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Original Article

Dynamic Estimation of Hourly Fluctuation of Influent Biodegradable Carbonaceous and Nitrogenous Materials Using Activated Sludge System

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ABSTRACT
The study was aimed at developing an alternative method to catch biodegradable concentrations in municipal wastewater, especially for designing wastewater treatment plants receiving storm water where the influent concentrations significantly changed in time. As conventional water analytical methods required lots of samples and numerous analysis, which was practically infeasible, a lab-scale nitrifying activated sludge reactor having on-line DO meter and quick-test nitrate kit was installed at the experimental site in Hue, Vietnam. By fixing the hydraulic retention time with 2.0 hours and aeration intensity, the biodegradable concentrations in the influent including carbonaceous and nitrogenous compounds were back-calculated from the dynamic response of dissolved oxygen concentration in the aeration tank and the nitrate concentration in the effluent using IWA Activated Sludge model. During the data collection event for 24 hours, the influent was also sampled at 1-hr interval and its concentrations were compared with those calculated. The field experiment successfully demonstrated that the back-calculation method could reasonably estimate the influent biological concentration on the basis of biological oxygen demand where the concentration was highly fluctuated in time. Based on the experiment, the feasibility to measure sudden elevation and decrease of pollutant load in the first flush was discussed in the paper.

Keywords: back-calculation, activated sludge model, storm water

INTRODUCTION

Along with population boom, a rapid development of the economy is one the most reason for the initiation of new wastewater treatment plants (WWTPs) in developing counties, especially in Vietnam. According to the report published by World Bank in 2013 [1], the average ratio of urban household connected to public sewerage or drainage system in Vietnam was estimated at around 60 percent and the local coverage depends on the residential density and fundamental infrastructure of each area. In order to deal with the potential pollution of water bodies, Vietnamese Government have been putting effort into improving urban sanitation with more than 30 projects implemented over the country as of 2013 [1,2].

Another fact revealed from the report that 60 percent of household discharging wastewater to septic tank placed prior to sewer was a compulsory regulation. Since septic tank is a kind of decentralized component contributing to reduction of pollutant load, a portion of biodegradable materials is decomposed during the period of retention [3]. Nevertheless, due to accumulation of pollutant associated with lack of regular maintenance, it is recognized that the septic tank process cannot produce high performance which remark-

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ably differs over areas and household [4,5]. Accordingly, the constituents and concentration of effluent from septic tank to combined sewage system which was the typical class in urban areas considerably varied, e.g. BOD_5: 36 − 135 mg/L, SS: 27 − 196 mg/L and Total Nitrogen: 11 − 40 mg-N/L [1]. In addition, because the combined sewerage systems in Vietnam play a role in collecting both wastewater and storm water which probably carries surface pollutant, the variation in influent concentration possibly becomes more enormous. All of these facts lead to a challenge in planning and designing WWTPs due to the impossibility of applying default influent concentration.

Usually, in order to determine the characteristic of wastewater, on-site water sampling combined with laboratory analysis is supposed to be the most common procedure. However, in case that the constituent and concentration of the objective fluctuate over time, a considerable number of water samples must be required to collect and then be analyzed in laboratory. Furthermore, for the reason that some materials in wastewater are readily decomposed in short time, a requirement of immediate analysis with abundant of manpower is undoubtable. For the purpose of timely catching the fluctuation of concentration besides wastewater flow, innovative and simple methods are desired to replace those cumbersome ones.

Recently, Nguyen *et al.* (2016) demonstrated a back-calculation method using a set of lab-scale activated sludge reactors, whereby the composition of activated sludge which was the direct consequence of the influent materials were analyzed and those were then calculated respectively [6]. Nonetheless, the research merely revealed the approach on weekly estimation of influent concentration associated with the acceptance of influent unchangeability during a specific time step (7 − 8 days). In reliance on the concept of this approach, considering that decomposition of biodegradable carbonaceous and nitrogenous compounds in wastewater, which consumes dissolved oxygen (DO), are responsible for the fluctuation of DO concentration in reactor, and the biodegradable nitrogenous materials are converted totally into nitrate form in effluent, the back-calculation of these constituents from dynamic response of the above-mentioned parameters using IWA Activated Sludge Model No.1 (ASM1) [7] as a mathematical calculation method may enable to detect the fluctuation of influent concentration over short interval. Thanks to the advance in sensory technology with numerous portable measurement devices which are available in commercial markets, the monitoring of DO and nitrate concentration over short interval are totally obtainable. Once this developed method would be applied, a significant amount of time and labor could be saved comparing to the conventional method. For instance, in the purpose of catching influent constituents and its fluctuation in concentration during first flush of storm weather, conventional method with on-site sampling followed by laboratory analyzing tons of sample is absolutely impossible solution to meet the initial purpose. In contrast, the continuous monitoring of sudden variation in parameter's information, which was DO concentrations in reactor and nitrate concentrations in effluent, can be totally obtained with the great assistance from modern portable meter combined with relevant probes. By this way, the possibility to estimate the sudden fluctuation in influent concentrations is anticipated. Based on the background, a lab-scale activated sludge module was installed at Hue Citadel area in Vietnam and operated for several months. From the intensive analysis for 24 hours, the DO concentration in aeration tank and nitrate concentration in the effluent were monitored with on-line probes. Using the dataset for ASM1, the municipal wastewater constituents and concentration at every 1-hour were calculated.

MATERIALS AND METHODS

Field Experimental Module

Installation of system

An activated sludge module was installed in Hue Citadel area, Vietnam. All households in this area had water-flush toilets connecting to each septic tank [8]. Since no full-scale WWTP was available in Hue, both the wastewater and storm water collected from the city's combined sewerage system were directly discharged to Ngu Ha canal and 41 lakes [9]. The region where the module was set up was located in the center of study area and close to the end discharge point of the local sewerage system prior to Tinh Tam lake. As illustrated in **Fig. 1**, the influent for feeding was pumped by a submerged pump (S-500LN, Tereda Pump Co. Ltd., Tokyo, Japan) covered by a coarse screen and this integrated apparatus was placed closely at the end of the sewer. The main module was composed of a primary settling tank, an aeration tank and a secondary settling tank. All tanks had 22-L working volume with conical cylinder shape. A solid scraper was equipped with each settling tank whilst aeration tank had an air diffuser made of air stone and a blower having maximum capacity of 6 L-air/min (OP-N026D, Iwaki Pumps Co. Ltd., Tokyo, Japan). For the recirculation of activated sludge from secondary settling tank to aeration tank, an air-lift pump composed of 12.5-cm PVC tube and blower (APN-057R,

