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Control of an alternating aerobic–anoxic activated sludge system — Part 2: optimization using a linearized model

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Abstract

Complex models, such as activated sludge model No. 1 (ASM1), have rarely been used in practice for process control or optimization. One major reason for this is the computational effort demanded by these models for both parameter estimation and simulation. Therefore, a linearized version of the ASM1 model is developed and applied to the control and optimization of a bench-scale alternating aerobic/anoxic activated sludge system. The model prediction was used to optimize the aeration time by manipulating t_c (total cycle time) and f_a (fraction of aeration cycle time) while meeting the permit requirement of the effluent ammonia concentration. The linear nature of the model facilitates its use for on-line calculations, and error feedback is used to counteract problems of model inaccuracy. The model was applied to two cases in which the influent compositions were either known currently or only the previous day's information was available. The average optimized f_a was found to be 0.30 for the first case and 0.37 for the second case, when the maximum effluent NH_4^+–N concentration was set at 1 mg/l. The efficiency of nitrogen removal was 76% for both test cases since nitrate could almost completely be removed through adequate anoxic cycle ratios resulting from the f_a optimization. © *2000 Elsevier Science Ltd. All rights reserved.*

Keywords: Optimization; Process control; Alternating aerobic–anoxic; Nitrogen control

1. Introduction

Nitrogen removal in wastewater can be easily accomplished by separate stages of nitrification (biological ammonia oxidation to nitrate) and denitrification (biological nitrate reduction to N_2) with the addition of external carbon (e.g., methanol) or more appropriately, in a variety of single-activated sludge systems by recycling the nitrified mixed liquor to the pre-anoxic tanks. These spatially alternated conditions provide suitable environments for aerobic nitrification and anoxic denitrification. Nevertheless, the energy associated with the high internal recycle flow (typically four times the influent wastewater flow rate) and the additional tankage volume needed for particular biological functions often limit their applications, specifically in the retrofitting of existing plants.

In contrast with the space-oriented processes above, time-oriented processes, such as SBR (sequencing batch reactor) and AAA (alternating aerobic/anoxic) techniques, can easily be incorporated into the existing nitrogen removal plants. In the AAA process, for example, a simple sequence of air-on/off cycles in activated sludge systems can provide nitrogen removal efficiencies of 70–90% (Ip, Bridger & Mills, 1987; Heduit, Duchene & Sintes, 1990; Nakajima & Kaneko, 1991; Hao & Huang, 1996; Sakai, Miama & Takahashi, 1997; Klapwijk, Brouwer, Vrolijk & Kujawa, 1998). The AAA process offers significant energy savings as well as high O_2 transfer efficiency during the initial period of aeration, in addition to the other advantages of single activated sludge systems, e.g., partial recovery of alkalinity lost through nitrification, a stable pH, and a slightly reduced sludge yield. Despite their apparent advantages, the use of these temporally alternated systems is not widespread, partially due to conservative nature of design engineers.

Generally, the operating sequence and the duration of each cycle (e.g., 2 hs air on and 2 hs air off in the AAA systems) are fixed in the time-oriented processes. Thus, under hydraulic and/or organic/nitrogen shock loading conditions, the process is *still* operated with the

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previously set cycle times resulting in degraded effluent quality. To provide operational flexibility, the need for process control is apparent, specifically, at the point of initiating/terminating the different cycles or when determining the duration of any particular biological cycle. For example, an inadequate air-off period would result in incomplete denitrification, and a prolonged anoxic period may present potential odor problems since anaerobic fermentation occurs after the disappearance of nitrate. By the same token, the prolonged aeration after the end of nitrification not only wastes energy but also may affect sludge settleability.

Unfortunately, on-line monitoring of ammonia and nitrate in the mixed liquor is too difficult and impractical to offer real-time control, due to its maintenance requirements. In the future, however, advanced instrumentation may facilitate on-line real-time process control. Consequently, this study was undertaken to find an optimization scheme to adjust both the fraction of aeration time (f_a) and total cycle time (t_c), two important parameters identified by Batchelor (1982,1983). Although the industrial standard of the popular activated sludge model No. 1 (Henze, Grady, Gujer, Marais and Matsuo, 1986) has been successfully used to model AAA process dynamics (Huang & Hao, 1996), the application of this complex model for process control is expected to be limited since it involves too much computational effort. As a result, the linearized model developed in the accompanying paper (Anderson, Kim, McAvoy & Hao, 2000) was used for the daily on-line control and optimization of a laboratory AAA reactor. Since the linearized model is essentially based on the concept of the ASM1, it still reflects its underlying fundamentals despite its simplicity. Model inaccuracy can be counteracted using reactor feedback information. In an earlier paper (McAvoy, Anderson, Hao, Boger & Kim, 1999) simulation results for the algorithm discussed here were presented. In this paper, experimental results are presented.

Essentially, the control of the AAA system is based on the optimization of the model predictions, given a set of effluent nitrogen measurements reflecting the current state (or recent history) and influent composition. The optimization was performed for two cases. In the first case study, the current influent composition was known. In the second, previous day's composition was available. In both cases, the mismatch between model prediction and real data was fed back into the optimizer for the model correction.

