Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.966329

56 (2015) 3075–3086
December

Taylor & Francis
Taylor & Francis Group

Activated sludge with low solids production: modified ASM1 modeling and simulation

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Received 23 January 2014; Accepted 10 September 2014

ABSTRACT

Dynamic activated sludge modeling (ASM) and the concept of chemical oxygen demand fractionation utilized by this modeling approach suggested the existence of new strategies for minimization of excess sludge. One of these strategies consists of eliminating the traditional sludge wastage (WAS) and avoiding the buildup of inert solids in the aeration tanks by other means: fine screens are used to remove the inert particulate organic fraction (X_I), hydrocyclones (HC) are used for inorganic suspended solids (ISS), and different types of online digesters are used to further biodegrade the endogenous residues (X_P) via the return activated sludge (RAS) line. In this research, a model and a simulation program were developed that were able to mimic the apparent behavior of activated sludge variants with low solids production (LSP-AS). The model is an extended ASM1 assuming a small first-order biodegradation constant for X_P ($k_{X_p} = 0.007\ d^{-1}$), and black boxes represent X_I and ISS removal. The simulations first depicted the way that different solid components build up in the aeration tanks when traditional activated sludge (C-AS) is operated at very high solids retention times (>100 d, without sieves and HC). Secondly, the modeling showed that the C-AS process could hypothetically be replaced by LSP-AS variants with similar levels of active biomass and mixed liquor total suspended solids in the aeration tanks (2,500–3,500 mg L^{-1} TSS). For the studied case, at least 2 and 6% of the RAS flow must be screened and digested, respectively, to avoid the accumulation of X_I, ISS, and X_P. Additionally, the size of the online digester will be approximately twice the volume of the aeration tank. The mathematical model implemented in Aquasim could serve as a didactical, operational, and research simulation tool for LSP activated sludge processes.

Keywords: Aquasim; ASM1; Endogenous residues; Inert matter; Sludge minimization

1. Introduction

In wastewater treatment, there is continuing interest in developing processes that produce lower amounts of sludge. Among the concepts proposed in recent years, there are modified activated sludge systems with low-sludge production (LSP-AS) or total solids retention. Instead of producing a large volume of sludge before stabilizing it off-line, the new

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proposals seek to reduce the generation of solids from the source (i.e. inside the water treatment lines) [1,2].

There are many new strategies put forward for minimizing excess sludge generation in biological wastewater treatment. Some of them were developed within the context of research on dynamic activated sludge modeling (ASM, 1, 2, and 3) [3]. Based on these models, the main components of secondary biological sludge are heterotrophic biomass (X_H); endogenous residues from decay (X_P); particulate, inert organic matter (X_I) from the influent; and inorganic suspended solids (ISS) from the influent.

The principle of some of the LSP systems is to eliminate the traditional waste-activated sludge stream (WAS) and selectively remove the three "inert" fractions (X_I, ISS, and X_P), which otherwise would accumulate in the aeration tanks. One of the known LSP-AS systems is the Cannibal™ process [4,5]. Part of the return activated sludge (RAS) flow is passed through fine sieves for removing X_I (typically, toilet let paper and hair [6]) and through hydrocyclones for grit removal (ISS [7]). An online digester installed in the RAS line is then proposed to further biodegrade the biomass residues, X_P, considered previously as completely inert [8]. There are many other LSP-AS processes known under different names, including OSA for oxic-settling-anoxic process [9,10], BIMINEX [11], and SSR for side-stream reactor [12,13]. These processes are claimed to reduce the biomass yield (Y_H) or to increase the biodegradability of the sludge components. Online digester units (RAS-DU) installed through the RAS line are used in the different proposals, which have aerobic, anaerobic, or hypoxic (HDU for Cannibal™) conditions (or alternate between these conditions). Different authors claim sludge reduction of up to 60% for the LSP-AS process [4,14] compared to the traditional activated sludge process (C-AS).

In the conventional activated sludge (C-AS) process, a continuous or intermittent wasting of a portion of the biosolids is required to maintain an acceptable level of the mixed liquor total suspended solids (MLTSS) in the aeration tank [15]. This level cannot be too high. However, when the traditional WAS, as it has been known thus far, is drastically reduced (sludge retention time or SRT > 100 d) or totally canceled (total solids retention), alternative solids wasting or degradation is needed. Instead of putrescible rejects, the claim of the LSP-AS processes is to produce inert sludge (from screens and cyclones), and in smaller quantities.

Even though the concept of low-sludge production systems is of great interest, the fact remains that the mechanisms of removal or degradation of the solids has not yet been clearly elucidated. For the same reason, the literature on modeling and simulation of the LSP-AS is very scarce.

Previously, a report was published [5] that described modeling of the Cannibal™ process, which used a home-built program based on the ASM2d model. In this report, ASM2d was modified by adding a new process, namely the anaerobic hydrolysis of the endogenous biomass products (X_P), to the particulate biodegradable fraction (X_S). A Monod-based rate function was used. The model could not be calibrated with actual treatment plant data. The proposed value for the maximum specific hydrolysis rate was $1.2\ d^{-1}$. There was another attempt to model an LSP-AS process [14] through laboratory experiments using a completely soluble artificial substrate (acetate). In this case, the authors used the traditional models outlined in previous versions of Metcalf & Eddy [16], including only the heterotrophic growth and death processes, with a decay rate constant (b_H of $0.024\ d^{-1}$) that was much smaller than the default value.