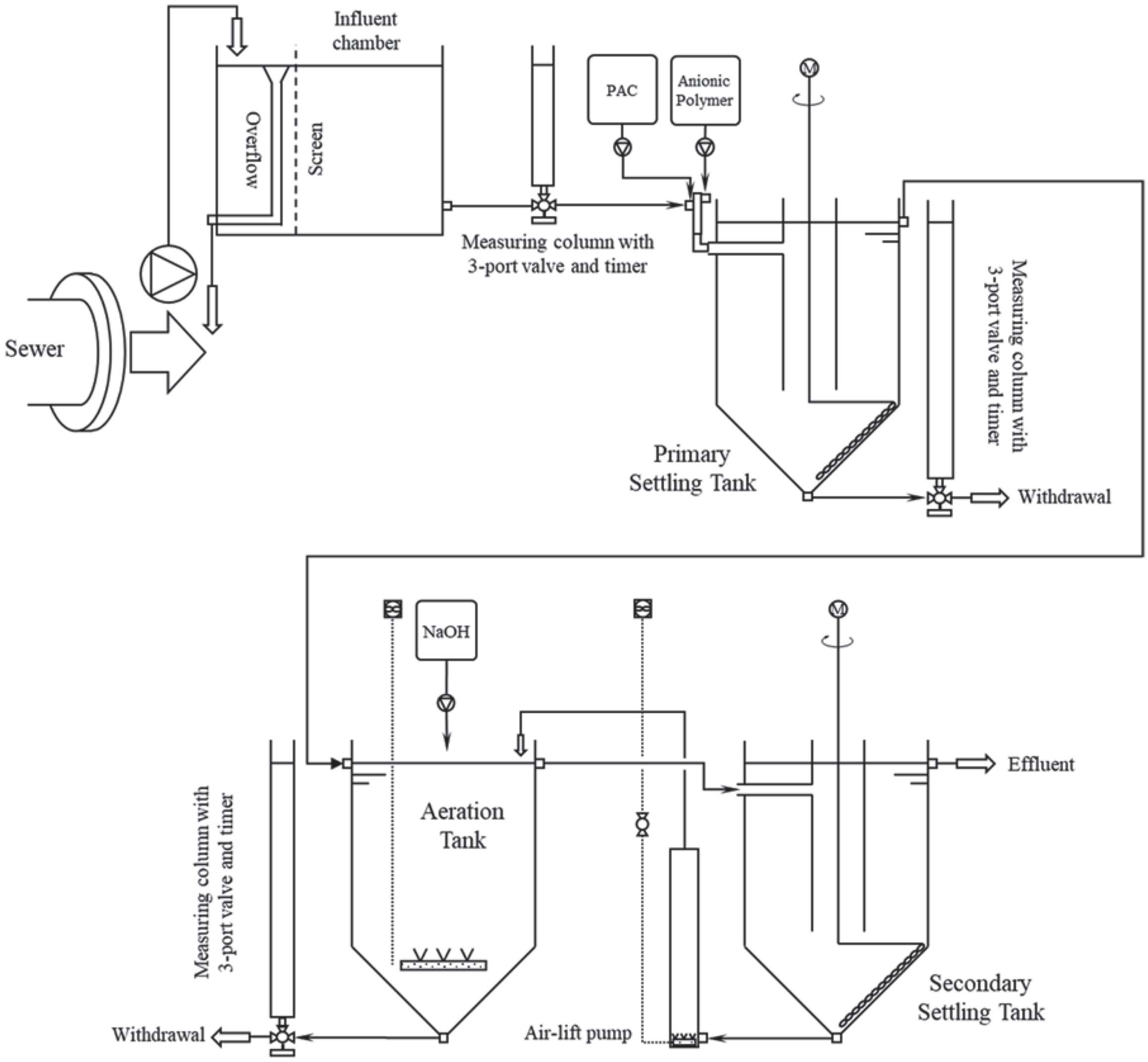

Fig. 1 Schematic flow of conventional activated sludge module.

Iwaki Pumps Co. Ltd., Tokyo, Japan) was put into use.

The wastewater pumped from the sewer at around 30 L/min of flowrate was continuously circulated and stored in a 50-L influent chamber positioned above the top of main module to feed the influent in gravity. A coarse screen was additionally inserted in the influent chamber to prevent from clogging by big particles, the excess wastewater was overflown from a small ditch at the top of the influent chamber to the effluent container and then was pumped back into sewer. A 2.5-L PVC measuring column which was responsible for feeding the influent was connected with the bottom of influent chamber via a 3-port ball valve (common-port, A-port and B-port which were closed and opened respectively by default) (EALB100-UTNE15A, Kitz Co. Ltd., Chiba, Japan) controlled by an on-off periodic timer (H3CA-A, OMRON Co. Ltd., Kyoto, Japan). During "on" period, the ball valve switched position to connect the common-port with the A-port resulting in the filling of wastewater in measuring column until the water level became the same as that of the influent chamber. Afterward, when the timer was "off", the ball valve was turned back and the common-port was connected with B-port, leading to emptying and withdrawal of wastewater from the measuring column to the module. In the same manner, the primary settling tank and aeration tank were also equipped with a corresponding measuring column for each sludge withdrawal.

Operating conditions

By using the measuring column with relevant apparatus mentioned above, the hydraulic loading of the influent was set at 264 L/d, meaning that hydraulic retention time of the aeration tank was 2 hours. The sludge retention time was steadily controlled to be 10 days. Inoculum activated sludge was obtained from a brewery located in a specific industrial zone nearby Hue Citadel area.

In order to maximize the solid-liquid clarification of primary settling tank, about 10 mg-Al/L of poly-aluminum chloride and 0.5 mg/L of anionic polymer (Organo Corp., Tokyo, Japan) were dosed directly on the basis of influent flow using an electromagnet metering pump (EHN-B11, Iwaki Pumps Co. Ltd.). A small amount of NaOH 5 g/L solution was also added to neutralize pH in the aeration tank ranging from 6.8 to 7.2. The air flow of aeration tank was carefully fixed at 2 L-air/min whilst the water temperature in the aeration tank varied between 24.5°C and 26.0°C during the experimental period.