2. Materials and methods

2.1. Experimental set-up and reactor operation

A bench scale AAA system was seeded with a mixed liquor sample from the local Parkway Wastewater Treatment Plant in Bowie, Maryland. The reactor is made of acrylic fiber plastics and has 5 l of working volume, with 4 l of the reactor volume and 1 l of the clarifier volume. The settled sludge in the clarifier was recycled internally (Fig. 1). The MCRT (mean cell residence time) was maintained at 12 days, and HRT (hydraulic retention time) at 12 hs. Saturated air was used for aeration and mixing in the reactor during air-on periods. Mixing to the AAA

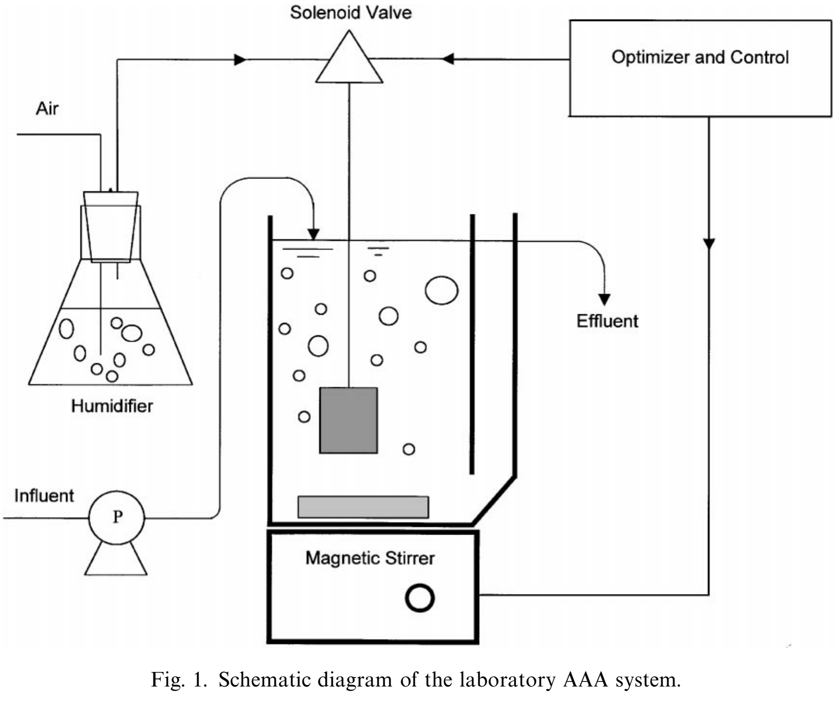

Fig. 1. Schematic diagram of the laboratory AAA system.

reactor during air-off periods was provided by a magnetic stirrer. During air-on periods, the DO concentration of the reactor was maintained above 5 mg/l. To minimize the attached growth of microbes on the reactor wall, cleaning the wall with a brush was performed daily.

The effluent from the primary clarifiers of the same local plant was collected twice a week, stored in a refrigerator and used as influent feed for the reactor. The influent feed was stored in a 15 l glass reservoir equipped with a turbine mixer to keep the feed wastewater homogeneous with intermittent mixing. The feed tank was immersed in an ice water tank at about 10°C. The influent feed reservoir was replenished daily with fresh wastewater. The wastewater in the reservoir was transferred to the reactor by a peristaltic pump (Cole–Parmer Masterflex 7518-00). A 15 l glass bucket was used to collect the effluent from the reactor.

Wastewater to the local plant was primarily of domestic origin, and typical raw wastewater usually consisted of total chemical oxygen demand (COD) of 150–350 mg/l, total Kjeldahl nitrogen (TKN) of 25–35 mg/l, and NH_4^+–N of 13–25 mg/l. An additional synthetic carbon source (a mixture of sodium acetate, methanol and ethanol) equivalent to 60 mg/l of COD was added into the reactor to provide adequate COD/N ratio.

The influent wastewater samples were collected from the influent reservoir just after the reservoir was refilled for analyses. Effluent samples for the system were taken from the effluent storage tank. The COD and TKN of the influent and effluent was measured every 3–4 days. NH_4^+ and NO_3^- were measured on a daily basis. The sample analyses followed the procedures in the Standard Methods (1995).

2.2. Optimization overview

The goal of the study was to control and optimize the operation of an AAA-activated sludge reactor, specifically referring to t_c and f_a. Because operating costs are directly related to the amount of aeration time, the goal was to select the optimal t_c and f_a values which minimize the energy costs while meeting the discharge limit of NH_4^+. During most of the study, a nominal limit of 1 mg NH_4^+–N/l was used. The optimization routine exploited a simple model of the AAA reactor to project daily average effluent levels of the NH_4^+ while making use of the most recently available measurement data. The routine then recommended values t_c and f_a based on the results from the model simulations.

It was assumed that the plant operator would have the laboratory results of either the previous day's or current day's influent compositions and the effluent quality, and the parameters t_c and f_a were then set at fixed values for the current day's operation. The measured parameters are the soluble and particulate COD (S_S and X_S), soluble and particulate organic nitrogen, ammonia, and nitrate. The optimizer and model were implemented for 75 days using current influent composition. Thereafter, the control scheme was run using only measurements available on the previous day.

In the first case it was assumed that the composition of the influent (at the time when the operator measured) would not change much for the rest of the day. The prediction duration was set at one day, since the on-line instruments for the key state variables (NH_4^+ and NO_3^-) of the influent and effluent were not available. However, in plants where such instrumentation is available, the optimization can be run after each cycle, allowing for more frequent manipulation of control parameters t_c and f_a. Because of the time constraint of the availability of current results, the second case with delayed results used the same assumption that water quality was similar.

