Improve the performance of full-scale continuous treatment of municipal wastewater by combining a numerical model and online sensors

Qiuwen Chen, Qibin Wang, Hanlu Yan, Cheng Chen, Jinfeng Ma and Qiang Xu

ABSTRACT

Mathematical models based on instant environmental inputs are increasingly applied to optimize the operation of wastewater treatment plants (WWTPs) for improving treatment efficiency. This study established a numerical model consisting of the activated sludge module ASM3 and EAWAG bio-P module, and calibrated the model using data from a full-scale experiment conducted in a WWTP in Nanjing, China. The calibrated model was combined with online sensors for water temperature, chemical oxygen demand, NH$_4^+$-N and PO$_4^{3-}$-P to optimize and dynamically adjust the operation of the WWTP. The results showed that, compared to the original default operation mode, the effluent water quality was significantly improved after optimization even without supplementation of external carbon or alkalinity, and the required aeration rate in spring, summer, autumn, and winter was reduced by 15, 41, 33 and 11%, respectively. The study indicated that there was the potential for application of closed-loop automatic control to regulate operating parameters to improve wastewater treatment processes through the integration of data on influent characteristics and environmental conditions from sensors, and results from simulation models.

Key words | nutrient removal efficiency, online sensors, operation optimization, process model, wastewater treatment plant (WWTP)

INTRODUCTION

Biological wastewater treatment plants (WWTPs) are critical infrastructure designed and operated for the removal of organic matters and nutrients to protect the receiving water environment and ecosystem. Despite these benefits, the removal efficiency, energy consumption, and local legacy are issues that must be considered during operation. Controlling each unit process in isolation is often not sufficient (Olsson 2012). Moreover, the wastewater characteristics and the environmental conditions are not constant for a given WWTP, which results in an unsecured effluent quality or a waste of energy. Therefore, a comprehensive view of the entire system is necessary to achieve the highest possible efficiency through adjusting multiple parameters in the activated sludge processes, such as dissolved oxygen (DO) and water temperature. Water temperature is of critical significance for the growth and activity of bacteria, and many studies have shown that temperature plays an important role in the nitrogen and phosphorus removal process (Lee et al. 2011; Lotti et al. 2015). Measures have to be taken to manage possible adverse effects incurred by water temperature variations. In recent years, more strict requirements on the effluent quality of WWTPs and reduction of energy consumption have been enforced (Flores-Alsina et al. 2008; Lorenzo-Toja et al. 2015). Therefore, it is necessary to further improve the performance of WWTPs through optimizing the operations under varying conditions.

Due to the complexity of biological wastewater treatment processes, gaining historical experience and heuristic optimization are time-consuming and tedious tasks. Mathematical models and simulation tools, which are useful for
the design (Rivas et al. 2008) and operation optimization of WWTPs (Coelho et al. 2000; Gernaey et al. 2004) and evaluating control strategies, have been developed. The International Water Association task group dedicated to the mathematical modeling of biological wastewater treatment launched the first activated sludge model (ASM1) in 1987. Since then, a series of ASMs and their extensions have been reported, including ASM2 (Gujer et al. 1995), ASM2d (Henze et al. 1999), ASM3 (Gujer et al. 1999), ASM3 with two-step nitrification–denitrification (Iacopozzi et al. 2007) and ASM3 + bio-p (Rieger et al. 2003). Using such mathematical applications, Souza et al. (2008) reduced the total batch time from 12 h (initial strategy applied with three feed steps) to 5 h via model-based optimization in a sequencing batch reactor system. Gabarron et al. (2015) improved nitrogen removal efficiency by 27% and reduced aeration energy by 7% based on model simulation without affecting the sludge properties or effluent water quality. Although numerous ASM applications have been carried out on specific WWTPs (Wichern et al. 2001; Lubello et al. 2009) there were no universal parameters utilized by these models in the sense that each system can be simulated with the same parameter values (Brun et al. 2002). Parameter values may differ from one plant to another in regard to process configuration and operation, which can affect WWTP nutrient removal. It is essential, therefore, to calibrate the parameters before applying a model to optimize the operation of a WWTP and improve the efficiency.

