removal; sensitive areas; sequencing batch reactor; small treatment plants

Introduction
Small residential areas along sensitive coastal zones are generally served by simple wastewater treatment plants with little operation and maintenance. These areas with significant tourist activities are subject to major population fluctuations, inevitably reflecting on sewage quantity and quality. Table 1 summarizes the results of a comprehensive survey conducted along the Turkish Mediterranean coast (Tasli et al., 2001). The table also includes typical values associated with Istanbul domestic sewage (Orhon et al., 1997) and enables us to observe that (i) wastewater characteristics of small communities are quite different and stronger as compared to cities; (ii) they exhibit a significant seasonal fluctuation, likely to affect retrofitting or design. Coastal waters need special protection, particularly from eutrophication, for the preservation of the expected high water quality. However, the treatment technology generally provided can hardly cope with these expectations.

SBR is one of the preferred technologies in the small communities as it is cheap and simple to operate for the removal of conventional parameters. It also offers a great flexibility of operation for effective nutrient removal, much required in the coastal areas. SBR is well studied for its N and P removal potential (Artan et al., 1998; Kuba et al., 1993; Manning and Irvine, 1985; Okada and Sudo,1986; Tasli et al., 1999) but scientific information derived from extensive research efforts is not totally translated into practical application (Wilderer et al., 2001). This paper provides a rational design procedure for simultaneous biological N and P removal using SBR technology. Specific emphasis is placed upon the required system flexibility to cope with seasonal wastewater quantity and quality fluctuations in small coastal communities. Available nitrate limitation for sequential denitrification and P removal within the mixed phase is kinetically described. A fundamental relationship between the effective sludge age, the recycle ratio and the cycle time is developed and used for the determination of physical design parameters.

Process description
The SBR is a single tank that serves both as a biological reactor and settler in a temporal sequence. The total reactor volume includes a stationary volume, $V_0$, holding settled
biomass and a fill volume, $V_F$, filled and discharged in each cycle. The $V_0/V_F$ ratio has the same function as the total recycle ratio in continuous-flow systems. The process operates in cycles, each cycle involving several consecutive phases. In the fill phase, $T_F$, wastewater is fed into the reactor on the aerated biomass maintained in the reactor. After fill, biological reactions further proceed during the react phase, $T_R$. Biomass is left to settle in the settle phase, $T_S$. The treated wastewater volume is discharged in the draw phase, $T_D$, and the reactor remains idle in the idle phase, $T_I$. The total cycle time, $T_C$, is basically the sum of these phases. Biological processes are assumed to take place only during the process phase, $T_P$, corresponding to the sum of fill and react phases. In nutrient removal SBR systems, the process phase includes an aerated phase, $T_A$, and a mixed phase, $T_M$. Depending on the presence or absence of nitrate in the mixed liquor, the portions of the mixed phase can be anoxic ($T_{DN}$) or anaerobic ($T_{AN}$). Relevant components of the cyclic operation in a nutrient removal SBR are shown in Figure 1.

### Fundamental relationships of SBR operation

Principles of a systematic approach to the design of the SBR can be formulated in a similar way to those for the continuous-flow systems. Though the possible design and operation choices seem to be abundant, steady-state SBR design involves the same basic relationships and mass balances with its intrinsic constraints.

A number of relationships may be formulated between physical parameters, the nominal hydraulic retention time and different sludge ages associated with SBR operation. The nominal hydraulic retention time, $\theta_h$ is a useful concept that compares SBR systems with each other and with their continuous-flow counterparts. In a single tank SBR operated with $m$ cycles per day, the daily flow rate, $Q$ will be:

$$Q = mV_F$$

(1)
In terms of the total reactor volume, $V_T = V_0 + V_F$, $\theta_h$ may be expressed as:

$$\theta_h = \frac{V_T}{mV_F}$$  

(2)

Substitution of $T_C = 1/m$, yields the basic relationship between $\theta_h$, $V_0/V_F$ and $T_C$:

$$\theta_h = \left(1 + \frac{V_0}{V_F}\right)T_C$$  

(3)

Since biological conversion only occurs during the process phase, biomass is not active throughout the entire cycle. In this context, an effective sludge age, $\theta_{XE}$ should be introduced to account for the effective periods, $T_E$, which is the sum of aerobic and anoxic periods, since heterotrophic growth and endogenous respiration are assumed to cease during the anaerobic period.