After about 1 month of preliminary continuous operation, the activated sludge was sampled from the aeration tank to measure kinetic parameters including specific decay and specific growth rates of microorganisms. The DO concentration in the aeration tank and the nitrate concentration in the effluent were continuously monitored where the DO concentration was measured by a portable on-line meter (Multi 3630 IDS) with attached sensor (FDO 925) (WTW-Xylem Corp., Weilheim, Germany) and the nitrate concentration was measured using a test kit including a main reflectometer (RQflex® plus 10) and test strips (116971-Nitric acid test, MiliporeSigma Cor., Burlington, USA) with a set of standard concentration, whilst the sampling of influent was also conducted at fixed interval. The volumetric mass transfer coefficient (K_La) of oxygen was also measured to calculate the biological oxidation rate in the aeration tank.

Laboratory Analysis

In order to determine specific decay rate (b_{OHO}) and estimate ordinary heterotrophic active biomass in the activated sludge ($X_{\mathrm{OHO}\,(0)}$), about 1,000 mL of activated sludge was collected from the reactor and immediately delivered to laboratory. For the measurement of $b_{\mathrm{OHO},}$ the endogenous oxygen uptake rates ($\mathrm{OUR}_{\mathrm{e\_OHO}}$) were daily measured. The activated sludge was poured into a beaker in a water bath to control the temperature as same as that of activated sludge in the reactor, and the sample was kept aerated continuously for a week. The pH of the sample was daily adjusted to about 7.0 using NaOH solution. About 100 mL of activated sludge of the aerated sample was then transferred to a Winkler bottle with addition of 20 mg/L of allylthiourea to inhibit the oxygen uptake by nitrification [7]. Afterward, the mixed sample was stirred at around 100 rpm and the period to reach the DO concentration from 7.0 mg-O_2/L to 1.0 mg-O_2/L was measured with a DO meter (TPX-1000, Toko Chemicals, Tokyo, Japan). This procedure was daily conducted during the experimental period and a dataset of $\mathrm{OUR}_{\mathrm{e\_OHO}}$ for 7 days was obtained. Based on the linear regression of semi-logarithm of OUR along with the incubation time, $\mathrm{b}_{\mathrm{OHO}}$ and the initial heterotrophic organism concentration ($X_{\mathrm{OHO}\,(0)}$) in the activated sludge were calculated according to the decay concept of ASM3 and the death-regeneration concept of ASM1 using equation (1), (2) and (3) [7,10,11].

$$\mathrm{OUR}_{\mathrm{e\_OHO(t)}} = (1-f_{\mathrm{U}}^{'})b_{\mathrm{OHO}}^{'}X_{\mathrm{OHO(0)}}\mathrm{e}^{-b_{\mathrm{OHO}}^{'}t} \tag{1}$$

$$b_{\mathrm{OHO}} = \frac{1}{1-(1-f_{\mathrm{U}})Y_{\mathrm{OHO}}}b_{\mathrm{OHO}}^{'} \tag{2}$$

$$f_{\mathrm{U}}^{'} = \frac{f_{\mathrm{U}}}{1-(1-f_{\mathrm{U}})Y_{\mathrm{OHO}}} \tag{3}$$

where:

$\mathrm{OUR}_{\mathrm{e\_OHO}\,(t)}$ = the endogenous oxygen uptake rate of heterotrophic organism at the incubation time = *t*.

f_{U} = the production of inert organic particulate (0.08 g-COD/g-COD) [7]

$b^{'}_{\mathrm{OHO}}$ = the specific endogenous decay rate of heterotrophic organism (1/d)

$X_{\mathrm{OHO}\,(0)}$ = the active biomass of heterotrophic organism (mg-COD/L)

Y_{OHO} = the biomass yield coefficient for heterotrophic organism (0.66 g-COD/g-COD) [7]

t = the incubation time (day).

In order to estimate maximum specific growth rate ($\mu_{\mathrm{max\_NAO}}$) and the active biomass of nitrifying autotrophic organism in the activated sludge (X_{NAO}), a batch incubation test was performed. The source of nitrogenous substrate was ammonium chloride, and the concentration was maintained at 50 mg-N/L during the batch experiment. From the enriched activated sludge, nitrifier's maximum oxygen uptake rate ($\mathrm{OUR}_{\mathrm{max\_NAO}}$) was daily monitored. Based on the exponential elevation of $\mathrm{OUR}_{\mathrm{max\_NAO}}$ along with the incubation time, the $\mu_{\mathrm{max\_NAO}}$ and initial X_{NAO} in activated sludge were calculated from equation (4) [12,13].

$$\mathrm{OUR}_{\mathrm{max\_NAO}} = \frac{(4.57 - Y_{\mathrm{NAO}})}{Y_{\mathrm{NAO}}} \mu_{\mathrm{max\_NAO}} X_{\mathrm{NAO}} + (1 - f_{\mathrm{U}}) b_{\mathrm{NAO}} X_{\mathrm{NAO}} \tag{4}$$

where:

$\mathrm{OUR}_{\mathrm{max\_NAO}}$ = the maximum oxygen uptake rate of autotrophic organism

$\mu_{\mathrm{max\_NAO}}$ = the maximum specific growth rate of autotrophic organism

Y_{NAO} = the biomass yield coefficient for autotrophic organism (0.24 g-COD/g-N) [7]

b_{NAO} = the endogenous oxygen uptake rate of autotrophic organism (0.15 1/d at 20°C) [7]

X_{NAO} = the active biomass of nitrifying autotrophic organism (mg-COD/L).

To estimate $K_{\mathrm{L}}a$ value, influent feeding was discontinued for a while until the DO concentration in the reactor reached air saturation. Afterward, the ammonium chloride solution was dosed at 100 mg-N/L of concentration, and the measurement of oxygen uptake rate together with monitoring of DO concentration that gradually reached a constant value were conducted. In gas-liquid system, the mass balance of DO in a given complete mixing reactor was described in equation (5) [14,15]. In this study by fixing the air flow at 2 L-air/min, the obtained $K_{\mathrm{L}}a$ value was 17.5 1/h.

$$\frac{dC_{\mathrm{L}}}{dt} = K_{\mathrm{L}}a(C^{*} - C_{\mathrm{L}}) - Xq_{\mathrm{O_2}} \tag{5}$$

where:

dC_{L}/dt = process rate of DO in the liquid phase (mg-O_2/L/h)

C^* = the saturation DO concentration in the liquid phase (mg-O_2/L)

C_{L} = the actual DO concentration in the liquid phase (mg-O_2/L)

X = the biomass concentration (mg-COD/L)

$q_{\mathrm{O_2}}$ = the specific oxygen uptake rate of the microorganism (1/h)

From the equation (5), the part of $K_{\mathrm{L}}a(C^* - C_{\mathrm{L}})$ represented the oxygen transfer rate (OTR) from the gas to liquid phase, in which C_{L} was determined as the constant value whilst Xq_{O2} was the oxygen uptake rate of microorganism (OUR). When dC_{L}/dt became almost zero, $K_{\mathrm{L}}a$ could be obtained from $(C^* - C_{\mathrm{L}})$ and Xq_{O2} in numerical manner [14,15].