Following the rapid development of sensor technology, these instruments could provide real-time information on the wastewater characteristics and the environmental conditions. Jeppsson et al. (2002) pointed out that sensors, whose accuracy, frequency, and reliability were high enough for their application in the online monitoring system of the wastewater treatment process, were no longer the main bottleneck for online control. Although there has been considerable interest in the optimal control of a WWTP using online sensors (Won & Ra 2011; McConville et al. 2014) and model simulations (Kim et al. 2014; Solon et al. 2017), the successful operation of an activated sludge system remains a challenge between balancing effluent quality and energy consumption (Dellana & West 2009; Olsson 2012).

The objective of this study was to: (1) develop the ASM3 + bio-p model and calibrate for a full-scale WWTP; (2) investigate the potential of improving WWTP performance by optimizing the operations through the model and sensor network. The results were expected to provide guidance to improve plant performance with respect to effluent requirements and energy consumption.

MATERIALS AND METHODS

Description of the WWTP

The Jiangxinzhou WWTP is located in Nanjing, China, and treats wastewater from the surrounding urban areas. The plant was initially designed and operated for treating organic pollutants and NH$_4^+$-N using physico-chemical and biological processes. The average pollutant load of the plant corresponds to a population equivalent of more than 3,000,000. The average inflow of wastewater (Qin) is 400,000 m$^3$/d with four lines and 240,000 m$^3$/d for the first- and second-stage segments of the treatment plant, respectively. The average daily variation coefficient is 1.15. Treated wastewater is directly discharged into the Yangtze River. The plant was upgraded in 2003 to remove nutrients and cope with increased wastewater discharge.

The WWTP is an anoxic/oxic activated sludge treatment plant with plug-flow characteristics after the upgrade, and consists of bar screens, aerated grit chambers, primary clarifiers, biochemical pools and secondary clarifiers (Figure 1). Each biochemical pool has a rectangular configuration. The volume ratio of anoxic to oxic tank is 1:3. Mixed liquor recirculation flow and returned activated sludge recirculation flow are usually set to 0% and 80% of Qin, respectively. The excessive sludge from the secondary clarifiers flows into thickeners, where partial liquid–solid separation takes place.

Mathematical model

In this study, ASIM ver. 5.0.1.5 (EAWAG) was used under the dynamic conditions of the plant. The activated sludge tank and secondary clarifier were simulated. The activated sludge tank was a plug-flow reactor, and thus the number of modeled reactors was important. There were four identical activated sludge lines in the first-stage plant, and only one line, which was 100,000 m$^3$/d, was selected as a representative for the model. Major components of the model scheme for the current plant were denitrification ring, nitrification ring, and secondary clarifier, which were named the anoxic reactor, aerobic reactor, and liquid/solid separator in the simulation model, respectively. The detailed description of the model for the Jiangxinzhou WWTP is given in Table S1 in Supporting Information (SI, available with the online version of this paper).

The water temperature in the primary effluent ranges from 10.8 to 30.5 °C. To consider the effects of seasonal temperature variations (Wang & Chen 2016) on treatment...
efficiency, three reference temperatures, which were 10, 20, and 30 °C, were used in the model according to the wastewater temperature range (Table S2 in SI, available online). For kinetic parameters depending on water temperature, the basic Arrhenius kinetic equation (Rieger et al. 2003) for temperature dependency was implemented in the model, which is given as:

\[ k(T) = k(T_B) \cdot \exp \left( \theta_T \cdot (T - T_B) \right) \]  (1)

where \( k(T) \) is the reaction rate at temperature \( T \), \( k(T_B) \) is the reaction rate at base temperature (10, 20 or 30 °C), and \( \theta_T \) is the temperature coefficient (1/K).

The ASM3 + bio-p model has 17 input variables of influent concentrations, including oxygen in raw wastewater, nine chemical oxygen demand (COD) fractions, ammonium, dinitrogen, nitrate, alkalinity, soluble phosphorus (primarily ortho-phosphates), polyphosphate (XPP), and total suspended solids.