Ultimately, a first-order model was proposed [17] for the decay of X_P, and a constant of $0.0075\ d^{-1}$ was achieved. Other authors [8,18] suggested that the endogenous residues from the biomass decay (X_P) could be biodegraded further, being a first-order kinetic reaction, with a decay constant k_{X_p} between 0.005 and $0.012\ d^{-1}$. A review [19] suggested that $0.007\ d^{-1}$ is a good estimate of the first-order constant for X_P degradation under aerobic conditions. This allowed improvement in sludge production estimations from different wastewater treatment plants (WWTP) operated with high SRTs.

Understanding the order of the value of the X_P degradation rate is a step forward in evaluating the feasibility of total sludge retention processes, which means operating activated sludge processes practically without wastage (SRT > 100 d). Although there is still no unanimous model to represent the degradation of the endogenous residues, it would be very useful to be able to simulate the behavior of the LSP-AS systems on the basis of current knowledge. Recently, the software Biowin [20] made another step forward by including sieves and hydrocyclones in the simulator, in conjunction with the above-mentioned types of process.

The development of a simulation program is proposed to reproduce the apparent behavior of activated sludge with low solids production (LSP-AS) by integrating black box models representing the physical removal of the inert particulates (ISS and X_I) with a modified ASM1 model that assumes slow X_P decay. To accomplish this, the software Aquasim [21,22], known for its flexibility, is used. The objective of the research was to develop a modified ASM1-based model that is able to mimic the behavior of LSP-AS processes in Aquasim and to evaluate the reaction volumes and flow needs of the extra processes. The most recent knowledge on the matter is taken in account, but it is important to notice that the simulation study is not intended to judge the mechanisms of removal or to consider the detailed characteristics or all possible complex behaviors of the unit operations and processes.

2. Materials and methods

The study was conducted in two main phases. The first phase was based on the classical approach of recent versions of Metcalf & Eddy [15], using an Excel spreadsheet to illustrate the dependence between the accumulation of the solids in the mixed liquor and the sludge retention time in the conventional activated sludge process (C-AS). In the second phase, gradual modeling was performed in Aquasim for SRTs from 25 to >100 d for the both variants, the C-AS and the LSP-AS processes (Sieve + hydrocyclone + online RAS digester unit).

2.1. Data of the WWTP

The case studied initially is a conventional activated sludge plant with a flow rate of 10,000 $m^3\ d^{-1}$. The operational data are shown in Table 1.

The influent contained 18 $mg\ L^{-1}$ ISS and 300 $mg\ L^{-1}$ total COD. The COD fractions were 57, 23, 13, and 7%, respectively, for X_S, S_S, X_I, and S_I. All the input parameters required to perform ASM1 simulations are given in Table 2. Concerning the equations of Metcalf & Eddy [15] used in parallel, the necessary concentration data are the total biodegradable substrate ($S_0 = 240\ mg\ L^{-1}$ COD, represented by the sum $X_S + S_S$) and the ISS of the influent (or TSS – VSS of the influent).

To simulate the modified activated sludge variant (LSP-AS), a sieve [6], a hydrocyclone [7], and an aerobic digester [23] were inserted in the RAS line. Initially, the volume of the online digester unit (RAS-DU unit) was 1,500 m^3, in conformity with the design criteria of 15 d SRT suggested earlier [5]. The initial flow rate of the sludge directed toward the RAS-DU unit was equal to the quantity of WAS that would be generated from the conventional activated sludge at 15 d SRT (100 $m^3\ d^{-1}$, as mixed liquor). Concerning the physical unit processes, at the beginning, the flow fed to the hydrocyclone and screen line was set at 10% of the RAS flow. Later, it was increased according to the desired levels of X_I and ISS in the aeration tank. From a theoretical point of view, these behave as inert tracers injected at the entrance of a CSTR tank (i.e. the equilibrium concentration is predictable as the SRT/HRT ratio multiplied by the input concentration).

2.2. Mathematical models and equations

In the case of the steady state solids mass balances, the following kinetic and stoichiometric parameters were used: the maximum specific substrate utilization rate, $k = 5$ g COD g^{-1} VSS d^{-1}; the heterotrophic yield, $Y_H = 0.4$ g VSS g^{-1} COD; the decay rate, $k_d = 0.18\ d^{-1}$; the substrate half-saturation constant, $K_S = 10\ g\ m^{-3}$ COD; and the endogenous biomass fraction from decay, $f_p = 0.27$. The basic equations (Eqs. (1)–(8), Table 3) were modified and extended from the bibliographical source [15]. The respective concentrations of the main sludge fractions (X_H, X_I, X_P, and ISS), the total sums (MLVSS, MLTSS, and MLCOD) and the

Table 1
Flow rates and dimensions of the modeled WWTP

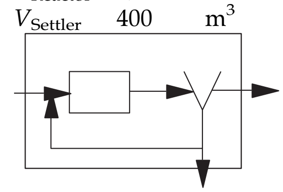
Operational data	Symbol	Value	Unit
Influent flow rate	Q_{in}	10,000	$m^3\ d^{-1}$
Recirculated activated sludge (RAS) flow	Q_{RAS}	3,300	$m^3\ d^{-1}$
Temperature	T	20	℃
Sludge retention time (Design)	SRT	15	d
Aeration tank volume	$V_{Reactor}$	6,000	m^3
Settler volume	$V_{Settler}$	400	m^3
Flow sheet of traditional activated sludge plant: Aeration tank followed by secondary settler, influent and effluent flows, recirculating line (RAS), and waste-activated sludge (WAS)			

Table 2
Characteristics of the influent (ASM1 nomenclature)

