Korean J. Chem. Eng., **23**(2), 203-208 (2006)

Use of Activate Sludge Model No. 3 and Bio-P module for simulating five-stage step-feed enhanced biological phosphorous removal process

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(*Received 24 June 2005 • accepted 4 November 2005*)

Abstract−The ASM3 with EAWAG Bio-P Module (ASM3+P) was used for simulating a five-stage step-feed Enhanced Biological Phosphorous Removal (fsEBPR) process and its applicability was compared with the ASM2d. The fsEBPR process was predicted to achieve effective nitrogen and phosphorus removal from the wastewater even with low C/N and C/P ratios without additional carbon sources. Application of the ASM3+P on this configuration will be an ample chance for expanding the new models in the activated sludge process. Sensitivity analysis and parameter estimation were conducted with the ASM2d and the ASM3+P prior to model application so that calibration of the models could focus only on the sensitive parameters. The ASM2d was less successful for predicting the process behavior. Moreover, the ASM2d required 6 times more computation time than that for the AMS3+P due to its decay-regeneration model structure. To confirm the applicability of parameters determined from the pilot-scale reactor operating results, those were tested on the field data without further correction. Only the ASM3+P successfully predicted nitrogen and phosphate variations in the full-scale plants. Overall examination of simulation results using the pilot and full-scale data has led to the conclusion that the ASM3+P is better than the ASM2d for simulating fsEBPR processes.

Key words: Activate Sludge Model, ASM2d, ASM3, EAWAG Bio-P Module, dPAO, EBPR, Sensitivity Analysis, Parameter Estimation

INTRODUCTION

A mathematical model for biological nutrient removal was initially developed with the ASM1 for carbon oxidation, nitrification, and denitrification in the activated sludge. It was extended to the ASM2 [Gujer et al., 1995] for including biological phosphorous removal by the phosphate accumulating organisms (PAOs). Later the ASM2d was built on the ASM2 by adding the denitrifying phosphate accumulating organisms (dPAOs) [Barker and Dold, 1996; Lee et al., 1998]. The TUDP model [Brdjanovic et al., 2000] combined the metabolic model for denitrifying and glycogen accumulating organism with the ASM1. In the meantime a completely new model structure was proposed as the ASM3 [Gujer et al., 1999] to resolve several difficulties experienced in the ASM1. This new ASM3 was introduced as a core model to be extended by adding phosphorous removal, toxic effects, and many other relevant processes [Henze et al., 2000]. The EAWAG Bio-P module was proposed to include biological phosphorous removal [Rieger et al., 2001] in the ASM3. Their combination may be denoted as the ASM3+P in this work. Now these activated sludge models are utilized for design, operation, control and education of the biological wastewater treatment plants.

For the enhanced biological phosphorous removal (EBPR) process, the arrangement of anaerobic, anoxic and aerobic reactors as well as the influent feeding distribution was known as very important aspects for design and operation. A five-stage step-feed EBPR (fsEBPR) process was developed to maximize the dPAOs' activity on simultaneous denitrification/phosphate uptake. This process was claimed to achieve effective nitrogen and phosphorus removal to reduce sludge production, aeration demands, and external carbon requirements [Park et al., 2003]. Optimization of operating conditions in the fsEBPR process (e.g., the fraction of step-feed ratio and internal/sludge recycle flow-rate) would be necessary to achieve the process target.

As mentioned above, the activated sludge models can be very useful tools for optimization and control of the fsEBPR process. Especially for biological phosphorous removal there are many cases where the application of ASM2d has been utilized [Hao et al., 2001]. However, application of the AMS3+P is relatively new yet. In this work, in order to expand application of ASM3+P, sensitivity analysis and parameter estimation were conducted for the fsEBPR process with comparing the AMS2d. The estimated parameters were tested on the full-scale operation of the fsEBPR process to confirm its practical applicability.

METHODS

1. Simulation Tools

Most of the simulations in this work were conducted using a commercial simulator, GPS-X (Hydromantis, Canada) where the ASM2d and ASM3 were already installed. For simulating fsEBPR with the

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ASM3 the EAWAG bio-P module [Rieger et al., 2001] was plugged into the ASM3 in GPS-X using the Model Developer and the combination of the two models was denoted as ASM3+P. The implementation of this model was validated by comparing simulation results obtained from other simulation tools such as the Aquasim and the simulation program made with Boland C++.