Dynamic Estimation of Influent Constituents and Concentration

The DO concentration in the aeration tank and the nitrate concentration in the effluent were monitored and measured using the above-mentioned apparatus (the DO portable meter with sensor and reflectometer with test strips). Apart from these target variables associated with active biomass (X_{OHO} and X_{NAO}) and kinetic parameters (b_{OHO} and $\mu_{\mathrm{max\_NAO}}$), concentrations of soluble biodegradable carbonaceous material (S_{B}) and soluble biodegradable nitrogenous material (S_{NHx}) were back-calculated respectively on basis of activated sludge model [7,16](**Table S1**).

As illustrated in **Fig. 2**, S_{B} concentration was mainly estimated from DO utilization whilst S_{NHx} concentration was estimated from the nitrification, DO utilization and nutrient uptake. Along with the physical and operational parameters of the activated sludge module, the obtained datasets including the kinetic parameters, DO and nitrate concentrations were transferred to a simulation layout created by a process simulator (GPS-X ver. 7.0, Hydromantis Inc., Hamilton, Canada). The S_{B} and S_{NHx} concentration were back-calculated with Dynamic Parameter Estimation (DPE) method programmed in the simulator.

In concept of functional principle, the optimized variable concentrations (S_{B} and S_{NHx}) were assumed to be constant at each time-step (defined as time window) and were alternatively changed at the next time-step in stepwise manner. By registering each specific value of the optimized variables as input parameters, the DPE firstly calculated the responsible user-defined output parameters (DO and nitrate concentration) and then compare these data to those measured, which were manually imported, by using a specific objective function. By this way, the optimized variable concentrations were adjusted within the pre-determined range until the calculated values of user-defined output parameters possibly fit to those of the measured values, which equal to the minimization of the objective function value. In this study, the S_{B} and S_{NHx} concentrations were randomly selected in the pre-determined range to reproduce the minimal and maximal DO concentrations during the sampling event (between 0 and 120 mg-COD/L for S_{B} and between 0 to 24 mg-N/L for S_{NHx}), Maximum Likelihood of the objective function was selected for the parameter regression. It was also noted that the regression process was programmed to be terminated when one of the below termination criteria was satisfied:

− Parameter Tolerance: by dividing the range between the largest and the smallest value which were considered as the possible values of a specific optimized variable by the differ-

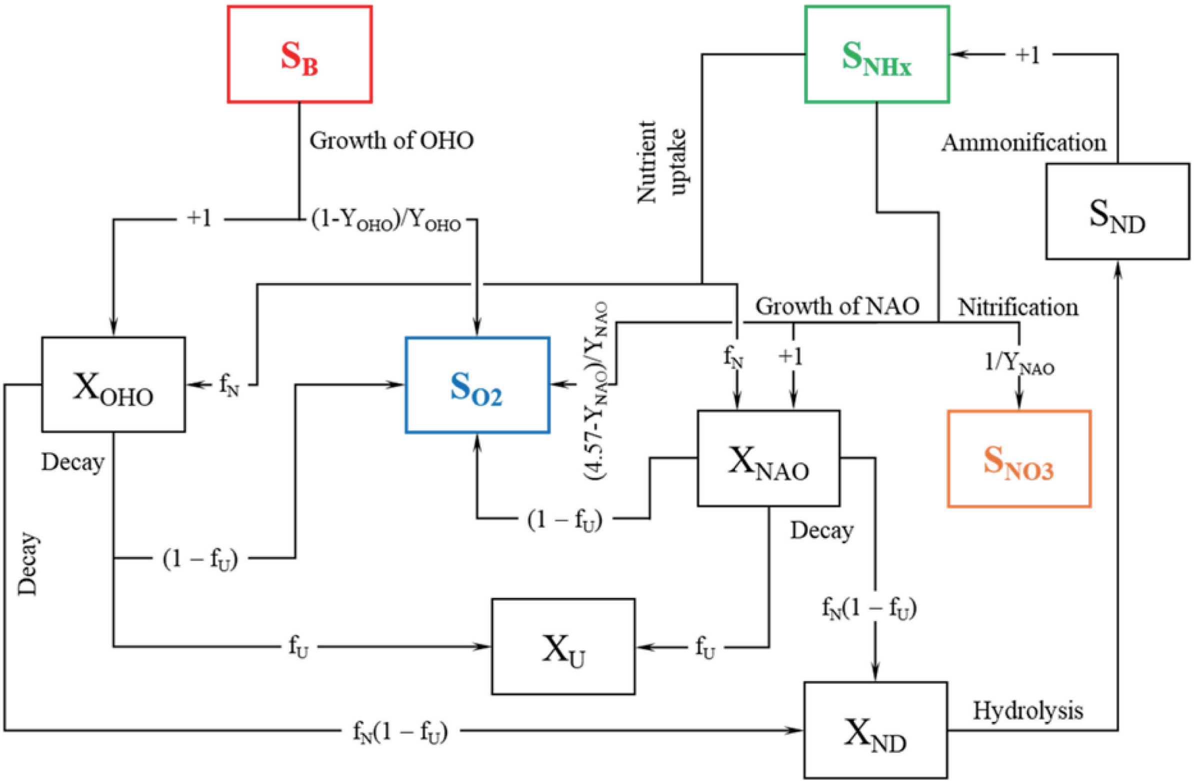

Fig. 2 Fate of influent materials in the activated sludge process.

ence between the upper and lower bounds for this optimized variable, a term of "singular maximum size" was obtained. If the maximums size for all the optimized variables are less than the parameter tolerance, the regression process is terminated.

− Objective function tolerance: if the range (largest minus smallest) of objective function values is less than the objective function tolerance, the regression process was terminated.

− Maximum number of optimizer iterations: The optimization process was terminated if the maximum number of iterations is reached.