Components	Symbol	Value	Units
Inert soluble organic matter	S_I	20	g COD m^{-3}
Readily biodegradable organic matter (soluble)	Ss	70	g COD m^{-3}
Inert particulate organic matter	X_I	40	g COD m^{-3}
Slowly biodegradable organic matter (particulate)	Xs	170	g COD m^{-3}
Heterotrophic active biomass	X_H	0	g COD m^{-3}
Autotrophic active biomass	X_A	0	g COD m^{-3}
Biomass residues from lysis	X_P	0	g COD m^{-3}
Dissolved oxygen (DO)	S_{Ox}	0	g O_2 m^{-3}
Nitrates and nitrites (NO_2 + NO_3)	S_{NO}	0	g N m^{-3}
Ammonium nitrogen (N–NH_4^++N–NH_3)	S_{NH}	18	g N m^{-3}
Soluble biodegradable organic nitrogen	S_{ND}	5	g N m^{-3}
Particulate biodegradable organic nitrogen	X_{ND}	10	g N m^{-3}
Alkalinity	S_{ALK}	5	Mol m^{-3}
Inorganic suspended solids (=TSS − VSS)	ISS	18	g TSS m^{-3}

observed yield (Y_{obs}) were calculated as functions of the SRT.

For the steady state equations, as well as for the Aquasim program, different known ratios were used to be able to convert the concentrations from VSS to TSS and COD (and vice versa). The values considered were the following: icv$_{\mathrm{bio}}$ = 1.42 mg COD mg^{-1} VSS (for X_H, X_P, X_A, and X_S); icv$_{\mathrm{influent}}$ = 1.50 mg COD mg^{-1} VSS (for X_I from the influent); and ivt$_{\mathrm{bio}}$ = 0.92 mg VSS mg^{-1} TSS (for X_H, X_P, X_A). The particulate biodegradable fraction and the autotrophic biomass (X_S and X_A) in the secondary sludge were neglected in the steady state equations, while they were still computed and included in the modeling approach.

The simulation program was developed in Aquasim and was based on ASM1 [3]. It has been modified by adding a new process (Table 4) for the degradation of the endogenous residues X_P in the digester. This transformation of X_P to X_S was activated in the digester, as well as in the aeration tank. As previously suggested in the literature [17–19], the digester (RAS-DU) could be aerobic [23]. The other eight ASM1 processes also were made active in the aeration tank and in the RAS-DU, to take into account the transformation of the other components in the digester (X_H decay, for example). The default values of the ASM1 parameters were used [3]. The dissolved oxygen concentration was made equal to S_{Ox} = 2 mg L^{-1} in the reactors. With respect to the extension made on the model, the k_{X_p} parameter value used was 0.007 d^{-1} [19].

As a flexible option in Aquasim [21], we chose to represent the traditional sludge wasting (WAS) as a simple reaction that removes mixed liquor solids directly from the aeration tank (Table 4). The rate of such removal is equivalent to the inverse of the sludge age (1/SRT). It can easily be shown that for each type of particulate solid X_j (= X_H, X_P, X_I, X_S, X_A, or ISS), the corresponding stoichiometric coefficient is $-X_j$. The SRT referred to, as computed, does not take into account the solids recovered (inerts) from the screen and the HC. It is a practical way to represent the non-stabilized part of the sludge, which is voluntarily wasted in the traditional way. The 150 d SRT would indicate quasi-total solids retention.

2.3. Process diagram as implemented in Aquasim

The flow sheet of the LSP-AS process was configured in Aquasim by defining the compartments (CSTR tanks) and links, as in Fig. 1. The sludge return line (RAS) was modified by connecting two bifurcations transporting the concentrated solids to the digester (RAS-DU) on one side and to the physical treatments on the other (screen and hydrocyclone). The parts of the flow that were diverted were set through the fractions frQ-to-RAS-DU and frQ-to-Sc-Hc, defined with respect to the total RAS flow rate from the settler (Q_{RAS}, Table 1). When frQ-to-RAS-DU and frQ-to-Sc-Hc are set to 0, the process becomes a traditional activated sludge (C-AS).

Black boxes were defined in Aquasim to simulate the physical processes as a point of material separation (settler, screen, and hydrocyclone, Fig. 1). For each unit operation, a "bifurcation" was drawn, which determines the types and amounts of solids (dry mass flow) to be extracted, and the water flow rate accompanying the separated particles. The settler point-model was set with 100% removal efficiency (Eff-sedim). The bifurcations to represent the screen and hydrocyclone were imbedded between wells 2

Table 3
Main equations used to calculate the concentrations in the mixed liquor

$X_{H\,\mathrm{VSS}} = \frac{\mathrm{SRT}}{\mathrm{HRT}} \times \frac{Y_H(S_0 - S_e)}{1 + k_d\mathrm{SRT}}$	$X_{P\,\mathrm{VSS}} = \mathrm{SRT} \times fp \times k_d \times X_{H\,\mathrm{SSV}}$	$S_e = \frac{K_s\,(1 + k_d\,\mathrm{SRT})}{\mathrm{SRT}\,(Y_H \times k - k_d) - 1}$
(Eq. (1)) Heterotrophic biomass in VSS (mg L^{-1})	(Eq. (2)) Endogenous residues in VSS (mg L^{-1})	(Eq. (3)) Soluble out bio-COD (mg L^{-1})
$X_{I\,\mathrm{VSS}} = \frac{\mathrm{SRT}}{\mathrm{HRT}} \times X_{Io\mathrm{SSV}}$	$\mathrm{ISS}_{\mathrm{TSS}} = \frac{\mathrm{SRT}}{\mathrm{HRT}} \times \mathrm{ISS}_{0\,\mathrm{TSS}}$	SRT: solids retention time HRT: hydraulic residence time (V/Q) $X_{I\,0}$ and ISS_0: values of the parameters in the influent $\mathrm{ivt}_{\mathrm{bio}}$: VSS/TSS ratio of biomass $\mathrm{icv}_{\mathrm{bio}}$: COD/VSS ratio of biomass $\mathrm{icv}_{\mathrm{Influent}}$: COD/VSS ratio in influent
(Eq. (4)) Inert organics in VSS (mg L^{-1})	(Eq. (5)) Inorganic solids (mg L^{-1} TSS)	