2. Simulation Procedure

2-1. Sensitivity Analysis

The sensitivity of parameters was tested against the steady state simulation results as reference values. This simulation was carried out by using operation and design information of the pilot plant and model default values from the literature [Henze et al., 2000; Rieger et al., 2001]. It was performed by varying the value of each parameter at 5% intervals of the default value in the range from 50 to 200% while all other parameters were fixed with their default values [Kim et al., 2005]. The sensitive parameters were identified based on the objective function, which was a weighted sum of squares normalized error (WSSNE) as shown in Eq. (1). The target variables of the objective function were TSS (total suspended solids), SCOD (soluble chemical oxygen demand), S_{NH} (ammonium), S_{NO} (nitrite and nitrate) and S_P (phosphate) of the effluent and in-process measurements. The sensitive parameters were determined based on WSSNE results shown as a gray-scale representation.

$$\mathrm{WSSNE} = wf_1 \cdot wf_2 \sum_{t=0}^{t_f} \sum_{i=1}^{n} \left[\frac{(C_{i,t,\mathrm{Calc.\ with\ model\ default\ parameters}} - C_{i,t,\mathrm{Calc.\ with\ changed\ parameters}})}{C_{i,t,\mathrm{Calc.\ with\ model\ default\ parameters}}} \right]^2 \quad (1)$$

where, $C_{i,t}$ =Concentration of component i at time t in effluent and in-process

i =TSS, SCOD, S_{NH}, S_{NO}, or S_P

wf_1=Weighting factor; 5 for effluent and 1 for in-process

wf_2=Weighting factor; 2 for S_{NH}, S_{NO}, and S_P; 1 for TSS and SCOD

2-2. Parameter Estimation

The values of the sensitive parameters were estimated by fitting the calculated data with the data obtained from the first 100 days of pilot plant operation applying the Jacobi method (the direct method of Gauss-Jordan) [Press et al., 1992]. Other non-sensitive parameters values were taken from the literature as the default values [Henze et al., 2000; Rieger et al., 2001]. The objective function and the target variables were identical with those used for sensitivity analysis. The Gauss-Jordan method was implemented as follows. At the beginning a simulation was carried out using default parameter values and the WSSNE was calculated [Lee et al., 2005]. Then one sensitive parameter determined from the above sensitivity analysis was changed and the simulations and WSSNE calculations were carried out like the sensitivity analysis procedure. When the WSSNE reached a certain constant small value, the sensitive parameter value used for that simulation was considered as a sub-optimum value. This procedure was repeated with another sensitive parameter until one could obtain other sub-optimum values for all sensitive parameters. And then another round of simulations and WSSNE calculations were conducted starting with these sub-optimum parameter values and changing one of them as the same procedure of sensitivity analysis. When the WSSNE reached a small constant value, the set of sub-optimum parameter values was considered as optimum.

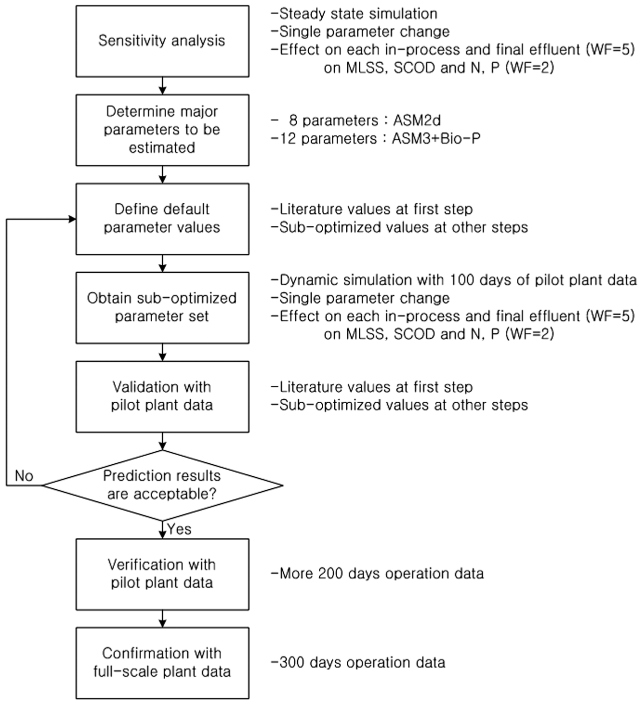

Fig. 1. Whole simulation procedure including sensitivity analysis, parameter estimation, verification and confirmation.