Data collections and model parameter configuration

In situ water quality monitoring of the Jiangxinzhou WWTP was conducted from March 2013 to February 2014, with an interval of 1 week. Measurements included concentrations of COD, \( \text{NH}_4^+ \cdot \text{N} \), \( \text{NO}_3^- \cdot \text{N} \), nitrite (\( \text{NO}_2^- \cdot \text{N} \)), total nitrogen, \( \text{PO}_4^{3-} \cdot \text{P} \) and alkalinity (APHA 2005). Online instruments of flow meters, and COD and \( \text{NH}_4^+ \cdot \text{N} \) sensors (produced by Hach, USA) were installed at the inlet and outlet of the WWTP. Water temperature and DO sensors (produced by Hach, USA) were installed in the anoxic and oxic zones. Online monitoring values were recorded and then averaged every 2 hours, and 12 sets of data were obtained per day. When necessary, water temperature and DO were measured in situ using a YSI 6600 V2 Multi-Parameter Water Quality Sonde (USA). The wastewater characteristics and effluent constituents are listed in Table 1.

In the model, the concentration of dinitrogen was assumed to be negligible due to very low concentration. Oxygen in raw wastewater and XPP were set as 2.0 mg/L and 0 mg/L, based on the measurement results, respectively. Based on the three reference temperatures, the influent conditions on January 30, April 28, and August 14, 2014, near the reference temperatures of 10, 20, and 30 °C, were selected for the simulations in order to avoid the effect of temperature fluctuations. Influent variation coefficients of the plant for dynamic simulation are given in Table S3 (available online).

For the ASM3 + bio-p model, division of the influent wastewater into various fractions is an indispensable step for simulation of the biotransformation process. It is critical to know these fractions in order to obtain reliable model results for nitrogen and phosphorus removal (Van Veldhuizen et al. 1999). Details about organic fractions of influent wastewater can be determined by physical separation and respirometry (Orhon et al. 1997). In this study, influent COD fractions were examined on the basis of the effluent concentrations of COD, \( \text{NH}_4^+ \cdot \text{N} \), \( \text{NO}_3^- \cdot \text{N} \), and \( \text{PO}_4^{3-} \cdot \text{P} \) at the three base temperatures. The influent of the model was the effluent of the primary clarifiers, where large particles were physically separated from wastewater. Therefore, particulate inert matter (\( X_I \), 7%) was lower than that of previous research (Ginestet et al. 2002), which reported more than 15% \( X_I \). A significant heterotroph fraction is contained in municipal wastewater (Koch et al. 2000), so the heterotrophic fraction was considered in the simulation process. The fraction of heterotrophs was set to...
9%, which agreed with that of Ginestet et al. (2002) (14 ± 6%). Other fractions such as nitrifiers and phosphorus-accumulating organisms (PAOs) were very low, so their fractions were set to 0% (Koch et al. 2000). Poly-hydroxy-alkanoate (XPHA) was an essential part of influent COD, and the fraction was set to 4%. Since there is little difference between the fractions in domestic wastewater (Koch et al. 2000), other fractions were obtained from relevant literature. The fractions of the influent COD used in the model are summarized in Table S4 in SI (available online).

**Optimization method**

Effluent quality fulfilling the discharge standard was the constraint (MEP 2002), while the objective was aeration energy. The parameters that needed to be optimized included: DO in the oxic zones, from 0.5 mg/L to 2.5 mg/L with an interval of 0.5 mg/L; sludge retention time (SRT) of the anoxic and aerobic tanks, from 8 days to 12 days with an interval of 1 day; the returned activated sludge recirculation ratio (R), from 60% to 100% with an interval of 10%. For a given reference water temperature, five values were taken for each parameter, thus there were 125 combinations marked as C1–C125, from which the best alternative could be selected through an optimization algorithm.