2.3. Linearized model and optimizer

The linearized model in a matrix form is presented in Table 1. The calibrated model was run to predict eight values for the day ahead, starting from their initial values, and eventually provided the optimal values for the control variables, f_a and t_c. The eight values are S_S and X_S, denitrifying and nitrifying bacteria concentration (X_{BH} and X_{BA}), effluent concentration of the three nitrogen species [ammonia nitrogen (S_{NH}), nitrate nitrogen (S_{NO}), and soluble organic nitrogen (S_{ND})], and the particulate organic nitrogen compounds (X_{ND}). In this study, since a high DO concentration was maintained during the aeration cycle, it was assumed that the dissolved oxygen was not a limiting nutrient. Details of the linearized model are provided elsewhere (Anderson, Kim, McAvoy & Hao, 2000).

The predictions of the linearized model were incorporated into an optimization scheme in the following way. For controlling plant effluent, the two control variables, t_c and f_a, are manipulated in order to minimize energy costs, subject to meeting the permitted effluent restriction. The control/optimization problem that is solved is

$$\min_{t_c,\, f_a} \{\text{cost}\}. \tag{1}$$

S.t.

$$NH_4^+ - N \le NH_4^+ - N_{\max},$$

$$f_a \times t_c \ge t_1,$$

$$(1 - f_a)t_c \ge t_2,$$

$$f_a \times t_c \le t_3,$$

$$(1 - f_a)t_c \le t_4,$$

where NH_4^+–$N_{\max}$ is the maximum allowable value of the average daily NH_4^+–N concentration in the effluent. The constants t_1, t_2, t_3, and t_4 represent corresponding time

Table 1
Process kinetics and stoichiometry in the linearized model

	Component	$i \rightarrow$	1	2	3	4	5	6	7	8	Process Rate,	ρ_i $[\mathrm{ML}^{-3}\mathrm{T}^{-1}]$
			S_S	X_S	X_{BH}	X_{BA}	S_{NH}	S_{NO}	S_{ND}	X_{ND}		
	Process	$j\downarrow$									Aerobic cycle	Anoxic cycle
1	Aerobic growth of heterotrophs		$\frac{1}{Y_H}$		1		$-i_{XB}$				$\mu_H J_1 S_S$	0
2	Anoxic growth of heterotrophs		$-\frac{1}{Y_H}$		1		$-i_{XB}$	$-\frac{1-Y_H}{2.86Y_H}$			0	$\mu_H \eta_g J_2 S_S$
3	Aerobic growth of autotrophs					1	$-i_{XB}-\frac{1}{Y_A}$	$\frac{1}{Y_A}$			$\mu_A J_3 S_{NH}$	0
4	Decay of heterotrophs			$1-f_\rho$	-1					$i_{XB}-f_p i_{XP}$	$b_H X_{B,H}$	$b_H X_{B,H}$
5	Decay of autotrophs			$1-f_\rho$		-1				$i_{XB}-f_p i_{XP}$	$b_A X_{B,A}$	$b_A X_{B,A}$
6	Ammonification of soluble organic nitrogen						1		-1		$k_a J_4 S_{ND}$	$k_a J_4 S_{ND}$
7	Hydrolysis of entrapped organics		1	-1							$k_h J_6 X_S$	$k_h \eta_h J_5 X_S$
8	Hydrolysis of entrapped organic nitrogen								1	-1	$k_h J_6 X_{ND}$	$k_h \eta_h J_5 X_{ND}$
	Observed conversion rate $[\mathrm{ML}^{-3}\mathrm{T}^{-1}]$						$r_i = \sum_j \nu_{ij}\rho_j$					

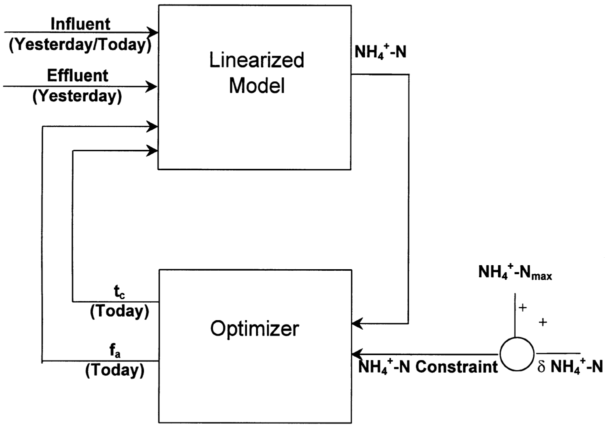

Fig. 2. Optimization scheme for an AAA system.

constraints. In Eq. (1), the cost of the operation that can be minimized is assumed to be only associated with the time that air is being turned on. Other costs such as those associated with pumping and mixing are neglected. The second and third constraints deal with the minimum air-on and air-off cycle time. If there were no constraints on the air-on time, the optimizer would tend to drive f_a toward 0, and this would eventually result in a washout of the X_{BA} bacteria. During this study, the lower limit of each cycle ranged from 0.5 to 1 h. Further reduction of the lower limit was not considered, since 0.5 h was assumed to be the minimum that could be accepted by the plant so as not to cycle the blowers frequently and to avoid washout of nitrifiers. The fourth and fifth constraints deal with the maximum air-on and air-off cycle time. During the study, the upper limit of each cycle was set at 4 h (t_3 and $t_4 = 4$ h).