$\mathrm{MLVSS} = X_{H\,\mathrm{VSS}} + X_{P\,\mathrm{VSS}} + X_{I\,\mathrm{VSS}}$

$\mathrm{MLCOD} = (X_{H\,\mathrm{VSS}} \times \mathrm{icv}_{\mathrm{bio}}) + (X_{P\,\mathrm{VSS}} \times \mathrm{icv}_{\mathrm{bio}}) + (X_{I\,\mathrm{VSS}} \times \mathrm{icv}_{\mathrm{Influent}})$

$\mathrm{MLTSS} = \frac{X_{H\,\mathrm{vss}}}{\mathrm{ivt}_{\mathrm{bio}}} + \frac{X_{P\,\mathrm{VSS}}}{\mathrm{ivt}_{\mathrm{bio}}} + X_{I\,\mathrm{VSS}} + \mathrm{ISS}_{\mathrm{TSS}}$

Mixed liquor concentrations in VSS ((Eq. (6)), COD (Eq. (7)), and TSS (Eq. (8))

Table 4
Definition of the additional processes used to extend the ASM1

Processes ↓ Components →	X_P	X_S	X_J	Rates
1. Degradation of X_P	−1	+1		$k_{X_P} \times X_P$
2. Activated sludge wasting (WAS)	$-X_P$	$-X_S$	$-X_J$	1/SRT

Notes: k_{X_p}: decay constant (d^{-1}), X_P: endogenous residue, X_S: slowly bio-COD, X_J: one column for ISS and each of the particulate components of the ASM1 (X_I, X_{ND}, etc.), and SRT: retention time.

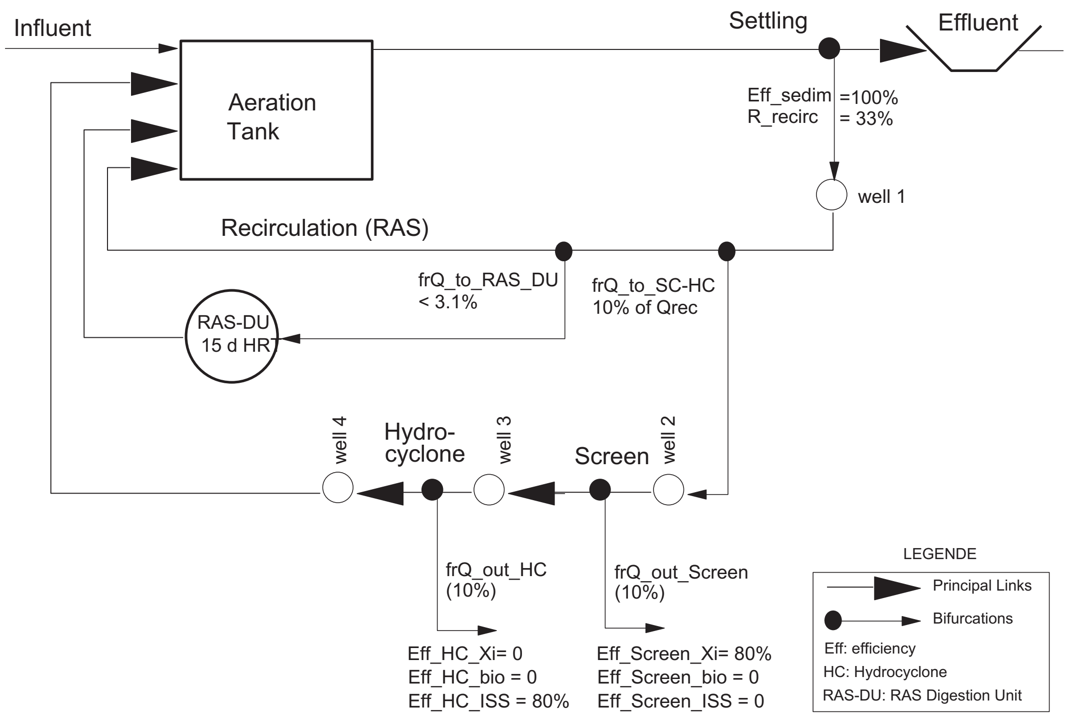


Fig. 1. Flow diagram implemented in Aquasim to simulate the LSP-AS process.

and 3, vs. between wells 3 and 4, respectively. Selective separation is obtained at these levels, defining three types of efficiencies depending on the types of solids:

(1) X_I removal efficiency (Eff_X_I).
(2) ISS removal efficiency (Eff_ISS).
(3) Efficiency on the biological materials X_H, X_P, X_S, and X_A (Eff_bio).

For the physical units, Eff_bio was set to 0%, while Eff_X_I and Eff_ISS were fixed at 80 and 0% in the sieve, against 0 and 80% at the hydrocyclone (HC).