The total daily oxygen demand in a wastewater treatment system is calculated using the following Equations (2)–(6) (Henze et al. 2008):

\[
FO_c = FS_{bi} \times \left(1 - f_{en} \frac{Y_{fl}}{1 + f_{fl} b_H SRT}\right) \tag{2}
\]

\[
FS_{bi} = FS_{hi}(1 - S_I - X_I) \tag{3}
\]

where \(FO_c\) (kgO\(_2\)/d) is the daily oxygen demand for organic material elimination; \(FS_{bi}\) (mg COD/d) is the readily biodegradable organics; \(f_{en}\) (mg COD/mg VSS) is the COD to VSS ratio of the sludge (1.48 mg COD/mg VSS); \(Y_{fl}\) (mg VSS/mg COD) is the volatile suspended solids (VSS) yield of the ordinary heterotrophic organisms (0.45 mg VSS/mg COD); \(f_{fl}\) (mg COD/mg COD) is the non-biodegradable fraction of the ordinary heterotrophic organisms (0.1 mg COD/mg COD); \(b_H\) (1/d) is the specific rate of endogenous mass loss of denitrification bacteria; \(Y_{hi}\) is the COD yield of heterotrophic bacteria (mg COD/mg COD); \(SRT\) (days) is the solid residence time; \(S_I\) is the soluble non-biodegradable fraction of total influent COD \((FS_{bi})\); \(X_I\) is the particulate non-biodegradable fraction of \(FS_{bi}\).

\[
FO_n(kgO_2/d) = 4.57 \times N_{ne} \times Q_i \tag{4}
\]

where \(FO_n\) (kg O\(_2\)/d) is the daily oxygen demand for nitrification, and 4.57 mg O\(_2\)/mg NH\(_4\)-N nitriﬁed to NO\(_3\)-N is a constant.

\[
FO_d = 2.86 \times (N_C - N_{ne}) \times Q_i \tag{5}
\]

\[
FO_{id} = FO_c + FO_n - FO_d \tag{6}
\]

where \(FO_d\) (kg O\(_2\)/d) is the daily recovery oxygen for denitrification; \(N_C\) (mg N/L) is the nitrification capacity; \(N_{ne}\) (mg N/L) is the effluent nitrate concentration; and 2.86 mg O\(_2\)/mg NO\(_3\)-N transferred to gaseous nitrogen is a constant; \(FO_{id}\) (kg/d) is the total oxygen demand transferred in the aeration tank under the standard state (20 °C, 1.013 \times 10^5 Pa).

The carbonaceous oxygen demand is given by the sum of oxygen demands for ordinary heterotrophic organisms.
and PAOs. It was assumed that the oxygen demand for 1 unit of PAOs was the same as for 1 unit of ordinary heterotrophic organisms, because the amount of PAOs was small and also $Y_{PAO,2}$ was slightly smaller than was $Y_{H,2}$ (Henze et al. 2008). Therefore, the oxygen demand for PAOs was neglected.

The actual air supply in the aeration tank was calculated using the following Equations (7)–(9):

$$R_0 = \frac{FO_t \times C_{s(t)}}{\alpha [\beta \times \rho \times C_{s(b)} - C] \times 1.024^{(T-20)}}$$

$$C_{s(b)} = C_{s(t)} \left( \frac{P_b}{2.026 \times 10^2} + \frac{Q_t}{42} \right)$$

$$Q_t = \frac{R_0}{0.21 \times 1.43 \times E_A \times 100}$$

where $R_0$ (kg/d) is the total oxygen demand transferred in the aeration tank under the actual state; $\alpha$, $\beta$, and $\rho$ are correction factors (in general, $\alpha = 0.85$, $\beta = 0.95$, and $\rho = 1$); $C_{s(t)}$ (mg/L) is the DO saturation in fresh water at $t^\circ C$; $C_{s(b)}$ (mg/L) is the average DO saturation in the aeration tank at $t^\circ C$; $C$ (mg/L) is the DO concentration at the outlet of the aeration tank; $Q_t$ (%) is the percentage of oxygen of bubbles leaving the surface of the aeration tank (19.3%, in this study); $P_b$ (Pa) is absolute pressure at the outlet of the air diffusion devices; $Q_t$ (m$^3$/d) is the actual air supply; 0.21 is a constant of fraction of oxygen in air; 1.43 (kg/m$^3$) is a constant of oxygen density in air; $E_A$ (%) is the oxygen transfer efficiency for aerator (10%, in this study). The determination of fixed oxygen transfer coefficient $\alpha$ was based on the concentration of COD in influents without considering the bubble size distribution dynamics, which has limits in accurate aeration efficiency modeling (Amaral et al. 2018).