The linearized model was used to solve the optimization problem given by Eq. (1). The optimization scheme is illustrated in Fig. 2. The prediction of the linearized model was for a average daily effluent of NH_4^+-N. To initiate the optimizer, it is assumed that the model predicts perfectly the actual plant data, i.e., $\Delta NH_4^+\text{-N} = 0$, where ΔNH_4^+-N is defined as

$$\Delta NH_4^+ - N = NH_4^+ - N_{real} - NH_4^+ - N_{prediction}. \quad (2)$$

The optimizer is fed with both the predicted NH_4^+-N and the constraint value for $NH_4^+\text{-N}_{max}$ (1 mg/l). The optimizer then manipulates f_a and t_c to solve this optimization problem and to meet other constraints in Eq. (1). The approach illustrated in Fig. 2 may not precisely meet the permitted requirements of the real process, because there will certainly be some inaccuracy in the predictions of the linearized model due to the assumptions and simplifications involved in its development. This inaccuracy is referred to as plant model mismatch. The following section addresses an approach to overcome this problem and force the optimizer to exactly track the actual reactor NH_4^+.

2.4. Plant model mismatch correction

An important issue that needs to be considered in using the linearized model for control is the mismatch existing between the model and the system it attempts to describe. This mismatch is due to both modeling errors and the effect of unmeasured disturbances. Feedback of information can be used to deal with this mismatch as follows.

On the first day of the AAA operation, the solution of Eq. (1) provides the estimated t_{C1} and f_{a1}. When these values are implemented in the reactor, the actual NH_4^+-N, measured at the end of the first day differs from that predicted by the linearized model; this difference is defined in Eq. (2). To counteract this plant model mismatch, one can subtract ΔNH_4^+-N from the value of $NH_4^+\text{-N}_{max}$ to bring the actual effluent NH_4^+-N closer to the constraint. For example, if $NH_4^+\text{-N}_{prediction}$ is 1 mg/l, and the actual NH_4^+-N is 0.8 mg/l, then the NH_4^+-N constraint can be increased to 1 mg/l minus the difference of -0.2 mg/l, and set at 1.2 mg/l. This method of overcoming the plant model mismatch is essentially the same as that used in commercially successful dynamic matrix control (Culter & Ranaker, 1979). The use of the Δ correction to the constraint involves feedback from the plant. To make this feedback robust and to avoid responding too sharply to daily fluctuations, the δ correction was implemented as an exponentially weighted moving average. The δ equation used is

$$\delta NH_4^+ - N|_{today} = 0.5 \times \Delta NH_4^+\text{-N} + 0.5 \times \Delta NH_4^+\text{-N}_{yesterday}, \quad (3)$$

where $\Delta NH_4^+\text{-N}_{yesterday}$ is the previous day's calculated mismatch value. As shown below, the result of this approach seldom violates the desired constraint for NH_4^+-N, even though it is applied to a real system with varying input compositions.

3. Results and discussion

Initially, the bench scale AAA system was controlled based on the linearized model prediction with current influent composition and the effluent data from the previous day's operation. For control, the influent composition of the current day and the error from the mismatch between the model prediction and the actual effluent data were fed into the model. Then the optimizer used the model to provide the optimized f_a and the total cycle t_c. The conditions for the optimization were initially set as follows. The maximum allowable concentration of effluent NH_4^+-N was initially set at 1.5 mg/l; the lower limit of each cycle mode was 1 h; and the upper limit was 2.5 h. This corresponds to the maximum and minimum total