The visiting registers or wells (1–4) are small virtual basins of only 1 m^3 that are used in the program to be able to calculate the concentrations at determined intermediary points (initial concentrated sludge quality; before and after the screen, the HC, and the RAS-DU). No WAS flow is visible in the diagram, in accordance with the method chosen to represent the wastage (Table 4 before).

2.4. Sequence of the simulations and outputs

The final program implemented in Aquasim was endowed with a high flexibility to allow its use to gradually explore different scenarios, ranging from the conventional activated sludge process (C-AS) to complete sludge retention (LSP-AS variant). Extended aeration C-AS may be simulated simply by closing the valves (frQ-to-RAS-DU and frQ-to-Sc-Hc = 0), changing the SRT to 25 d, and deactivating the calculation in some of the compartments (RAS-DU and wells 2, 3, and 4). To begin the mutation toward a low-sludge production process (LSP-AS), the SRT must first be changed to 150 d. To simulate the removal of X_I and

ISS through the sieve and HC, frQ-to-Sc-Hc should be set at 0.1 (10% of the RAS) after reactivating the calculation in the compartments. To add the digester and successfully degrade X_P, frQ-to-RAS-DU should be fixed at 0.0303 (or 3.03% of the RAS flow, as a first scenario), which allows operation of the 1,500 m^3 digester unit at 15 d SRT (also = HRT). Later, several other scenarios may be tested with different digester volumes, HRTs, and inflows.

The simulations were focused on static conditions (constant flow rates and constant concentrations in the influent). At the initial time for each simulation, the initial conditions artificially imposed in the basins may change the trajectories of the output curves (concentration–time). However, the long-term behavior of the calculated parameters (concentrations) is not affected and reaches a steady state plateau, which is information of interest. In some scenarios, the steady state will never be observed in the time window of the simulation. The apparent behavior for these cases is a continuously rising curve, indicating excessive accumulation of the compound in question for all practical purposes.

3. Results and discussion

3.1. Relation between the SRT and sludge production in C-AS processes

This analysis was conducted to illustrate some basic features of traditional activated sludge (C-AS) and to clearly identify the needs of a future LSP-AS process (total biological solids retention). Calculations at the beginning with Excel (on the basis of the steady state Eqs. (1)–(8), Table 3) were also a way to verify proper operation of the simulation program developed later in Aquasim.

The variables related to the quality and quantities of sludge in the reactor were calculated at different SRTs (Fig. 2). At 15 d SRT, for instance, the composition of the mixed liquor would be 687 mg L^{-1} X_H, 524 mg L^{-1} X_P, 667 mg L^{-1} X_I, and 450 mg L^{-1} ISS, for a total of 2,230 mg L^{-1} MLTSS or 1,780 mg L^{-1} MLVSS. The ivt and icv ratios of the mixed liquor as a whole, in this case, would be 0.77 g VSS g^{-1} TSS and 1.45 g COD g^{-1} VSS, while the net sludge production would be 0.4 mg TSS per mg biodegradable COD (observed yield, Yobs). These results were verified and in total accordance with the predictions made in parallel with the simulation in Aquasim.

According to Fig. 2(a), increasing the SRT would be one of the ways to reduce the sludge generated (Y_{obs}). This strategy is already practiced with extended aeration activated sludge. For the case studied, increasing the operational SRT will decrease Y_{obs} from 0.51 to 0.3 g TSS g^{-1} COD. An additional feature associated with high SRTs is the reduction of the active biomass fraction (X_H/X_T), which could reach values as low as 20% or less (Fig. 2(a). At high SRTs (>50 d), the total concentration of solids (MLTSS, Fig. 2(b)) in the mixed liquor will be so high that it would be impossible to satisfactorily perform the process. It would be difficult to meet the aeration and the mixing needs in an economic way.

Fig. 2(b) shows the detailed composition of the mixed liquors at different values of SRT. From a certain residence time (>20 d), the concentration of active biomass (X_H) reaches a plateau, which is dictated by the amount of substrate available in the influent. However, unlike the active biomass, the MLTSS continue to increase sharply with the SRT due to the continuing accumulation of inert matter in the mixed liquor (X_I, X_P, and ISS).

Therefore, wasting the active biomass (X_H) is not a requirement, while it remains necessary to extract from the process the same amounts of X_I and ISS driven in the influent and X_P generated in the aeration basin. In conventional activated sludge as well as in low-sludge production processes, wastage of solids must be performed anyway. However, ideally, the solids removed from the latter type of process (from the hydrocyclone and sieves) are inert matter that should not require any further stabilization.

In summary, the analysis performed in this section clearly shows the functional requirements of the activated sludge processes operated with low active biomass wasting, that is, at high SRTs or complete solids retention. The needs are to minimize the amount of putrescible waste sludge while maintaining the mixed liquor concentrations at acceptable levels. The challenge in such processes (LSP-AS) would be to achieve a selective removal or destruction of the components X_I, X_P, and ISS. This subtends the logic in the Cannibal™ process, for example [4,5], with a sieve to remove X_I, hydrocyclone to separate the ISS, and a digester to degrade X_P.

3.2. Simulation of the C-AS process in Aquasim (from 25 to 150 d SRT)

The first simulation performed on Aquasim was for conventional activated sludge (C-AS) at 25 d SRT. Typically, this is an extended–aeration variant type, usually chosen to minimize the sludge in small WWTP. For comparison, the simulation was also carried out at other different SRTs up to 150 d, which in practice represents a hypothetical process operated without purging (no WAS).