Measurements showed that the effluent COD concentrations during the year were always less than 60 mg/L (class 1B limit) (MEP 2002); therefore, the constraints focused on effluent nitrogen and phosphorus concentrations. The optimization is formulated by Equation (10):

$$\text{Min } Q_t$$

subject to

$$C_{NH_4-N} \leq 4.0 \text{ mg/L}$$

$$C_{NO_2-N} \leq 13.0 \text{ mg/L}$$

$$C_{NH_4-N} + C_{NO_2-N} \leq 15.0 \text{ mg/L}$$

$$C_{PO_4-P} \leq 1.2 \text{ mg/L}$$

where $C_{NH_4-N}$, $C_{NO_2-N}$, and $C_{PO_4-P}$ (mg/L) are effluent water quality levels predicted by the model.

RESULTS AND DISCUSSION

Model calibration and parameter analyses

The initial model parameter values were obtained according to previous research (Gujer et al. 1999; Koch et al. 2000; Rieger et al. 2001). Kinetic parameters were calibrated for three reference temperatures (10, 20, and 30 °C) of wastewater in the biochemical tanks. The parameters were repeatedly adjusted until the model outputs were close to the observed values. Tables S5 and S6 in SI (available with the online version of this paper) show the values of the main kinetic and stoichiometric parameters corresponding to the best calibration results. The model was validated using an independent data set from the plant. The validations were conducted for 24 hours at the three reference temperatures, and the comparison was based on COD and NH$_4$-N concentrations in the secondary effluent (Figure 2).

Although many factors such as DO, SRT, hydraulic retention time, and water temperature affect the pollutant removal efficiency of WWTPs, temperature is recognized as having distinct effects on the performance of nutrient removal (Koch et al. 2000; Rieger et al. 2001). For example, the PAOs were reported to have a growth advantage at temperature of 10 °C or less in activated sludge systems compared to non-PAOs (Erdal et al. 2003). In this study, three reference temperatures were considered in the model development. The initial model parameter values at 10 °C and 20 °C were obtained from relevant literature (Gujer et al. 1999; Koch et al. 2000; Rieger et al. 2001). For the kinetic parameters at reference temperature of 30 °C, the initial model parameter values were preliminarily assumed based on process knowledge (Erdal et al. 2003; Lee et al. 2011; El Shorbagy et al. 2013). After calibration, the model validation results showed that the parameter values obtained were reasonable, as the root mean square error (RMSE) was less than 20% (Gabarron et al. 2015).

The sensitivity of COD, NH$_4$-N, NO$_2$-N and PO$_4^-$-P related parameters was analyzed using a one-variable-at-a-time approach, and the results for 15 kinetic and nine stoichiometric parameters at the base temperature of 20 °C are presented in Figure 3. The maximal storage rate of $XH$ ($k_{STO}$), aerobic endogenous respiration rate of $XH$ ($b_{H,OX}$) and yield coefficient for $XH$ growth on $S_S$ ($Y_{H,OX}$) showed great influence on the model results of COD (Figure 5(a)).
yield biomass per cell-internal storage product of PAOs (\(Y_{PAO,O2}\)), aerobic endogenous respiration rate of \(X_A (b_{A,O2})\), anoxic endogenous respiration rate of \(X_H (b_{H,NO})\), and \(Y_{STO,NO}\) had considerable influence on the calculation results of NH\(_4\)-N (Figure 3(b)). \(Y_{PAO,O2}, Y_{STO,NO}, Y_{H,NO},\) and \(\mu_A\) had marked effects on the predicted results of NO\(_3\)-N (Figure 3(c)). \(Y_{STO,NO}\) was the most sensitive parameter for the simulation of PO\(_4\)-P concentration in the effluent (Figure 3(d)). \(Y_{PAO,O2}\), maximal endogenous respiration rate of \(X_{PAO} (b_{PAO})\), rate constant for storage of \(X_{PHA} (K_{PHA})\) and maximal storage rate of \(X_{H} (k_{STO})\) also affected the results of PO\(_4\)-P significantly. The other model parameters had no significant influence on the output of COD, NH\(_4\)-N, NO\(_3\)-N or PO\(_4\)-P concentrations.