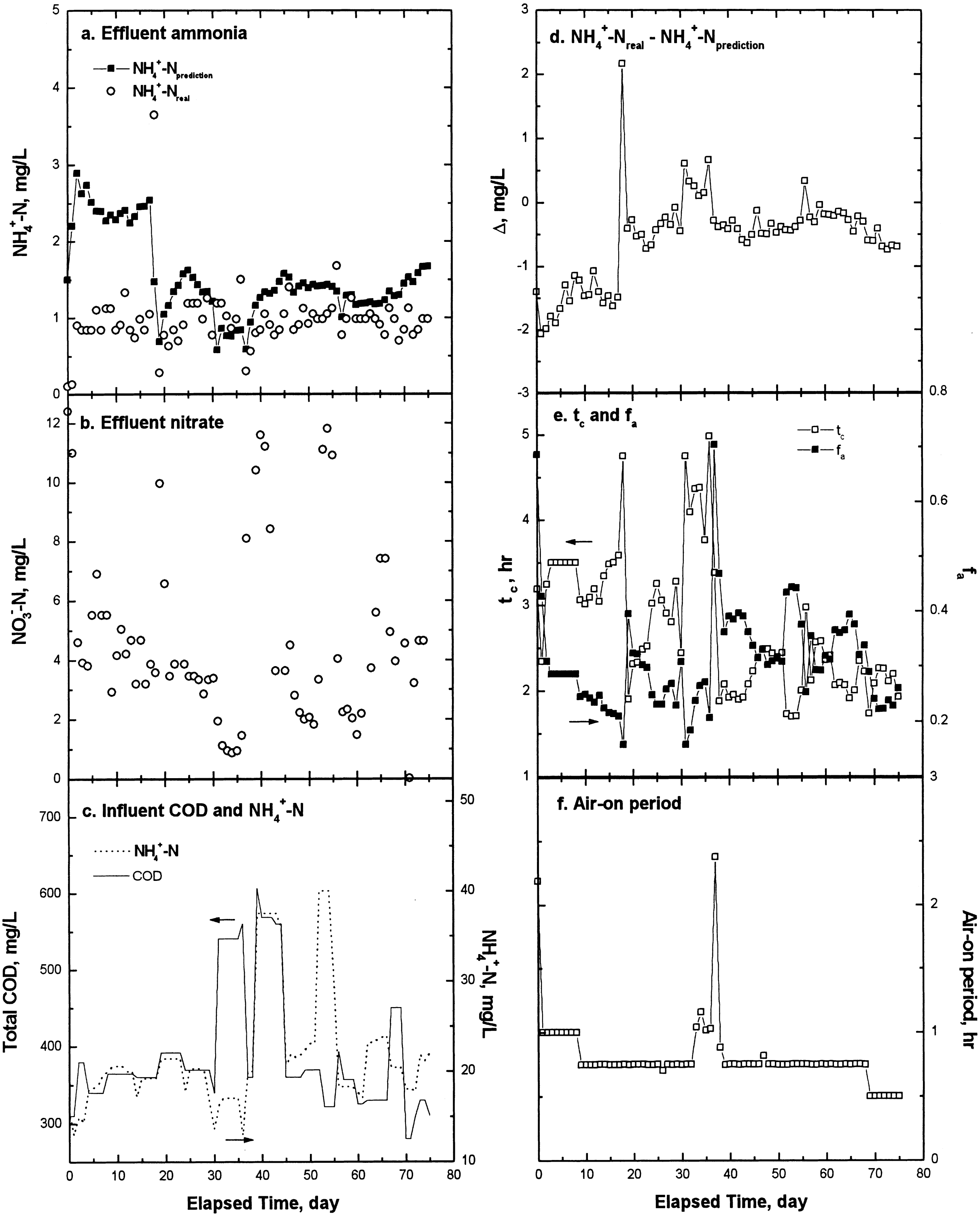

Fig. 3. Optimization results based on the model predictions with current day's influent compositions.

cycle times of 5 h (2.5 h air-on and 2.5 h air-off) and 2 h (1 h air-on and 1 h air-off), respectively, and the maximum and minimum aeration fraction of 0.71 (2.5 h air-on and 1 h air-off) and 0.29 (1 h air-on and 2.5 h air-off), respectively.

The results are shown in Fig. 3, including effluent NH_4^+ concentrations (Fig. 3a), effluent nitrate (Fig. 3b), influent COD and NH_4^+ (Fig. 3c), ΔNH_4^+ (Fig. 3d), f_a and t_c (Fig. 3e) as well as air-on periods (Fig. 3f). On the first day, the optimizer was operated without adjusting the constraints (i.e., with the assumption that on the previous day it made perfect predictions). The optimizer automatically set $f_a = 0.68$ and $t_c = 3.2$ h (Fig. 3e), with the model prediction of effluent NH_4^+-N = 1.5 mg/l. The next day, the actual effluent NH_4^+-N measured was 0.1 mg/l. With the large negative mismatch ($0.1–1.5 = -1.4$), the δ adjustment fed into the optimizer on the next day was calculated to be -0.7 from Eq. (3)

$$\delta NH_4^+\text{-N} = 0.5 \times (-1.4) + 0.5 \times (0) = -0.7.$$

The new NH_4^+-N constraint for the optimizer was then calculated to be $-2.2[1.5-(-0.7)]$, and the optimizer was used to determine the f_a and t_c to make the plant meet the new constraint. Setting f_a and t_c to the values 0.44 and 2.5 h, respectively, the effluent NH_4^+-N (0.13 mg/l) was still much lower than the $NH_4^+\text{-N}_{max}$. To continue, the optimizer repeated the same procedures as outlined before; e.g., the plant mismatch (Δ) was -2.1 mg/l on the next day and the resultant weighted correction (δ) was calculated to be -1.4 mg/l, which resulted in $f_a = 0.31$.

Four days into the operation, it was found that the optimizer had set the lowest limit for the aeration fraction ($f_a = 0.29$) by providing 1 h for air-on cycle time and 2.5 h for air-off cycle. With $f_a = 0.29$, the effluent NH_4^+-N was measured at about 0.8–0.9 mg/l, which meant the aeration cycle ratio could be further lowered while still meeting the 1.5 mg/l limit of $NH_4^+\text{-N}_{max}$. On day 8, the lower limit of each cycle mode was changed to 0.75 h, and the upper limit to 4 h, resulting in the minimum aeration fraction of 0.16 (0.75/4.75). The effluent $NH_4^+\text{-N}_{max}$ concentration was also lowered to 1 mg/l, since it was found that the system was able to nitrify ammonia quite well under normal conditions. Under the relaxed constraints, the optimizer seldom hit the lower limit of air-on fraction.

Since the objective of the optimization is to achieve a minimum aeration cycle ratio, the optimizer may try to set the aeration cycle time at the lower limit and adjust the non-aeration cycle time to provide an optimum aeration ratio.

Although the optimizer was working, substantial differences between the model predicted and the measured values of NH_4^+ motivated an adjustment of the model parameters. Consequently, on day 18, the yield of heterotrophs (Y_H) in the model was changed to 0.42. Thereafter, the mismatch between model predictions and the measured values was within ± 0.5 mg/l (Fig. 3d).