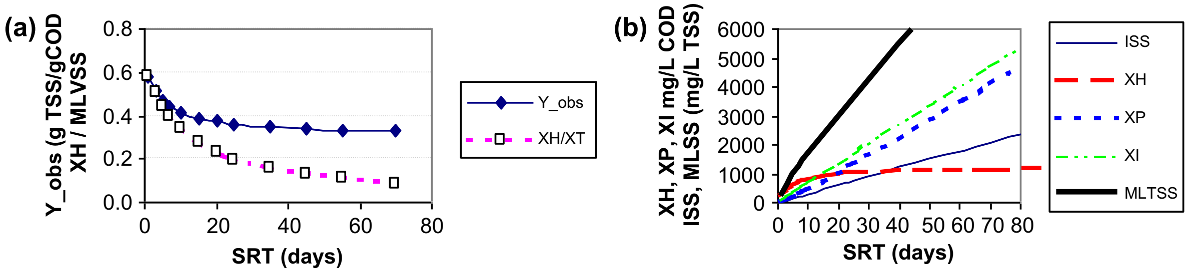


Fig. 2. Sludge production of the C-AS process (a) and composition of the sludge (b).

Fig. 3 shows the composition of the sludge in the reactor at 25 d SRT compared to 150 d (i.e. practically without WAS). The area of interest is where the curves reach the steady state plateau.

At 25 d SRT, the conventional activated sludge process works with concentration levels that are stable and acceptable for all the mixed liquor components (Fig. 3, left). In this case, the MLTSS stabilize at 3,600 mg L^{-1}, which includes 750 mg TSS L^{-1} of active biomass (X_H). At 150 d SRT (Fig. 3, right), the active fraction is 890 mg L^{-1} TSS, which remains stable and is not very different from the previous value (at 25 d). In contrast, X_I, X_P, and ISS, and thereby the MLTSS in the mixed liquor, tend to accumulate, reaching unsustainable high levels at the end (>10,000 mg L^{-1}, Fig. 3, right). At the time of this writing, it seems clear that all C-AS that claim to be able to run in complete solid retention mode actually need additional processes to remove the excess X_I, X_P, and ISS (not necessarily the X_H).

In conclusion, the tendency of the inert matter (ISS X_I) and of endogenous residues (X_P) to accumulate in conventional activated sludge processes operated without sludge wastage contradicts total solids retention claims without special mechanisms that remove these fractions.

3.3. Simulation of the effects of the screen and hydrocyclone

From this point on, the system under study is the modified activated sludge system (LSP-AS) equipped with a screen and a hydrocyclone [6,7] and operated at 150 d SRT (i.e. practically with the WAS valve closed). By installing the sieve and the hydrocyclone on the process, the aim was to prevent the accumulation of X_I and ISS. This inert matter behaves as a tracer injected in the influent at a constant rate, so the equilibrium concentrations in the reactor depend only on the fraction of RAS flow sent and treated in the physical units (frQ-to-Sc-Hc). The relationship between the concentration of inert matter in the reactor and the flow rate sent to the physical treatment is given in Fig. 4.

As a reminder, the levels of the components X_I and ISS in the reactor of conventional C-AS, operated at 150 d SRT, were approximately 6,600 and 4,500 mg TSS L^{-1}, respectively. By adding the screen and hydrocyclone, these levels drop abruptly to approximately 250 mg L^{-1}, with a flow fraction lower than 10% of the RAS flow (Fig. 4). A greater flow does not contribute to major decreases in the levels. The concentration of X_I and ISS in the reactor may be lowered to the same values or less of that existing in standard C-AS operated without sieves at 25 d SRT (1,110 mg L^{-1} X_I and

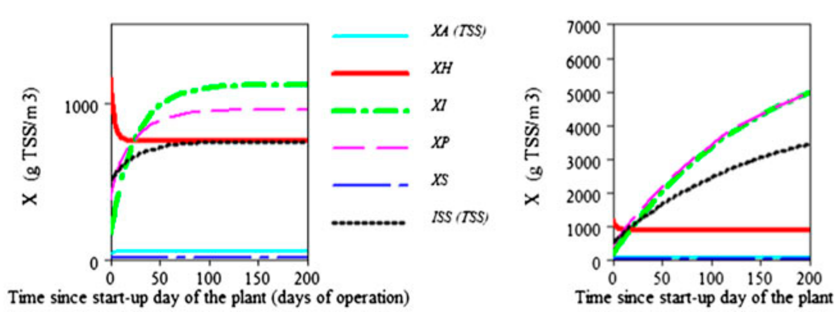


Fig. 3. Mixed liquor composition of the C-AS process at 25-d SRT (left) and 150-d SRT (right).

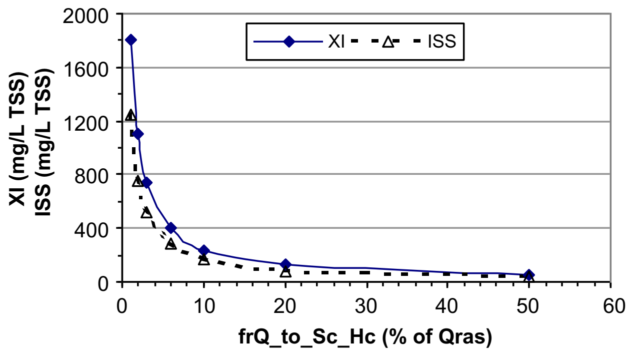


Fig. 4. Concentration of X_I and ISS in the reactor as a function of frQ-to-Sc-Hc.