$$\theta_{XE} = \theta_X \frac{T_E}{T_C} = \theta_X \frac{T_C - T_{AN} - T_{S+D+I}}{T_C}$$  

(4)

Similarly, the aerobic sludge age, $\theta_{XA}$, a decisive parameter for nitrification is defined as a function of the aerated phase, the only period of the operating cycle sustaining autotrophic growth:

$$\theta_{XA} = \theta_X \frac{T_A}{T_C}$$  

(5)

An equally essential relationship for the appropriate assessment of SBR design and operation is the one that correlates $V_0/V_F$ to $T_C$ and other system/sewage characteristics. It is derived from the basic stoichiometry between biomass and sludge retention time, $\theta_X$ (Artan et al., 2001):

$$V_0 = Y_N QC_{SI} \theta_X SVI10^{-6}$$  

(6)

where, $Y_N = i_{TSS,COD} \left(Y_{NH} + \frac{X_H}{C_{SI}}\right)$

Manipulation of the above equation indicates the conditions that $V_0/V_F$ must satisfy, with the selection of an appropriate MLSS at $V_0$, $X_{TSS,0}$, to allow enough clear zone over the settled sludge zone based on SVI:

$$\frac{V_0}{V_F} = \frac{mY_NC_{SI}\theta_X}{X_{TSS,0}} = \frac{Y_NC_{SI}\theta_{XE}}{X_{TSS,0} T_E}$$  

(7)

As shown by this equation, $V_0/V_F$ is a function of the number of cycles per day (or cycle time) as well as the biodegradable COD in the wastewater and the desired $\theta_X$. Using the relationship between $\theta_X$ and $\theta_{XE}$ as defined in Eq. (4), Eq. (7) can be rearranged to estimate the appropriate cycle time, $T_C$ based on recycle ratio ($V_0/V_F$) necessary for the required nitrate removal.

$$T_C = T_E + T_{AN} + T_{S+D+I} = \frac{\theta_{XE} Y_N f_{CS} C_{TL}}{(V_0/V_F) X_{TSS,0}} 24 + T_{AN} + T_{S+D+I}$$  

(8)

A rational procedure for design

As previously mentioned, the quantity and quality of sewage generated in small coastal tourist areas exhibit huge fluctuations. In this respect, design and operation of a single treatment plant that would be equally functional under severe seasonal flow and load transients and yet remain effective for carbon and nutrient removals is a delicate task. The task is even
more delicate and difficult for SBR incorporating a higher flexibility of operation, therefore a higher level of options is needed to choose the optimum operation strategy. It can only be accomplished if relevant principles of process kinetics and stoichiometry are properly translated into a logically structured design procedure. SBR design for conventional parameters is well understood (Orhon and Artan, 1994). Recently, SBR received considerable attention as far as fragmented scientific investigation of its behaviour for nutrient removal, but with only a few interpretations and adaptations of existing knowledge into practical application (Artan et al., 2001). In this context, a rational design procedure will be described and tested for fluctuating summer and winter conditions, reflecting typical sewage characteristics associated with small coastal tourist areas.

**SBR design for summer conditions**

**Input of design data**

A rational design has to rely on meaningful data on sewage characteristics and applicable effluent limitations for N and P. The minimum package required for sewage is the influent COD, TKN, total P concentrations, the minimum sewage temperature and the alkalinity level for nitrification/denitrification balance. In most cases no other information may be available. Then, assumptions have to be made on the biodegradable COD fraction and the basic kinetic/stoichiometric coefficients necessary for mass balance calculations.

For the design exercise in this part, \( C_{T1} = 700 \text{ mg l}^{-1} \), \( C_{TKN} = 50 \text{ mg l}^{-1} \) and \( C_{TP} = 10 \text{ mg l}^{-1} \) were selected as they reflect the sewage characteristics from small communities – hotels, vacation centers, summer houses with \( N < 10,000 \) – along the Turkish Mediterranean coast, at full season. Alkalinity was not included in the evaluation. The lowest critical sewage temperature was assumed as 20°C. The influent biodegradable COD, \( C_{S1} \) was taken as 560 mg l\(^{-1} \), corresponding to a total non-biodegradable fraction of 0.2. The kinetic and stoichiometric coefficients adopted for the evaluation are listed in Table 2.