When performing the DPE method to estimate the influent concentration, along with the selected objective function options and termination criteria, other two parameters also needed to take into account were the time-step (defined as time window) and the calculation frequency (defined as communication interval). The length of the time-step was defined the interval at which the optimized variables (S_B and S_{NHx}) were assumed to be constant whilst the calculation frequency was defined the frequency to calculate and update the output parameter values (DO and nitrate) from the optimized variables. In order to ensure proper termination of the back-calculation routine, the time-step and the calculation frequency were chosen such that the time-step was an integer multiple of the calculation frequency. For the ease of comprehension, the termination criteria were selected as Parameter Tolerance = 1.0×10^{-6} and the maximum number of optimizer iterations was set at 200 number due to no significant improvement recognized when more trials (the higher maximum number of optimizer iterations) were performed. It was also noted that the only meeting the criterion of the objective function tolerance without satisfying the criterion of the parameter tolerance would indicate that the objective function was not very sensitive to some parameters, therefore the criterion of the objective function tolerance was disabled by setting a large negative value (-1×10^{10}) [17]. For the setting of time-step, in case that the time-step was set as greater than the data collection frequency, it was unmeaningful due to a certain number of consecutive data points were calculated as same result. For instance, when the time-step was set at 2 hours, the optimized variables (S_B and S_{NHx}) were assumed to be constant for 2 hours, leading to same calculated results for each pair of two consecutive data point (at the 1-hour interval) of the optimized variables. On the other hand, in case that the time-step was set as smaller than the data collection frequency, there would be a significant scattering in

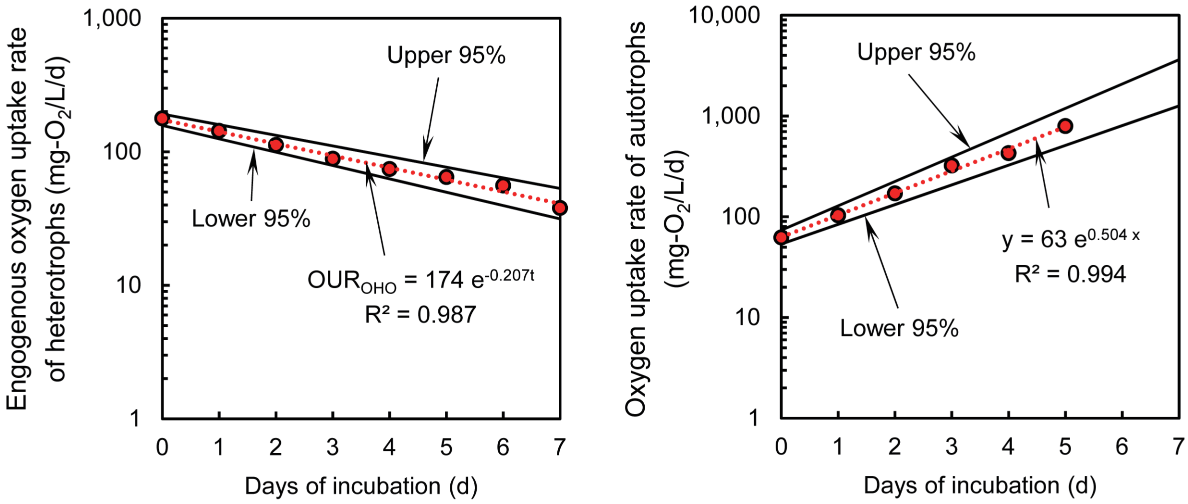

Fig. 3 Batch test to estimate specific decay of ordinary heterotrophs and specific growth rate of nitrifying autotrophs (water temperature = 27°C).

the calculated results of the optimized variables due to no provision of data within each pair of consecutive output data point (at 1-hour). For these reasons, the time-step was set at 1 hour as same as the interval of data collection frequency and the proper length of calculation frequency was evaluated as discussed in the Results and Discussion section.

To justify the above dynamically estimated influent concentrations, hourly sampling of the influent was conducted using an auto sampler equipped with portable refrigerator (Avalanche, Teledyne ISCO, Lincoln, USA), whereby carbonaceous BOD_{30} (C-BOD_{30}) and ammonium nitrogen concentrations were measured according to standard methods [18] (**Table S2**), which were approximated to be S_B and S_{NHx} respectively. For the conversion between C-BOD_{30} and S_B, as C-BOD_{30} was the consequence of ultimate biomass growth (Y_{OHO}) and decay (f_U'), S_B was given from C-BOD_{30}/ ($1 - Y_{OHO} \times f_U$'). For simplification, ammonium nitrogen was assumed to be the dominant soluble biodegradable nitrogen in the influent.

RESULTS AND DISCUSSION

Kinetic parameters and concentration of heterotrophic and autotrophic organism

As shown in **Fig. 3**, OUR_{e_OHO} and OUR_{max_NAO} were reasonably plotted with a high correlation coefficient, especially the OUR_{max_NAO} ($R^2 = 0.99$). The b_{OHO} was estimated to be 0.270 1/d whilst μ_{max_NAO} was calculated to be 0.654 1/d. From these kinetic parameters and the intersection of the graphs ($t = 0$), the initial concentration of heterotroph and autotroph in the activated sludge were calculated as $X_{OHO\ (0)} = 1{,}049$ mg-COD/L and $X_{NAO\ (0)} = 105$ mg-COD/L respectively. For the purpose of providing a probable range of specific decay rate and growth rate as well as active biomass concentration, a linear regression with 95% confidence interval was applied. For heterotroph, the statistical analysis revealed that the specific decay rate and the biomass concentration were placed into a range between 0.183–0.230 1/d and 855–1308 mg-COD/L whilst those of autotroph were placed into a range between 0.601–0.707 1/d and 98–114 mg-COD/L respectively. For the reason that temperature was an influencing factor on microbial kinetics [17], the b_{OHO} and μ_{max_NAO} were normalized at 20°C with the temperature coefficient $\theta_{OHO\ (20°C)} = 1.029$ and $\theta_{NAO\ (20°C)} = 1.072$ [7,19], leading to $b_{OHO\ (20°C)} = 0.169$ 1/d and $\mu_{max\_NAO\ (20°C)} = 0.402$ 1/d respectively. These obtained kinetic parameter values from the batch experiments seemed to be comparable to those in literature [6,7,11,20]. The probable ranges of specific decay and specific growth rate after normalization at 20°C were respectively calculated as $b_{OHO\ (20°C)} \approx 0.150$~0.188 1/d and $\mu_{max\_NAO\ (20°C)} \approx 0.369$~0.435 1/d.