750 mg L^{-1} ISS). An frQ-to-Sc-Hc of 2% (or 63 m^3 d^{-1}) applied to the LSP-AS process, operated at 150 d SRT (closed WAS), is enough to achieve these desired levels (Fig. 4). By treating 6% of the RAS flow, the final TSS concentrations in the mixed liquors will be 240 mg L^{-1} of X_I and 165 mg L^{-1} of ISS, which are much less than the levels in a standard C-AS at 25 d SRT.

Fig. 5 shows the composition of the mixed liquor over time, when the modified process is operated with a sludge age of 150 d (practically without purge) and approximately 2% of the recirculation flow rate (RAS) is treated through the screen and hydrocyclone.

In contrast with the behavior previously noted in Fig. 3, right, all the fractions (X_I, ISS, X_H, X_A, and X_S) are now controlled (Fig. 5) to a stable and acceptable level; however, X_P would continue to accumulate at the moment because it is not yet treated.

In summary, for the studied case and regarding the feasibility of the physical operations, the simulation shows that diverting and treating 2% of the RAS flow would be enough to prevent the accumulation of X_I and ISS, which reach the same levels achieved in a C-AS process operated at 25 d.

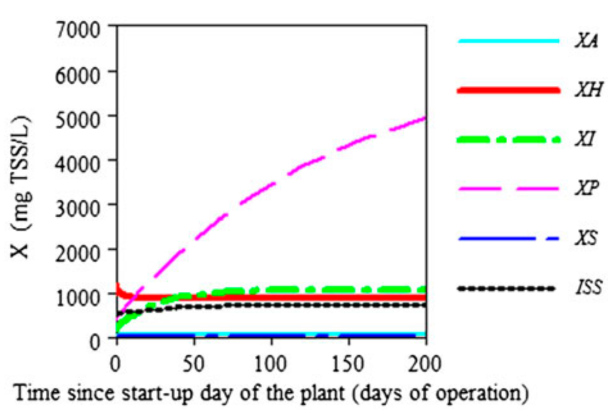


Fig. 5. X_I and ISS under control in the aeration tank (frQ-Sc-Hc = 2% of Q_{RAS}, 150 d SRT).

3.4. Simulation of the degradation of X_P in the online digester

By installing an aerobic digester (RAS-DU) through the RAS line of the LSP-AS process, the aim was to prevent the accumulation of X_P and maintain its concentration at an acceptable level. The excess X_P should be eliminated at the same rate that it is produced by decay in the reactor and in the digester itself. Starting with a 15-d HRT recommended earlier for the RAS-DU unit [5], the corresponding flow fraction (frQ-to-RAS-DU) to be directed to the digester is approximately 3% of the total RAS flow.

From a theoretical point of view, both for the first scenario (15-d HRT) as for others, it is possible to estimate the X_P removal efficiency that will be reached in the RAS-DU itself. In general, assuming a first-order kinetic rate law and assuming the digester to be a completely stirred tank reactor (CSTR), the relationship between the hydraulic residence time (HRT) and efficiency (E) of removal of X_P between the inlet and outlet of the digester is given by the following equation:

$$E = \frac{\text{HRT} \times k_{X_P}}{(1 + \text{HRT} \times k_{X_P})} \tag{9}$$

E: efficiency for a given HRT (values of E expressed as fractions between 0 and 1); and k_{X_p}: first-order constant (d^{-1}).

The above equation allows calculating the X_P removal efficiency that can be reached with a k_{X_p} magnitude value of approximately 0.007 d^{-1}, as suggested in various studies. For 15 d HRT, the value of E is 0.095 (or 9.5%), against 30% at 60 d.

For each HRT (and thus for each efficiency), the required volume can be calculated for different flow rate scenarios (frQ-to-RAS-DU). Different combinations of flow rates and digester volumes were tested in the simulator (Table 5). Efficiencies greater than 50% require unrealistic HRTs, which therefore were not tested.

The first scenario in Table 5 (V = 1,500 m^3 and frQ-to-RAS-DU = 3.03%) corresponds to the criterion of 15-d HRT in the digester, as in [5]. The expected efficiency (9.5%) can now be calculated, based on the knowledge of the k_{X_p} order of value (0.007 d^{-1} [18]).

Beyond the efficiency in the digester, the final response of interest from the simulations is the level

Table 5
Concentration of X_P in the aeration tank for the different scenarios

frQ-to-RAS-DU (%) =>		3.03%	6%	10%	20%
Q-to-RAS-DU (m^3/d) =>		100	198	330	660
E (%)	HRT (d)	Conc. of X_P in Reactor (mg/L TSS)			
9.5	15	2,510	1,940	1,480	930
17.4	30	1,980	1,360	960	
29.6	60	1,450	900	590	
38.7	90	1,200	700		
45.7	120	1,030			
51.2	150	930			

of X_P that is consequently reached in the aeration tank for each scenario. These values are reported in Table 5 (from 3,450 to 565 mg L^{-1} TSS).

As a reference, the concentration of endogenous residues reached in the C-AS process operated with a closed RAS (SRT of 150 d) was hypothetically estimated at 6,600 mg L^{-1} TSS. The LSP-AS scenarios that allow lowering these levels to near those of a standard C-AS satisfactorily operated at 25 SRT are identified in color in Table 5 (residual X_P of approximately 950 mg L^{-1} TSS).

The volume of the RAS-DU unit for the best scenarios was between 10,000 and 15,000 m^3, which is 1.7–2.5 times the volume of the aeration tank, or three to five times the volume of an off-line stabilization digester. This is information that can help to evaluate the advantages and disadvantages of the complete solids retention processes (LSP-AS).