Model application and water temperature dependency analyses

The calibrated model was applied to the Jiangxinzhou WWTP using the stoichiometric and kinetic parameter values shown in Tables S5 and S6 in SI. The required data for model running, including DO concentrations in the anoxic and aerobic tanks, water temperature, and inflow, were obtained by online sensors. The model simulation period was 1 year, from March 2013 to February 2014. The modeled results and observations are presented in Figure 4 for comparison.

The modeled COD values from the ASM3 + bio-p model were generally in accord with the observed COD concentrations in the effluent of the WWTP, with an RMSE value of 11% (Figure 4(a)). This was likely due to the fact that the influent was mainly domestic sewage, resulting in relatively stable effluent COD composition. The modeled effluent NH\(_4\)-N concentrations also showed good agreement with the measured values (RMSE: 18%) (Figure 4(b)). The modeled nitrate concentration (Figure 4(c)) and PO\(_4\)-P concentrations (Figure 4(d)) were acceptable, with an RMSE of 4% and 8%, respectively. It was found that the plant was efficient at phosphorus removal, which may be because of the uptake in the oxic

Figure 2 | Comparison between simulation results and measured data of effluent COD (left) and NH\(_4\)-N (right) for the Jiangxinzhou WWTP at the base temperatures of 10, 20, and 30 °C.
Figure 3 | Effect of the kinetic and stoichiometric parameter values on the model outputs at the base temperature of 20 °C.

Figure 4 | Measured and simulated concentrations of COD, NH$_4^+$-N, NO$_3^-$-N and PO$_4^{3-}$-P of the Jiangxinzhou WWTP effluent during March 2013 to February 2014 (measured data in (a) and (b) are from our previous study (Wang & Chen 2016)).
zones and denitrifying phosphorus removal under the anoxic conditions (Wang & Chen 2016).

**Plant operation optimization and comparison to original operation**

WWTPs are often operated in a fixed mode throughout the year, which is disadvantageous in coping with the influent water quality changes and seasonal water temperature variations. In this study, the operation of Jiangxinzhou WWTP was optimized, focusing on the most important controllable parameters of DO in the oxic zones, SRT, and $R$, which could be easily adjusted by aeration rate, excess sludge flow, and recirculation flow, respectively, through the calibrated model, and were dynamically adjusted according to online sensing data. The relationships between the output targets and controllable parameters were determined using the validated model. The results (Table 2) indicated that the optimized controllable parameters not only improved effluent quality but also reduced aeration energy consumption.

Optimal operating parameters achieved from scenario analysis and proposed for the full-scale plant over four seasons are presented in Table 3. The response relationship between output target and control parameters was determined by orthogonal analysis. Consideration of the change of DO saturation with temperature is helpful to obtain accurate operating parameters in scenario analysis, though the DO saturation remains constant at a certain temperature. Furthermore, it was found that DO was one of the most important factors affecting phosphorus removal, and lower oxygen conditions were also favorable to nitrogen removal under the premise of a good nitrification process. In the Jiangxinzhou WWTP, the actual DO concentration in the oxic zones was greater than 3 mg/L. After optimization, DO concentrations were maintained at 2.0, 1.5, 2.0, and 2.5 mg/L in spring, summer, autumn, and winter, respectively, which were sufficient for biochemical reactions and beneficial to nitrogen removal as well as phosphorus reduction. The plant operation optimization not only had effects on the activity of microorganisms and nutrient removal efficiency, but also directly affected the aeration energy consumption. The aeration rate before optimization was $4.6 \times 10^6$ m$^3$/d based on the designed influent loading (COD of 260 mg/L, total Kjeldahl nitrogen of 30 mg/L, and water temperature of 25°C). After optimization, the aeration rate in spring, summer, autumn, and winter was reduced by 15, 41, 33, and 11%, respectively, compared to the current operation mode.