DO concentration in aeration tank and nitrate concentration in effluent

The variation of DO concentration in the reactor over the monitoring campaign and the effluent nitrate concentration were summarized in **Fig. 4A** and **Fig. 4B**. The datasets obviously revealed that the DO concentration was sinusoidally fluctuated from 5.90 mg-O_2/L at the midnight (0h00) and reached the peak of 7.06 mg-O_2/L at the time of 8h00. During

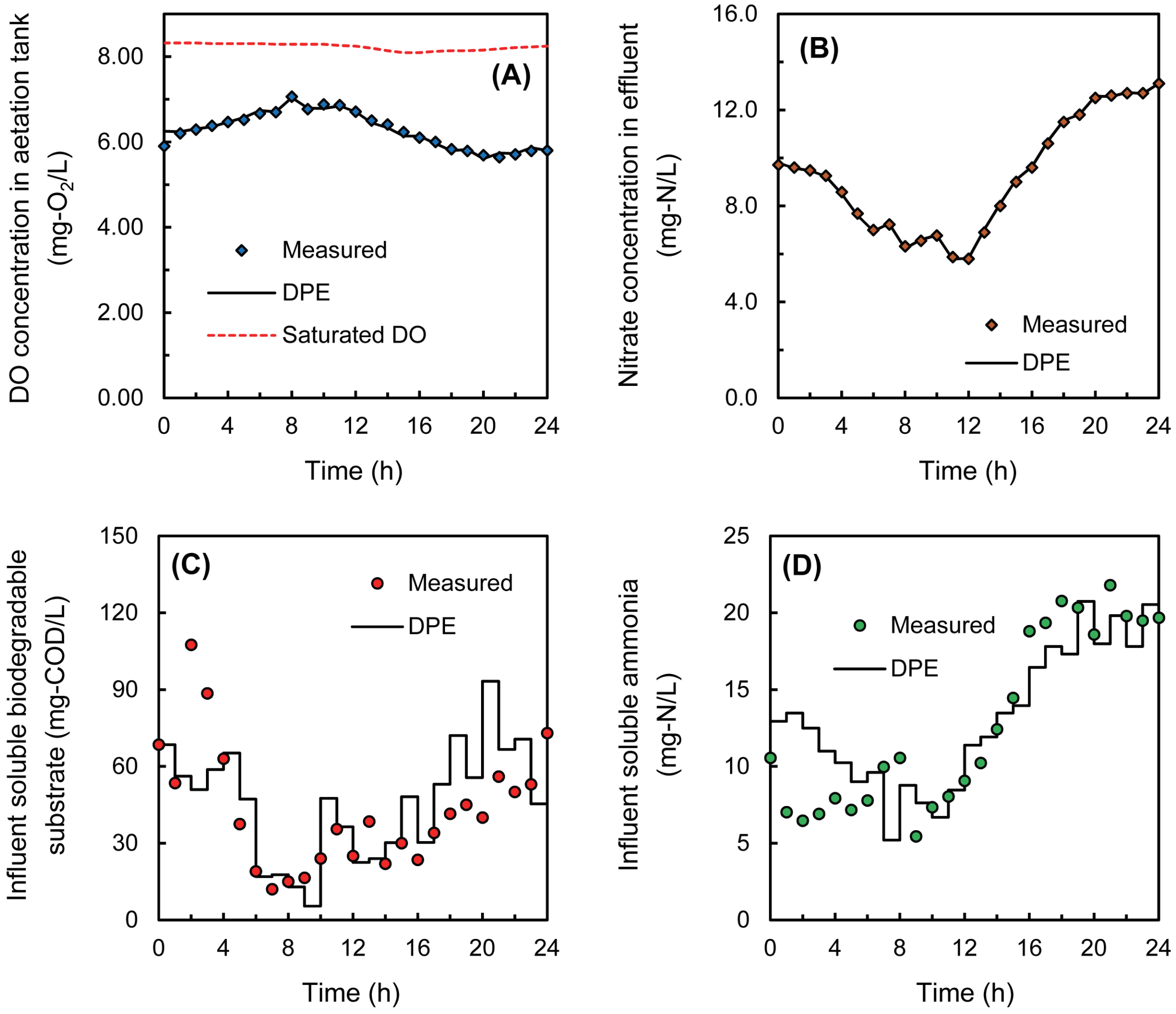

Fig. 4 The concentration of DO in the reactor (top left), effluent nitrate (top right), influent soluble biodegradable organic (bottom left) and nitrogenous compounds (bottom right).

the period from 12h00 to 20h00, the DO concentration gradually decreased to 5.69 mg-O_2/L and seemed to be unchanged during the end of the day (from 21h00 to 24h00). Throughout the experiment, the DO concentration in the reactor was ranged between 5.64–7.06 mg-O_2/L within the day and this fluctuation was attributed to the low concentration of influent material due to considerable dilution mostly caused by rain. According to Tran [21], the average concentration of soluble BOD_5 and total nitrogen at the sewer outlet on dry days in wet season was 35.2 mg/L and 16.6 mg/L respectively. It was also noted that the hourly data of the DO concentration in the aeration tank reached in range from 70% to 85% of saturated DO concentration (at corresponding temperatures).

With respect to the nitrate concentration in the effluent, it appeared that an inverse response was obtained comparing to that of DO concentration in the reactor. The nitrate concentration was ranged between 5.8–13.1 mg-N/L starting with a decrement from 9.7 mg-N/L at the midnight (0h00) to 5.8 mg-N/L at the time of 12h00 followed by an increment in which the nitrate concentration reached 12.5 mg-N/L at the time of 20h00, and seemed to be unchanged during the period from 20h00 to 24h00. As the dynamic responses of DO concentration and nitrate concentration were distinct, these could be used for reliable keys to calculate the 2 kinds of influent material concentrations as S_{B} and S_{NHx}.

Back-calculation of influent constituents

Along with the above obtained datasets including kinetic parameters (specific decay rate of X_{OHO} and specific growth rate of X_{NAO}), initial active biomass (X_{OHO} and X_{NAO}), the monitored datasets (DO and nitrate concentration) and $K_{\mathrm{L}}a$ of oxygen from the aeration were transferred into a simulation layout. By using the DPE method, each S_B and S_{NHx} within each time-step was identified as the "optimized" variable through the curve fitting of DO and nitrate concentration which were selected for the target variables.