2-3. Verification and Confirmation

Parameter verification was conducted by using the data obtained from day 100 to day 300 of the pilot plant operation. Confirmation was carried out using the data obtained from a full-scale plant. The whole simulation procedure is summarized in Fig. 1.

3. Five-stage Step-feed EBPR Process and Pilot-scale Plant

This process was developed to optimize the dPAOs' activity and therefore to require less external carbon addition, which would be operated at an SRT of 20-30 days [Park et al., 2003]. Consequently, the chemical cost and the sludge treatment cost would be reduced and the process would be advantageous over other EBPR configurations. The configuration of the fsEBPR process is shown in Fig. 2 and the major function of each reactor is described as follows.

- Pre-anoxic tank for denitrifying nitrate in sludge recycle flow, where 10% of influent fed.
- Anaerobic tank for phosphate release and PHA storage, where 60% of influent fed.
- Anoxic1 tank for denitrifying nitrate in nitrate recycle flow and phosphate uptake.

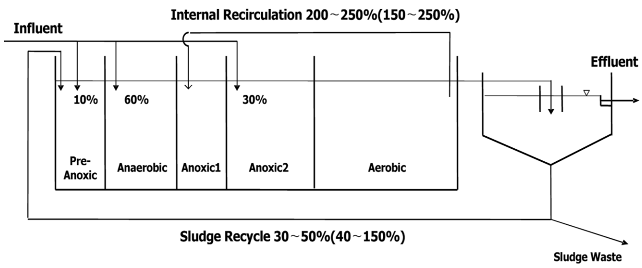

Fig. 2. Schematic diagram of the fsEBPR process.

Table 1. Operating conditions and reactor volume in pilot-scale and full-scale plant

	HRT						Sludge recycle	Internal recycle	Temp. (°C)
	Total	Preanoxic	Anaerobic	Anoxic1	Anoxic2	Aerobic			
Pilot-scale plant	7.5	0.5	1.0	0.5	2.0	3.5	0.3-0.5Q	2.0-2.5Q	11-28
Full-scale plant	11.25	1.25	1.25	1.25	2.5	5.0	0.4-1.5Q	1.5-2.5Q	12-26

Table 2. Influent composition into pilot-scale plant and full-scale plant

		TSS	$SCOD_{Cr}$	BOD_5	NH_4^+-N	T-P	PO_4^{3-}-P	pH
Pilot-scale plant	Min.-Max	76-270	80-219	50-143	18.5-38.5	4.1-10.2	3.8-9.5	7.0-7.9
	Average	129	103	80	27.2	7.2	6.5	7.5
Full-scale plant	Min.-Max	20-184	10-132	23-170	9.8-34.0	1.1-7.2	1.0-3.3	6.5-7.2
	Average	81	57.5	88	23.4	3.8	2.2	6.8

- Anoxic2 tank for denitrifying residual nitrate, where 30% of influent fed.
- Aerobic tank for nitrification and phosphate uptake.

A pilot plant with a working volume of 15.6 m^3 was installed at the Seongnam sewage treatment plant in Korea, whose layout was identical with that in Fig. 1. It was operated for about 450 days from February 2000 to April 2001. Pre-settled sewage was supplied to the pilot plant by using a step-feeding ratio of 0.1, 0.6 and 0.3 to the pre-anoxic, anaerobic and anoxic2 reactors, respectively. The SRT was maintained at 20-30 days. Although the plant was operated for 450 days, only the last 300 days data were used in this research when stable operation was maintained. Design criteria, operating conditions and influent conditions are shown in Tables 1 and 2.

4. fsEBPR Process as Full-scale Plant

The Jisan sewage treatment plant in Korea consisted of nine tanks-in-series with a total working volume of 1,036 m^3 treating an equivalent of 80,000 p.e. of sewage. In this study, 300 days of plant data from August 2002 to May 2003 were used for model confirmation. This plant was designed and constructed initially as an A2O pro-