On day 31, the influent COD was increased to 540 mg/l to check the optimizer functioning under shock loading conditions. The concentration of influent NH_4^+-N was unchanged, or 17 mg/l. Despite the high COD loadings for a week, the lower f_a ratios set by the optimizer were able to remove COD and achieved good nitrification. Additionally, the optimizer was able to set large anoxic cycle ratios resulting in excellent denitrification (NO_3^--N around 1 mg/l). On day 36, because of high influent NH_4^+-N (20 mg/l), the f_a at 0.2 set by the optimizer was unable to fully nitrify the influent ammonia, resulting in a relatively high effluent NH_4^+-N concentration (1.5 mg/l). Subsequently, the optimizer responded by increasing f_a to 0.7, which resulted in low effluent NH_4^+-N. However, it resulted in a high nitrate concentration (8.4 mg N/l) because of low anoxic cycle ratio. Note that nitrate regulation was not the goal of optimization. Again, the optimizer adjusted f_a to 0.43, resulting in low effluent NH_4^+ concentrations which also produced low NO_3^- concentrations.

On day 37, both COD and nitrogen were increased to 610 and 38 mg/l, respectively, to test the optimizer response to the stress. At the high loadings of NH_4^+ and COD, the optimizer set f_a at 0.35–0.4. With these f_a values, the effluent NH_4^+-N was maintained at 0.8–1.0 mg/l, which means the optimizer responded properly to the shock loadings of COD and NH_4^+. However, the anoxic cycle ratio was not long enough to remove the nitrate generated from the additional large quantity of ammonia, resulting in 10 mg NO_3^--N/l in the effluent. Nevertheless, the model/optimizer controlled the reactor quite well by maintaining the effluent NH_4^+-N below the objective (1 mg/l) even with the sudden increase of the ammonia input. Note again that nitrate was not the goal of optimization. If the nitrate constraint were to be included, the optimizer would respond by increasing air-off cycle.

After an evaluation of the response of the optimizer to the sudden increase of COD and NH_4^+, the system was tested for a sudden increase of NH_4^+ (40 mg N/l) only while the COD was maintained at 360 mg/l (day 51). Again, the optimizer responded quite well against the stress by setting the optimal f_a to 0.43, resulting in about 1 mg/l of the effluent NH_4^+-N. As seen from Fig. 3e, f_a was maintained almost constantly during 3 days of ammonia stress. High concentrations of effluent NO_3^- (about 10 mg N/l) were detected during the high loadings of NH_4^+.

On day 69, the minimum aeration cycle time was reset to 0.5 h and the system was monitored. As seen from Fig. 3e, f_a and t_c remained at a similar level as when the minimum aeration cycle time was set at 0.75 h. Data in Fig. 3f indicate the corresponding air-on periods that result from this optimization approach. Note that the air-on period was forced off its constraint of 0.75 h for a brief time on several occasions. The experimental results are in complete agreement with the simulation data (McAvoy et al., 1999).

Generally, even though the influent fluctuated day by day, the model with the optimizer satisfied the objective of the process to make the effluent NH_4^+-N meet the permitted requirements of NH_4^+-N, while the aeration cycle time was minimized. The summary of the study is presented in Table 2. Throughout the study of the first

Table 2
Performances of the AAA system controlled with the linearized model fed with current influent composition

Wastewater characteristics	Influent mg/l	Effluent mg/l	Removal efficiency (%)	Reactor
Total COD	388	56	86	
Soluble COD	318			
Particulate COD	70			
TN	30.4	7.2	76	
Organic N	8.6	1.6		
Soluble organic N	4.7			
Particulate organic N	3.9			
NH_4^+–N	21.9	1.0	96	
NO_3^-–N	—	4.6		
Reactor conditions				
MCRT, day				12
HRT, h				12
Average air-on fraction (f_a)				0.3
Average total cycle time (t_c)				2.7

case, the average influent NH_4^+–N concentration was 21 mg/l. That of effluent was slightly lower than the objective (1 mg NH_4^+–N/l), with the average aeration cycle time fraction of 0.30. The average nitrate concentration was 4.6 mg/l, with about 75% TN removal efficiency.

After the successful demonstration of the optimizer by using the current day's data, the control strategy was switched to the second case, i.e., influent composition and the effluent data from the previous day's operation were used. This case would correspond to the normal conditions where the results of laboratory assays in a real plant are only available on a delayed basis. The conditions were similar to before: the lower and the upper limits of the each cycle mode were set at 0.5 and 4 h, respectively; the objective of the optimization was 1 mg/l of the effluent NH_4^+–N.

On the first day, the optimizer was run with the assumption that the model did not make any error for the previous day's operation with $f_a = 0.5$. After about three days, the optimizer had provided a rather steady f_a of 0.28–0.29 (Fig. 4e). Thereafter, the optimizer functioned relatively well even under ammonia shock loading (day 19 and 26, Fig. 4c) and the malfunction of aerator (day 30). For example, the malfunction of aeration resulted in effluent $NH_4^+\text{–N} = 4.2$ mg/l, and the optimizer responded by setting f_a to the upper boundary, 0.91. Such a high aeration time eventually reduced effluent NH_4^+–N concentration to 0.14 mg/l. The overall results using the influent data of the previous day were quite similar to those of controlling the system with current data. The removal efficiencies of COD and TN from both control schemes were identical (Tables 2 and 3). However, unlike the first case in which the effluent NH_4^+ concentration was quite stable whether there was a shock loading of influent composition or not, control with the delayed data produced some oscillations of effluent ammonia concentrations after any stresses (Fig. 5).