An effluent total N level of 20 mg l\(^{-1} \) was targeted as suggested for the small communities along the Turkish Mediterranean coast. This level corresponds to 60% removal for the adopted influent N content of 50 mg l\(^{-1} \). Similarly, \( S_{NH} = 2 \text{ mg l}^{-1} \) and \( C_p = 2 \text{ mg l}^{-1} \) (80% removal) were selected as additional effluent limitations.

Select \( \theta_{XA} \) and calculate \( S_{NH} \). The ability of SBR for efficient nutrient removal chiefly depends on the selection of an appropriate sludge age for the autotrophs, \( \theta_{XA} \), and the heterotrophs, \( \theta_{XE} \). \( \theta_{XA} \) should be greater by a safety factor than a minimum aerobic sludge age that would ensure full nitrification for the critical sewage temperature. In this design exercise, \( \theta_{XA} \) was selected as 5 d in view of the high sewage temperature prevailing under summer conditions and the value of the ammonia nitrogen concentration in the effluent, \( S_{NH} \) is calculated on the basis of the fundamental mass balance equation related to nitrification, for the selected \( \theta_{XA} \) and other process coefficients.

### Table 2 Kinetic and stoichiometric coefficients adopted for the evaluation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Characterization</th>
<th>Temperature</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_A )</td>
<td>Maximum growth rate for autotrophs autotrophs</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>( b_A )</td>
<td>Decay rate for autotrophs</td>
<td>0.15</td>
<td>0.05</td>
</tr>
<tr>
<td>( K_{NH} )</td>
<td>Saturation coefficient for ammonium</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>( Y_H )</td>
<td>Yield coefficient for heterotrophs</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td>( b_H )</td>
<td>Endogenous respiration rate for heterotrophs</td>
<td>0.20</td>
<td>0.12</td>
</tr>
<tr>
<td>( f_E )</td>
<td>Inert fraction of the biomass</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>( i_{NBM} )</td>
<td>N content of biomass</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>( i_{COD,TSS} )</td>
<td>TSS to sludge COD</td>
<td>0.90</td>
<td>0.90</td>
</tr>
</tbody>
</table>
As shown above, the resulting $S_{NH}$ is below the effluent limit of 2.0 mg/l$^{-1}$ imposed on the system by a large margin, thus providing the necessary justification for the selected $\theta_{XA}$.

Select $T_{DN}/T_E$ and calculate $\theta_{XE}$. The $T_{DN}/T_E$ ratio should be selected high enough to ensure completion of the denitrification process to the extent of the available nitrate. A $T_{DN}/T_E$ of 0.23 was adopted and $\theta_{XE}$ may then be calculated as a function of these two selected parameters:

$$\theta_{XE} = \frac{\theta_{XA}}{(1 - T_{DN}/T_E)} = \frac{5}{(1 - 0.23)} = 6.5 \text{d}$$

(10)

The procedure should include, as given in the following steps, the necessary provision for controlling the suitability of the selected $T_{DN}/T_E$ ratio.

Calculate $N_X$ and $N_{OX}$. The amount of nitrogen removal per unit volume of wastewater treated as part of the excess sludge, $N_X$ is one of the essential parameters for N balance. Its calculation required by definition, the assessment of the net heterotrophic yield, $Y_{NH}$:

$$Y_{NH} = \frac{1 + f_e b_h \theta_{XE}}{1 + b_h \theta_{XE}} y_h = 0.35 \text{g cell COD (g COD)$^{-1}$}$$

(11)

From basic stoichiometry on organic carbon removal $N_X$ may be expressed as follows:

$$N_X = i_{NB} Y_{NH} C_{S1} = 0.07 \times 0.35 \times 560 = 13.7 \text{mg/l$^{-1}$}$$

(12)

The computation given above shows that 27% N removal is already accomplished by conventional COD removal, with system operation at the selected $\theta_{XE}$ value of 6.5 d.