Another important aspect in the choice of the most viable alternatives is the impact of the online digester and its long HRTs on the active biomass fraction X_H. More biomass decay will result in the RAS-DU unit. Table 6 shows the simulated concentrations of X_H, MLTSS, and MLVSS in the aeration basin for each of the previously retained four scenarios. The value of X_H registered a sharp drop in scenarios 3 and 4 (490 and 370 mg L^{-1}), compared to the value of 750 mg L^{-1} TSS that prevailed in the reference scenario (C-AS at 25 d SRT). Between the other two remaining scenarios, the digester option 2 seems to be the best compromise (shorter HRT, 60 d, and smaller volume).

The final levels of X_P and MLTSS in the aeration tank are under control, for all the four scenarios of Table 6. In particular, for the selected scenario 2, the endogenous residue concentrations between the input and the output of the digester decreased from 3,600 to 3,070 mg L^{-1} TSS. This allowed the final level of X_P to be kept under control in the aeration tank (approximately 900 mg L^{-1} TSS). In contrast to the behavior that was observed earlier in Fig. 5, now all the fractions X_P, X_I, X_H, and ISS are reduced to reasonable and stable levels in the aeration basin (Fig. 6(a)).

Finally, other aspects of the performance of scenario 2 were studied. On average, the oxygen uptake

Table 6
Heterotrophic biomass (X_H) and MLTSS concentration in the aeration tanks

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Reference
frQ-to-RAS-DU (%) =>	3.03%	6%	10%	20%	no digester
HRT of digester	150 d	60 d	30 d	15 d	C-AS process
Digester volume	15,000 m^3	11,880 m^3	9,900 m^3	9,900 m^3	25 d SRT
Concentrations (mg/L TSS) in the aeration tanks					
X_P	930	900	960	930	950
X_H	690	590	490	370	755
MLTSS*	3,450	3,300	3,250	3,090	3,600
Digester TSS*	9,670	10,460	11,100	11,230	–

*with the screen and HC in service (frQ_to_Sc_HC = 2%).

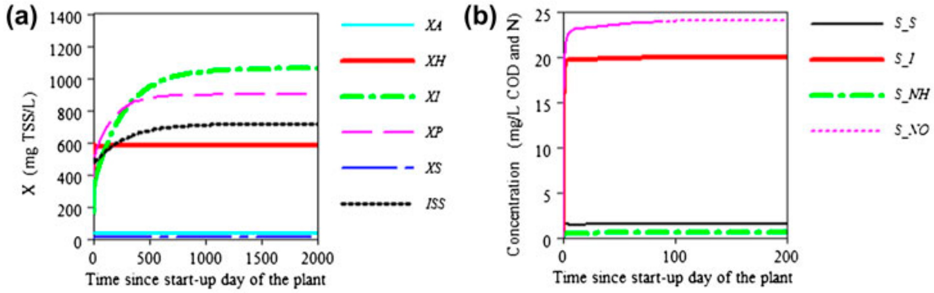


Fig. 6. Final concentration of the fractions in the aeration tank (a) and treated effluent quality (b).

rate (OUR) in the aeration basin was estimated at 40 mg L^{-1} h, including 30 mg L^{-1} h due to the nitrification. The COD and nitrogen concentrations in the treated effluent (Fig. 6(b)) testify to good performance of the nitrification (>24 mg L^{-1} N-NO_3 produced) and of the organic matter removal. The ammonia nitrogen (S_{NH}) and the biodegradable organic matter (S_S) were reduced to less than 2 mg L^{-1}. As expected, the level of the soluble inert COD in the effluent remained equal to that of the influent.

In summary, with respect to the control of the endogenous residues, the simulations showed that with a k_{X_p} of approximately 0.007 d^{-1}, a treatment with 6% of the RAS flow in the online digester would avoid the buildup of the X_P components in the aeration basin. The mathematical model implemented in Aquasim could serve as a didactical, operational, and research simulation tool for LSP-AS processes.

4. Conclusions

(1) The modified ASM1 model, including the slow degradation process of endogenous residues (X_P) in a digester, combined with black boxes representing the physical removal of the inert matter (X_I and ISS), adequately reproduced the apparent behavior of activated sludge with low-sludge production (LSP-AS).
(2) The tendency of the components X_I, ISS, and X_P to accumulate in activated sludge operated without wastage contradicts total solids retention claims in processes that do not have special mechanisms to remove these fractions.
(3) According to the simulations performed, a conventional activated sludge process (C-AS) may be replaced by an LSP-AS process (sieve, HC, and online RAS digester) that would operate with similar levels of active biomass and MLTSS in the aeration basin.
(4) For the studied effluent, the online treatment of 2% of the RAS flow, with screens and hydrocyclones (80% efficiency) in an LSP-AS process would prevent the accumulation of X_I and ISS, reaching the same levels as in a conventional C-AS process operated at a 25 d SRT.
(5) Regarding the endogenous residues and the k_{X_p} value of approximately 0.007 d^{-1}, the modeling showed that treating 6% of the RAS flow in the online digester will avoid the buildup of the X_P components in the aeration basin. The volume of the RAS-DU required would be approximately twice the volume of the aeration basin.
(6) The model and the simulation program implemented in Aquasim could serve in process optimization, training, and as an experimental design tool in low solids production variants of activated sludge.

Acknowledgments

Thanks to Consejo Nacional de Ciencias y Tecnología, CONACYT CB10-152,943 (Mexico). Many Thanks also to École Polytechnique de Montréal (Quebec, Canada) and the Autonomous University of the State of Mexico (UAEM).

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