4. Summary and conclusions

This paper has discussed the use of a linearized version of the ASM1 model for the control and optimization of an AAA activated sludge reactor. To overcome the plant model mismatch, an exponentially weighted feedback of information from the reactor was employed. An optimization problem was solved daily to determine the f_a and t_c that minimized the cost of aeration. Minimum constraints on the effluent NH_4^+, air-on and air-off periods were incorporated into the optimization. Maximum constraints on the air-on and air-off periods were also included.

The control/optimization approach was demonstrated to be effective with real wastewater feed input. The operation was performed for two cases. The first case was where the influent composition for the current day's operation was fed into the optimizer along with the mismatch between the model prediction and the real effluent data from the previous day's operation, based on the assumption that the composition of the influent would not change much for the following 24 h. During the operation of the AAA system with the control scheme, the COD and TN removal efficiencies were 86 and 76%, respectively, and the average effluent NH_4^+–N was slightly below the objective 1 mg/l. Similar results were obtained from the system using the previous day's data. It is expected that the control approach can be directly applied to full-scale plants as long as the hydraulic pattern is completely mixed.

During the operation, low nitrate concentration was maintained, except when there were sudden shock loadings. Since the aeration cycle ratio for nitrification was optimized (minimized), the anoxic cycle ratio might be enough to support the complete denitrification. Even without constraints for the other nitrogen compounds in the effluent, the system could maintain a TN of the effluent below 8 mg/l.

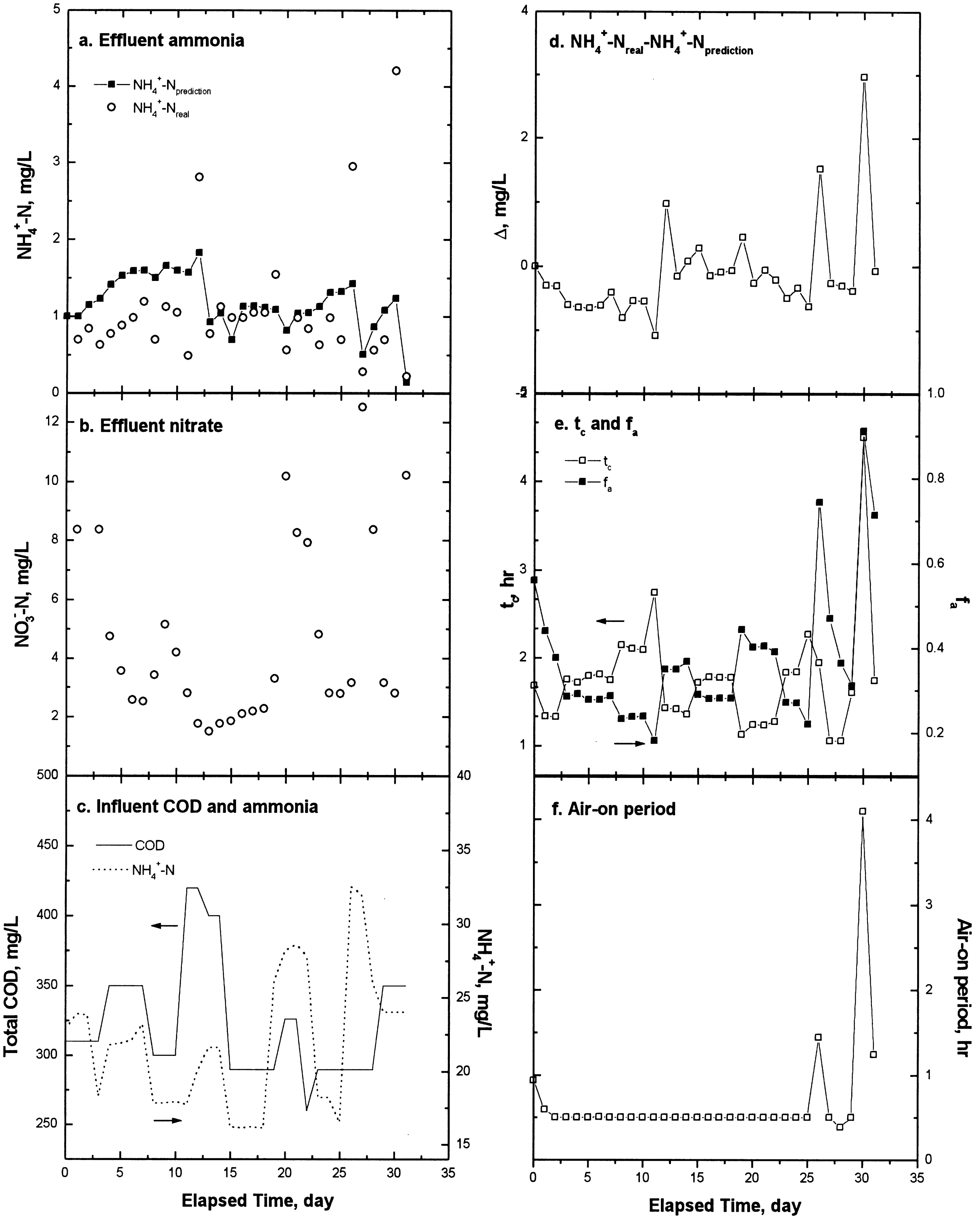

Fig. 4. Optimization results based on the model predictions with the previous day's influent compositions.