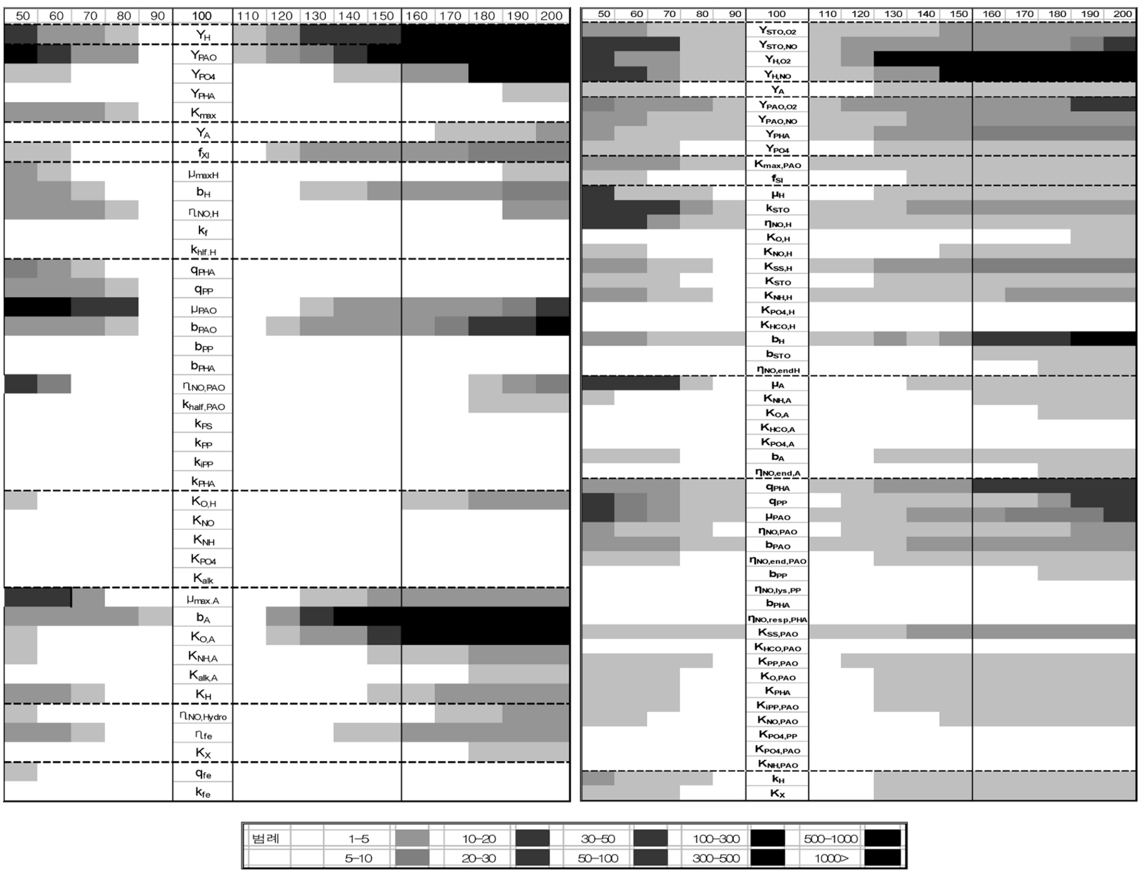

Fig. 3. Visualized sensitivity of parameters of ASM 2d (a) and ASM3+P (b) for simulating five-stage step-feed EBPR process. The darker one was more sensitive.

cess and modified later into the fsEBPR process. Design criteria, operating conditions and influent composition are shown in Tables 1 and 2. The sludge recycle ratio was 40-150% and the internal recirculation ratio was 150-250%.

5. Analytical Methods

pH, DO and temperature were monitored on-line while TCOD, SCOD, NH_4^+-N, NO_3^--N, PO_4^{3-}-P, TSS, VSS and alkalinity of each reactor and in the influent and the effluent were measured 1 to 3 times a week. Additionally, TP and TN were measured in the final effluent. All analyses were performed according to the procedures in the Standard Methods [AWWA, 1998].

RESULTS AND DISCUSSTION

1. Sensitivity Analysis

The sensitivities of all parameters in ASM2d and ASM3+P were examined, except f_{SI} which has default value of zero. The sensitivity of parameters was determined when the objective function, WSSNE, showed more than 20% variation compared to the reference while the parameters were varied from 50% to 200% of default values. For increasing visibility the results were represented as a grey-scale figure as shown in Fig. 3. If the color of the gray-scale is dark, then it means sensitive. White color means that the WSSNE was less than 1% compared to the reference. The sensitive parameters were 8 for ASM2d and 12 for ASM3+P as follows:

ASM2d : Y_H, Y_{PAO}, Y_{PO4}, $\mu_{max,PAO}$, b_{PAO}, $\mu_{max,A}$, b_A, $K_{O,A}$
ASM3+P: $Y_{STO,NO}$, $Y_{H,O2}$, $Y_{H,NO}$, $Y_{PAO,O2}$, Y_{PO4}, K_{STO}, η_{NO}, b_H, $\mu_{max,PAO}$, q_{PHA}, q_{PP}, $\mu_{max,A}$

Interestingly the sensitive parameters in both models were related to nitrogen and phosphate removal, which would be expected because the weighting factors for for S_{NH}, S_{NO}, and S_P were larger than those for TSS and SCOD. However, their default values were somewhat different from each other between two models. The parameters affecting effluent quality substantially were related with yield and decay of *heterotrophs*, those of PAOs, and maximum growth rate and decay of *autotrophs.* This was due to the fact that these parameters represented the direct effects on biomass concentration and nutrients removal rates. However, in the ASM3+P the parameters related with yield and maximum uptake rate of internal storage materials of *heterotrophs* and PAOs were very much sensitive, which was not the case in the ASM2d. This finding might be explained as follows: in the ASM3+P the volatile fatty acid (VFA), which the PAOs could use, was not differentiated from the long chain carbon source. Therefore, the variation of parameters might significantly affect the phosphorous removal rate and denitrification rate.

2. Optimization of Sensitive Parameters

The estimated parameter values are summarized in Table 3 and compared to the default values. Most of the estimated values were lower in their magnitude than the default values. This might be a reflection of the low sludge production caused by the long SRT. The decay coefficients in ASM2d and the endogenous respiration constants in ASM3+P were also smaller than the default values. The largest difference occurred in the estimated maximum specific growth rate of the *autotrophs* ($\mu_{max,A}$), which was 2.5 times higher than the default value. This result might be due to low C/N ratio in the influent, consumption of most carbon in the anaerobic and anoxic reactors and high nitrification rate in the aerobic reactor.

Table 3. Estimated sensitive parameter values of ASM 2d and ASM3+P

ASM2d			ASM3+P		
Parameter	Default	Estimated	Parameter	Default	Estimated
Y_H	0.63	0.4	$Y_{STO,NO}$	0.8	0.23
Y_{PAO}	0.63	0.5	$Y_{H,O2}$	0.63	0.48
Y_{PO4}	0.4	0.32	$Y_{H,NO}$	0.54	0.35
$\mu_{max,PAO}$	1.0	0.65	$Y_{PAO,O2}$	0.60	0.9
b_{PAO}	0.2	0.11	Y_{PO4}	0.35	0.23
$\mu_{max,A}$	1.0	2.73	K_{STO}	5.0	8.4
b_A	0.15	0.025	η_{NO}	0.6	0.8
$K_{O,A}$	0.5	0.073	b_H	0.2	0.08
			$\mu_{max,PAO}$	1.0	0.37
			q_{PHA}	6.0	8.0
			q_{PP}	1.5	3.0
			$\mu_{max,A}$	1.0	2.35
WSSNE	33473	8422	WSSNE	18089	6769

The required simulation time and the number of sub-optimizations were quite different from each other depending on the model. In the case of ASM2d, it needed 8 sub-optimizations and 576 hours for simulation, while the ASM3+P needed 6 sub-optimizations and required only 96 hours for simulation. This was probably due to the model structure where ASM2d had decay-regeneration closed-loop structure that required substantially more time for optimization. However, the ASM3+P was open-loop structure. Therefore, if the ASM2d was applied for process control it might be difficult to respond rapidly enough for variation of disturbance or control set values. The WSSNE of ASM2d was 20% higher than that of ASM3+P, and repeated attempts to decrease the value were not successful after the sixth sub-optimization. This meant that the ASM3+P was more effective to describe the fsEBPR process operation.

3. Verification of Estimated Parameters with Pilot-scale Plant Data

The verification of estimated parameters was conducted by using 200 days of data from the pilot-scale plant. In Fig. 4 the measured and simulated values for PO_4^{3-}-P and NH_4^+-N concentrations in the effluent and anaerobic reactor are compared. The ASM2d predicted the calculated soluble phosphate concentrations were higher than the measured data, while the ASM3+P results showed a better prediction. Both ASM2d and ASM3+P successfully predicted the NH_4^+-N variation in both the effluent and anaerobic reactor by optimizing only one parameter, namely, the autotrophic growth rate ($\mu_{max,A}$). This was due to the fact that in the fsEBPR process the COD was removed almost completely during anaerobic and anoxic reactors, and in the aerobic reactor only the phosphate uptake and nitrification were occurring. Therefore, in the aerobic reactor the calculation of NH_4^+-N became relatively simple and prediction was well made in both models.