The amount of nitrogen oxidized (nitrate generated) per unit volume of wastewater volume treated, $N_{OX}$ may then be calculated from simple mass balance

$$N_{OX} = C_{TKNI} - N_X - S_N - C_{IN} = 50 - 13.7 - 0.5 = 35 \text{mg/l$^{-1}$ N}$$

(13)

Calculate $N_{OX} - S_{NO}$. In this step, the nitrate concentration, $S_{NO}$ that could be allowed in the effluent for the compliance of the effluent limitations should be evaluated. As previously calculated, the impact of $S_{NH}$ on the effluent total N concentration is minimal. Considering the N content of biomass escaping the system and soluble inert N fractions by-passing biological conversion, process adjustment to sustain an $S_{NO}$ level of 15 mg/l$^{-1}$ can safely ensure safe operation in terms effluent limitations. In this context, the amount of nitrate removed by denitrification per unit volume of wastewater treated, may be calculated as:

$$N_{OX} - S_{NO} = 35 - 15.0 = 20 \text{mg/l$^{-1}$ N}$$

(14)

Calculate $N_{DP}$ and check $N_{DP} > N_{OX} - S_{NO}$. This parameter defines the nitrate concentration that may be potentially removed by denitrification, provided that enough nitrate is supplied to the anoxic period. With the simplifying assumption that the electron acceptor uptake rate is uniformly distributed throughout the effective period, $N_{DP}$ may be calculated by the following expression:

$$N_{DP} = \frac{(T_{DN}/T_E) \eta (1 - Y_{NH}) EC_{S1}}{2.86}$$

$$N_{DP} = \frac{0.23 \times 0.80 \times (1 - 0.35) \times 0.90 \times 560}{2.86} = 21 \text{mg/l$^{-1}$ N}$$

(15)

As shown above, $N_{DP}$ is slightly greater than the amount of oxidized nitrogen to be denitrified, thus providing the necessary justification for the selected $T_{DN}/T_E$. 

$N. Artan et al.$
Calculate $N_A$ and $V_0/V_F$. The available nitrate, $N_A$ defines the magnitude of oxidized nitrogen that can be introduced or kept in the anoxic phase for denitrification. As an inherent property of SBR, $N_A$ is basically the nitrate remaining in volume $V_0$ at the end of the previous cycle and must be equal to $N_{OX} - S_{NO}$. It will be determined by the $V_0/V_F$ ratio and effluent nitrate concentration. Then the required nitrate recycle ratio may be formulated as follows:

$$\frac{V_0}{V_F} = \frac{N_{OX} - S_{NO}}{S_{NO}} = \frac{20}{15} = 1.3$$  \hspace{1cm} (16)

Calculate $T_E$ and $T_C$. Eq. (8) presented earlier in the paper gives the fundamental relationship between $T_E$, $V_0/V_F$ and $\theta_{XE}$, based on process stoichiometry. The use of this equation requires the assessment of the overall yield coefficient, $Y_N$, and appropriate assumptions on the design SVI and pertinent characteristics of sewage. In this exercise, the settled MLSS was selected as $X_{TSS,0} = 9,000$ mg/l corresponding to an SVI of 100 mg/l with a safety factor of 1.1. The other coefficients were adopted as given in Table 2. In this context,

$$Y_N = 0.9 \times (0.35 + 0.10) = 0.40 \text{gTSS(gCOD)}^{-1}$$

and

$$T_E = \frac{\theta_{XE} Y_N / C_{S1}}{(V_0/V_F) X_{TSS,0}} = \frac{0.40 \times 560 \times 6.5}{1.3 \times 9000} \times 24 = 3 \text{h}$$

Accordingly $T_{DN} = 0.23 \times 3 = 0.7$ h \hspace{1cm} $T_A = 3 - 0.7 = 2.3$ h

Select $T_{AN}$, calculate $T_P$. For enhanced biological phosphate removal (EBPR), the process sequence must include an anaerobic period within the cycle. The anaerobic period fraction, $T_{AN}/T_P$, can be selected from experience. $T_{AN}$ was selected as 1 h yielding a $T_{AN}/T_P$ ratio of 0.25, which is usually sufficient for EBPR. Therefore,

$$T_M = 0.7 + 1 = 1.7 \text{h} \hspace{1cm} T_P = 3 + 1 = 4 \text{h}$$

Select $T_{S+D}$ and calculate $T_C$. 1–4 h have to be devoted to settle and draw phases in each cycle depending on factors like the employed method of decantation, sludge settling velocity, etc. A value of 2.0 h was chosen for $T_{S+D}$. Therefore $T_C$ was calculated as 6 h. Then, the total sludge retention time of the system, $\theta_X$, may be calculated as 13 d, on the basis of Eq. (4).