As shown in **Fig. 4A** and **Fig. 4B**, the calculated DO and nitrate concentrations completely fitted with those measured except the initial data plot of DO concentration (**Fig. 4A**). This mismatch was believably due to the measurement error caused by device's sensitivity. For the S_B and S_{NHx} concentration, it is obvious that the measured data reasonably appeared around the calculated curve given from DPE feature (**Fig. 4C** and **Fig. 4D**). In the dynamic simulation, underestimation and/or overestimations of the S_B and S_{NHx} concentrations in some time-step were recognized, particularly during the period from 0h00 to 4h00 and from 17h00 to 22h00. Although the exact reasons of the mismatch were not clear, it might be due to the limitation of analytical accuracy of nitrate in the study. Since 1 gram of ammonium required 4.57 gram of oxygen for its oxidation, even small analytical error of nitrate-N would cause large estimation error of S_B as S_B and S_{NHx} were both estimated from DO. For instance, assuming that the true nitrate concentration of effluent at the time of 2h00 and 3h00 were lower than the measured concentration, the DPE method was obliged to underestimate S_{NHx} concentration, leading to the lower oxygen consumption which resulted in overestimation of S_B in the influent. In order to compensate the gap, new S_B concentration should be recalculated to be higher than that of obtained from the first DPE. This could be carried out in such way that the nitrate concentration in the dataset was intentionally manipulated (slight increase of nitrate concentration). In this way the unwanted underestimation of S_B concentration and the overestimation of S_{NHx} concentration could be eliminated. In addition, due to the low concentration of influent biodegradable materials that corresponded to low oxygen uptake rate in the reactor, the DO concentration in the reactor occasionally became close to the saturated concentration. In this case the small driving force ($C^* - C_L$) caused the part of calculation error for both S_B and S_{NHx} in the influent. On the other hand, one of the possible reasons for the mismatch in the calculated and measured data of S_B and S_{NHx} concentrations was the HRT delay (2 hours), which the change of the nitrate concentrations in the effluent were triggered by the nitrate concentrations in the reactor over 2 hours ago.

With respect to the dynamic simulation, the dataset of the measured S_B and S_{NHx} were imported as the input parameters (**Fig. 5C** and **Fig. 5D**) then the DO concentration in the aeration tank and the nitrate concentration in the effluent were calculated by using the initial-defined simulation layout. The simulated data of the DO and nitrate concentration were compared to those. As shown in **Fig. 5A** and **Fig. 5B**, the simulated data reasonably matched to those measure in both case of DO and nitrate. Based on these outcomes, it was noted that both the conventional and the developed approach in water analysis hold a certain extent of analytical error. Furthermore, since the both analytical approaches provided comparable productivity, a comparison in advantages and disadvantages is going to be discussed in the below sub section.

From the measured and estimated concentration of carbonaceous and nitrogenous material, the hourly loads of integrated oxygen demand were calculated (integrated oxygen demand = $S_B + 4.57S_{NHx}$) as shown in **Fig. 6**. Although the consistency between the calculated and measured data of both S_B and S_{NHx} were at reasonable level, the calculated oxygen demand still properly matched those measured. It is undeniable that the load of influent oxygen demand is considered to be a very important information for designing and controlling the aeration intensity. Because the sudden elevation of pollutants concentrations followed by the decrement of that due to the dilution usually occurs at very short period of time, the specific determinations for the oxygen demand of the carbonaceous and nitrogenous materials are supposed to be infeasible. Therefore, the influent load of integrated oxygen demand is considered an attractive approaching. Obviously, from this result the possibility of estimating the load of influent oxygen demand to the aeration tank, in case that the influent concentrations continuously fluctuated over time, was revealed.

Next, the state variables obtained from the DPE were converted to the conventional water quality indices [17]. In average, the sewage at the sampling area contained approximately 37 mg/L of C-BOD_{30} and 12.8 mg-N/L of ammonium nitrogen respectively (**Table S2**). From the DPE, C-BOD_{30} and ammonium nitrogen in the influent were supposed to be approximately 41 mg/L and 13.4 mg/L. Although some data plots were not consistent with the measured ones, the method used in this study seemed to generate accurate 1-day average concentration. These estimated concentrations were comparable to those obtained by Tran [21].

Proper configuration for dynamic estimation

In conjunction with the time-step which was set at 1 hour, the calculation frequency was set in the range from 0.025 to 1 hour (the calculation frequency value could not be greater than that of the time-step). Based on the mathematically