4. Confirmation of Verified Parameters to Full-scale Plant

The model predictions were then tested with the data from the full-scale plant. It was to make sure that the operating conditions (i.e., sludge and nitrate recycle flow-rates and temperature) of the

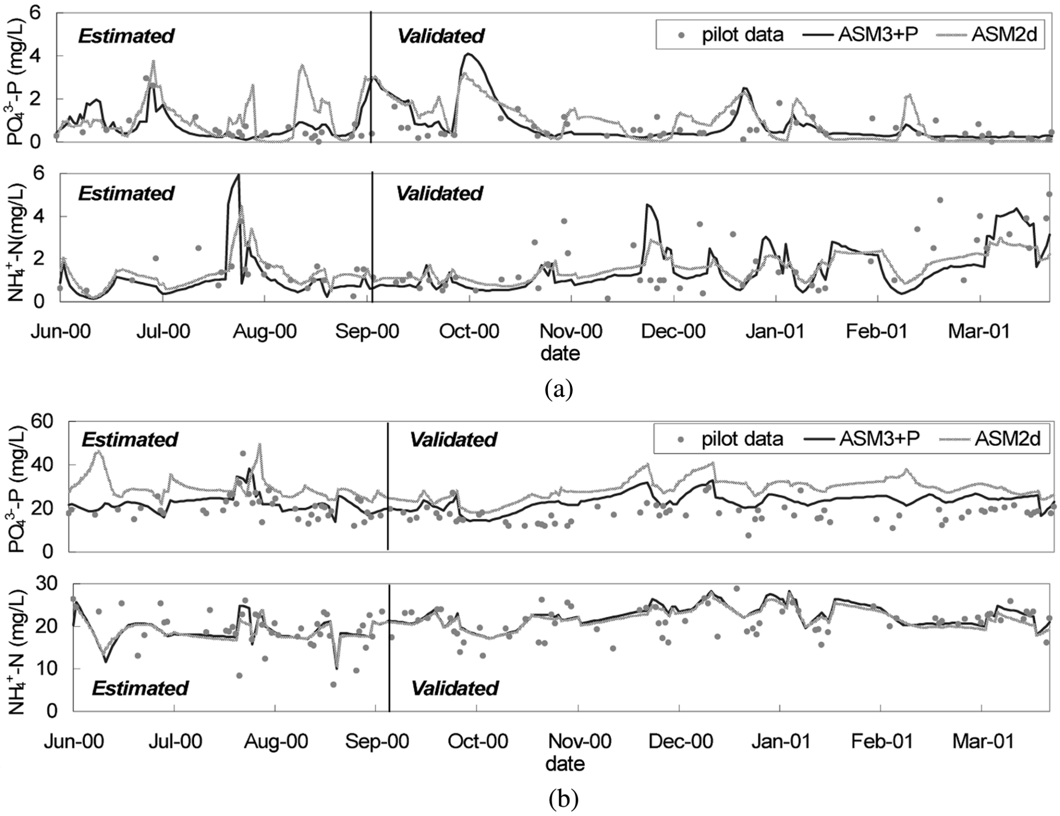

Fig. 4. Measured and simulated (solid line for ASM3+P, dotted line for ASM2d) soluble PO_4^{3-}-P and NH_4^+-N concentrations in pilot plant; (a) effluent (b) anaerobic reactor.