Calculate $\theta_h$ and $X_{TSS}$. Using Eq. (3), the nominal hydraulic retention time of the system may be calculated in terms of $V_0/V_F$ and $T_C$:

$$\theta_h = 6(1 + 1.3) = 14 \text{h}$$

This value for $\theta_h$ is satisfied in most continuous flow package activated sludge units installed in small communities, so that they can be readily retrofitted to SBR for nutrient removal. The MLSS concentration sustained in the reactor can also be calculated as follows:

$$X_{TSS} = \frac{V_0/V_F}{1 + V_0/V_F} X_{TSS,0} = \frac{1.3}{2.3} \times 9000 = 5000 \text{mg/l}$$ \hspace{1cm} (17)

The procedure outlined above provides a rational basis for achieving the desired $S_{NO}$ in the effluent. The same approach cannot be translated to P removal, as the related process stoichiometry is too complex for direct evaluation. For this purpose Activated Sludge Model No. 2d (Henze et al., 1999) implemented by AQUASIM (Reichert, 1994) is used for simulating the fate of N and P for selected conditions. The simulation results obtained are
plotted in Figure 2. As shown in this figure, model simulation fully confirms the proposed design procedure based on simple process stoichiometry. As expected, nitrate concentration, $S_{NO}$, is depleted and anaerobic conditions occur after 0.7 hours of mixing. Effluent nitrate concentration of 15 mg/l is achieved as estimated.

**SBR design for winter conditions**

It is essential that the operating characteristics of the SBR designed for summer conditions be reevaluated and adjusted to different winter conditions for an equally satisfactory performance. In this context, the evaluation was carried out with the assumption that the sewage flow was only half the level it reached in summer ($Q/2$), with a COD and N content of $C_{TI} = 480 \text{ mg}^{-1}$ and $C_{TKN} = 52 \text{ mg}^{-1}$ as indicated in Table 1, and a prevailing sewage temperature of 16°C.

The starting point of the evaluation should be the fact that design and operation parameters previously identified are not likely to represent the optimum conditions for winter. The first concern on reevaluating the proposed plant should be maintaining full nitrification at lower sewage temperatures, in view of the fact that the process is highly sensitive to temperature effects. In this respect, the aerobic sludge age, $\theta_{XA}$, was increased to 9 d. A two-fold increase in $\theta_{XA}$ could provide an $S_{NH}$ below the effluent limitation.

The next step should be the assessment of a comparably higher $T_{DN}/T_{E}$ ratio and effective sludge age, $\theta_{XE}$ that can be safely maintained for the system under winter conditions due to a substantially lower organic load. A $T_{DN}/T_{E}$ of 0.40 which yields a $\theta_{XE}$ value of 15 d was adopted. A higher $T_{DN}/T_{E}$ ratio is needed because of (i) the lower COD/TKN ratio and (ii) the new N balance necessitating a higher $N_{DP}$ for the same N removal efficiency. In fact, for $\theta_{XE} = 15$ d, $N_X$ drops to 8 mg/l, with a parallel increase in $N_OX$ to 43 mg/l.

If the same effluent $S_{NO}$ level of 15 mg/l is desired, $N_A$ would have to be increased to 28 mg/l, corresponding to a $V_d/V_F$ ratio of 1.87. These conditions are satisfied with a longer effective cycle time of 4 h. Allowing 1.5 h for $T_{AN}$, 2.5 h for $T_{S+D+I}$, $T_C$ will be 8 h and therefore, $\theta_{h} = 23$ h. This $\theta_{h}$ value is lower than the one calculated for winter sewage flow. Hence, the SBR can be run with these operation conditions in winter. Simulation results justify the evaluation outlined above as shown in Figure 3.

**Conclusion**

Design and operation of SBR under seasonal fluctuation conditions requires an accurate balance between process stoichiometry related to nitrification and denitrification and basic systems parameters. In this context, a stepwise design procedure is defined based on fundamental
relationships of SBR operation and applied to fluctuating summer and winter conditions. The procedure provides the necessary mechanistic tools to (i) ensure full nitrification, (ii) to establish available nitrate limitation in the anoxic phase in relation to the desired nitrate concentration to be maintained in the effluent and (iii) to allow enough additional organic carbon pool and anaerobic reaction time necessary for EBPR. The procedure also develops and makes use of a basic relationship which enables selection of an appropriate cycle time $T_C$, as a function of the effective sludge retention time, $\theta_{XE}$, and the recycle ratio, $V_0/V_F$.

Acknowledgements

This study was conducted as part of the sponsored research activities of The Environmental Biotechnology Center of The Scientific and Research Council of Turkey. The Research and Development Fund of the Istanbul Technical University also supported it.

References