Sufficient SRT is essential to biological nutrient removals because it plays an important role in the selection of microbial species; however, long SRT could also cause negative impacts on the phosphorus removal. This may take place for at least three reasons (Grady et al. 1999): (1) long SRT results in reduced solid production, so that less phosphorus is removed from the system; (2) long aerobic SRT results in relatively complete oxidation of organic storage products and a reduced rate of phosphorus uptake in the aerobic zones; (3) decay reactions cause secondary phosphorus release. $R$ was related to recycled oxygen and denitrification capacity, and the latter in turn affects the

<table>
<thead>
<tr>
<th>Season</th>
<th>Key controllable parameter</th>
<th>DOa (mg/L)</th>
<th>SRT</th>
<th>R (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>DO</td>
<td>2.0</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>Summer</td>
<td>DO</td>
<td>1.5</td>
<td>8</td>
<td>70</td>
</tr>
<tr>
<td>Autumn</td>
<td>DO</td>
<td>2.0</td>
<td>10</td>
<td>80</td>
</tr>
<tr>
<td>Winter</td>
<td>DO</td>
<td>2.5</td>
<td>12</td>
<td>100</td>
</tr>
</tbody>
</table>

*aAverage DO concentration in the oxic zones.*

### Table 2

<table>
<thead>
<tr>
<th>Season</th>
<th>Activity (kg/d)</th>
<th>Aeration ratea ($\times 10^6$ m$^3$/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nitrogen Beforeb</td>
<td>After</td>
</tr>
<tr>
<td>Spring (Mar., Apr., May)</td>
<td>$4.96 \times 10^3$</td>
<td>$5.29 \times 10^3$</td>
</tr>
<tr>
<td>Summer (Jun., Jul., Aug.)</td>
<td>$3.80 \times 10^3$</td>
<td>$4.52 \times 10^3$</td>
</tr>
<tr>
<td>Autumn (Sep., Oct., Nov.)</td>
<td>$4.88 \times 10^3$</td>
<td>$4.95 \times 10^3$</td>
</tr>
<tr>
<td>Winter (Dec., Jan., Feb.)</td>
<td>$3.90 \times 10^3$</td>
<td>$4.38 \times 10^3$</td>
</tr>
</tbody>
</table>

*aRequirement for the first stage ($4.0 \times 10^5$ m$^3$/d). bFrom our previous study (Wang & Chen 2016).
oxygen demand in the wastewater treatment system. Therefore, the optimal SRT and $R$ of a WWTP must be selected based on the compromise between nitrogen and phosphorus removal so as to realize the maximization of denitrification and phosphorus removal efficiency. In line with this strategy, the SRT and $R$ were optimized for the Jiangxinzhou WWTP, and the results are given in Table 3.

**Engineering significance of the study**

The optimization of WWTP operation proposed in this study could provide guidance for energy saving without affecting effluent water quality, which can be extended to other WWTPs. A flow chart of an online data monitoring and control system for WWTP operation is given in Figure 5. Rational coordination between the individual units of the plants was critical for the success of plant operation. Moreover, online monitoring and the real-time control system should be taken into account in order to enable a robust and efficient treatment process. During the operation, dynamically optimized parameters could be obtained by the numerical model of the wastewater treatment systems, so as to adjust the controllable variables in a timely fashion according to the changes in conditions. The integration of online monitoring data and numerical models has great potential in closed-loop automatic control systems to regulate operation parameters for achieving efficient and economic management of WWTPs.

**CONCLUSION**

- In this study, an ASM3 + bio-p model was developed and calibrated for a full-scale experimental WWTP.
- The model was integrated with an online sensor network to optimize controllable variables of WWTPs.
- The results showed that nitrate, nitrogen, and phosphate removal efficiency was improved and aeration energy was reduced, compared to the original fixed operation mode.
- The integration of simulation models and an online monitoring system could be a valuable technology to achieve relatively higher nitrogen and phosphorus removal rates at lower aeration costs.

**ACKNOWLEDGEMENTS**

This research was supported by the National Key R&D Program of China (2016YFC0502205), the National Nature Science Foundation of China (No. 91547206), the Jiangsu Water Protection Project (2015005), Jiangsu Science Fund (BE2016617), Jiangsu Innovative Group Fund, and Innovative Fund of Nanjing Hydraulic Research Institute. The authors are grateful to Dr Catherine Rice for proofreading the English.

**REFERENCES**


First received 7 June 2018; accepted in revised form 10 October 2018. Available online 16 October 2018.