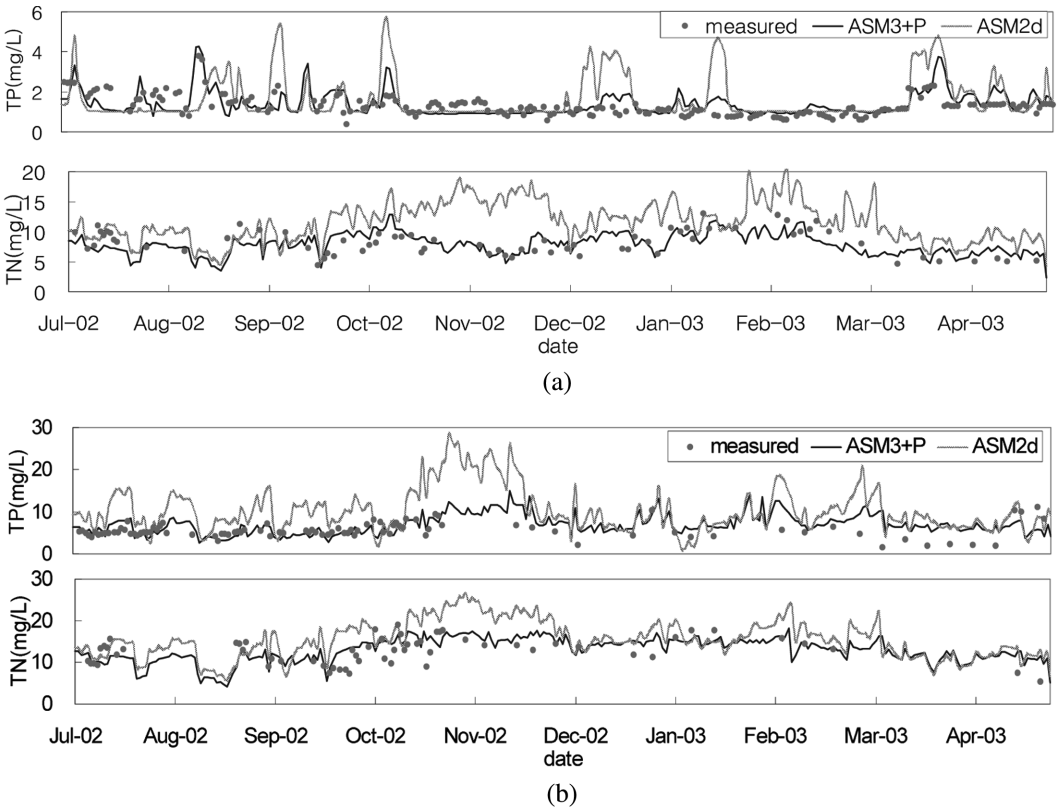

Fig. 5. Measured (dots) and simulated (solid line; ASM3+P, scatted line; ASM2d) T-P and T-N concentrations in field plant; (a) effluent (b) anaerobic reactor.

full-scale plant were properly practiced in the model. The parameter sets estimated with the pilot-scale plant data were directly used in these simulations without further correction. Fig. 5 shows the measured and simulated TP and TN concentrations in the effluent and the anaerobic reactor. The TP and TN concentrations were much more accurately predicted with ASM3+P compared to ASM2d. Operating conditions were changed in October 2002 such that the sludge recycle flow-rate, the internal (nitrate) recycle flow-rate and the SRT were changed from 1.0Q to 0.7Q, 1.5Q to 2.0Q and from 20 days to 12 days, respectively. Moreover, the ambient temperature started to decline as winter began. After that time, the ASM3+P showed better prediction performance than ASM2d. The ASM3+P could successfully reflect the variation of operating conditions and temperature, while ASM2d seriously overestimated T-N and T-P concentration. The prediction capability with the ASM2d was susceptible to influent and temperature variations and usually overestimated the effluent concentration. From these simulations, it was considered that the ASM3+P was a better model for this fsEBPR process configuration.

CONCLUSIONS

Overall examination of simulation results using the pilot and full-scale data has led to the conclusion that the ASM3 with the EAWAG bio-P module (ASM3+P) was better than the ASM2d for simulating five-stage step-feed EBPR processes. The sensitivity analysis and the parameter estimation exercise were conducted with the ASM2d and the ASM3+P prior to model application so that calibration of the models could focus only on the sensitive parameters. The ASM2d was less successful for predicting the process behavior. Moreover, the ASM2d required 6 times more computation time than that for the AMS3+P due to its decay-regeneration model structure. To confirm applicability of parameters determined from the pilot-scale plant to the full-scale plant, those were tested with the field data without further correction. Only the ASM3+P successfully predicted nitrogen and phosphate variations caused by changing of operating conditions in the full-scale plants.

ACKNOWLEDGMENT

This study was supported financially in part from the Basic Research program of Korea Science and Engineering Foundation (project No. R01-2003-000-10714-0) and Busan Metropolitan City through the Institute for Environmental Technology and Industry (IETI), Pusan National University, Korea (project No. R12-1996-015-00079-1 & R12-1996-015-00080-1).

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