In this study the optimizer was run to calculate the optimum f_a on a daily basis. However, if the on-line instrument is available for ammonia, the information available can be fed into the computer at the end of each cycle. Since the linearized model prediction only takes a few minutes, the optimizer can easily be used for determining the optimal f_a for the next cycle of operation.

The key to the implementation of this optimization-based control approach was the availability of a simple dynamic model that was computationally efficient and

Table 3
Performances of the AAA system controlled with the linearized model fed with the previous day's composition

Wastewater characteristics	Influent mg/l	Effluent mg/l	Removal efficiency (%)	Reactor
Total COD	322	45	86	
Soluble COD	231			
Particulate COD	92			
TN	29.6	7.0	76	
Organic N	8.0	1.3		
Soluble organic N	3.2			
Particulate organic N	4.8			
NH_4^+-N	21.6	1.1	95	
NO_3^--N	—	4.6		
Reactor conditions				
MCRT, day				12
HRT, h				12
Average air-on fraction (f_a)				0.37
Average total cycle time (t_c)				1.76

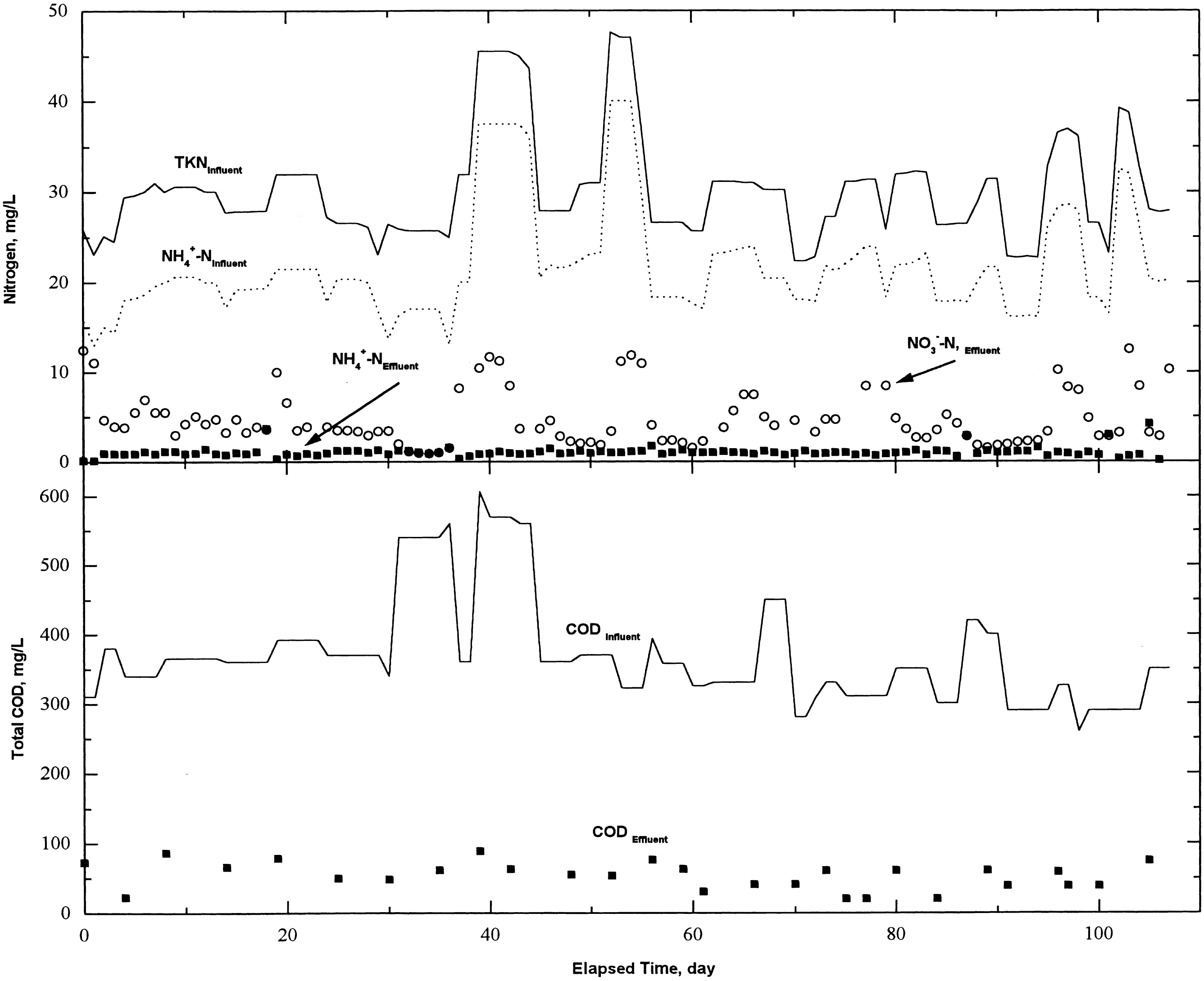

Fig. 5. Overall performance of the AAA system operated with an optimizer and linearized model.

fairly reliable under the normal operating conditions of the AAA system. Contrary to the full ASM1 equations, the simplified model allowed many simulations to be conducted in a short space of time (approximately 2 min) using an ordinary personal computer. Although the optimizer occasionally recommended larger-than-necessary control actions, its recommendations for parameter settings can still be considered by an operators as a useful first estimate.

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