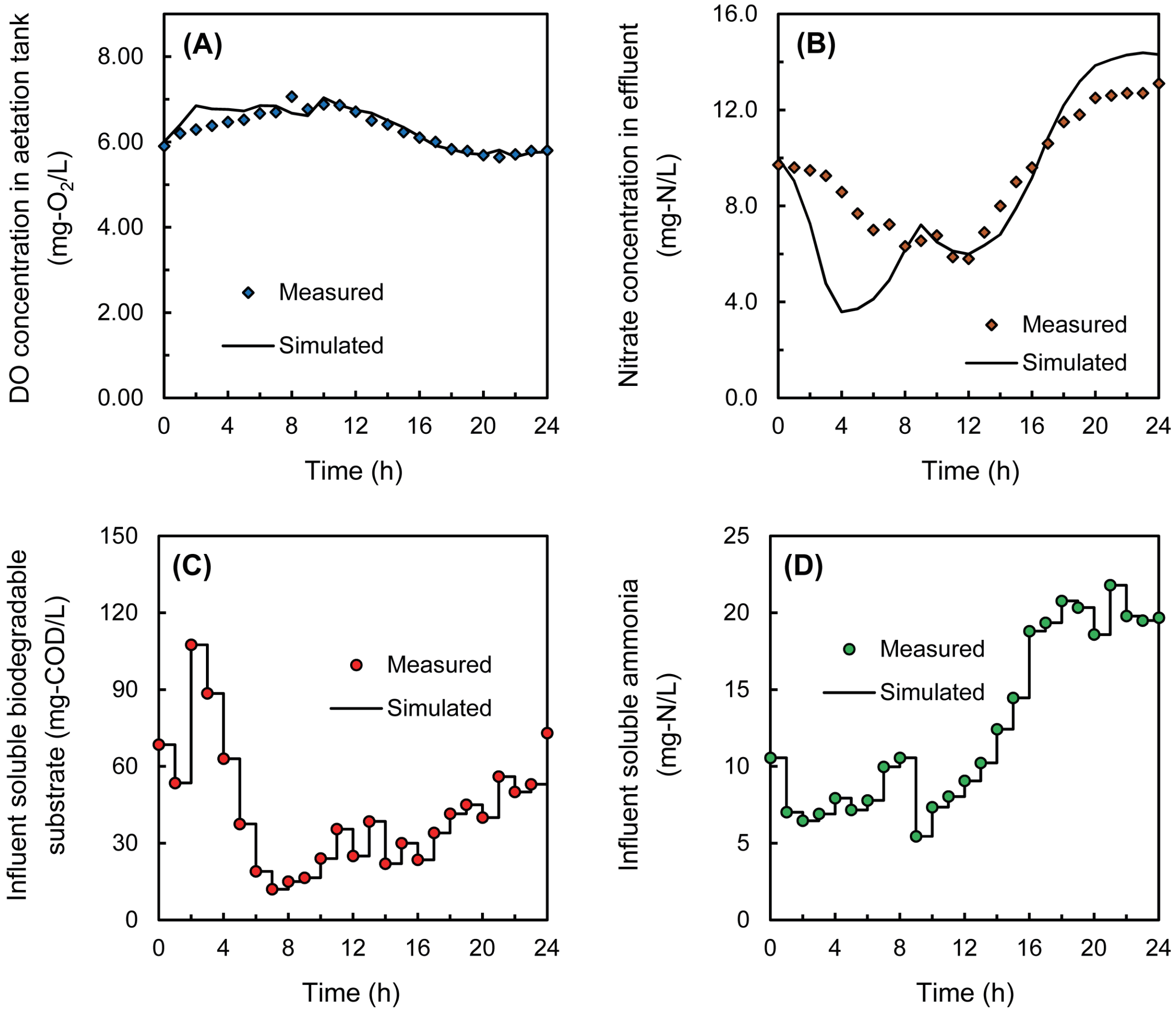

Fig. 5 Comparison between the measured and simulated results of the DO concentration in the aeration tank (left) and the nitrate concentration in the effluent (right).

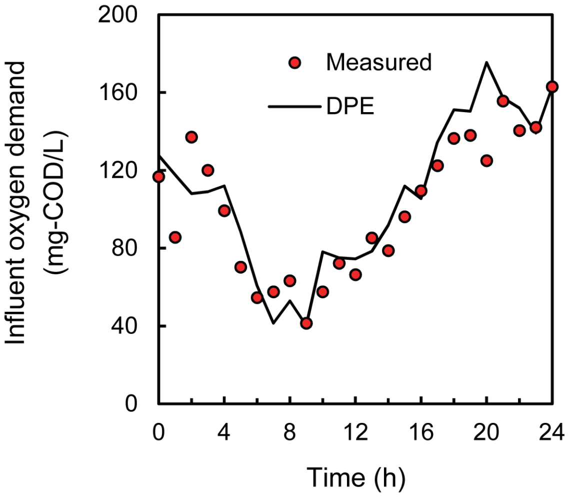

Fig. 6 Load of influent oxygen demand to the aeration tank.

limiting condition that the time-step was an integer multiple of the calculation frequency, a set of simulation scenarios with the identical parameters except calculation frequency was respectively defined as 0.025, 0.05, 0.1, 0.2, 0.5 and 1.0-hour Com. Int. (communication interval), whereby the corresponding-calculated results were compared (the default value of calculation frequency as 0.05 hours was originally selected for the configuration of back-calculation mentioned in "Back-calculation of influent constituents" subsection).

As shown in **Fig. 7**, the obtained results indicated that there was mostly no significant difference among the second (Com. Int. = 0.1 hour), the third (Com. Int. = 0.2 hours) and the fourth scenario (Com. Int. = 0.5 hours). For the first scenario (Com. Int. = 0.025 hours), there was a very soon appearance of overestimation in the S_B concentration during the period from 6h00 to 12h00 followed by a series of fixed values (S_B

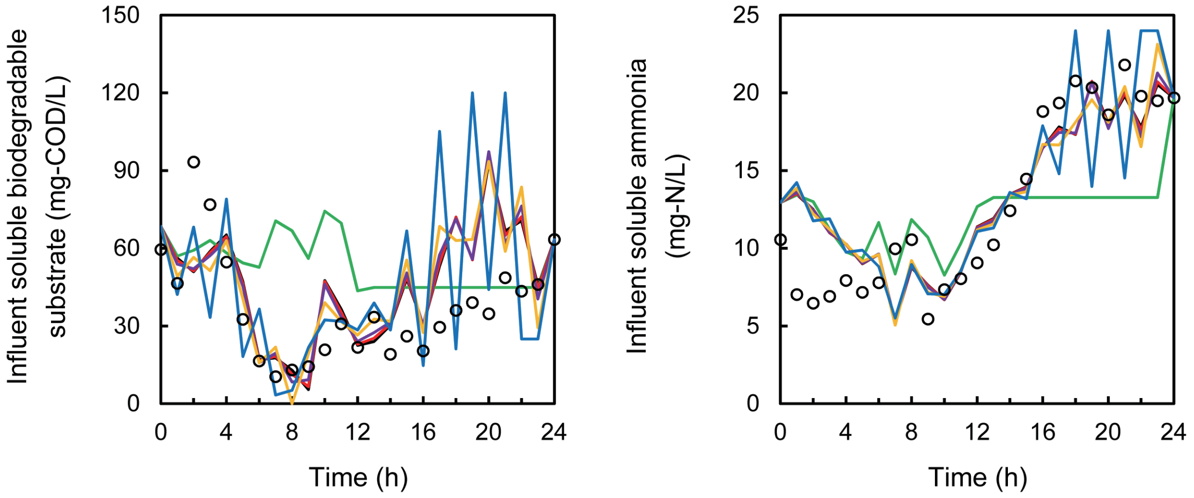

Fig. 7 The comparable results obtained from each differentiated scenario of the estimation (Circle: measured data; Line: calculated data) (Black: Original Scenario-0.05 Com. Int.; Green: 1st Scenario-0.025 Com. Int.; Red: 2nd Scenario-0.1 Com. Int.; Violet: 3rd Scenario-0.2 Com. Int.; Yellow: 4th Scenario-0.5 Com. Int.; Blue: 5th Scenario-1.0 Com. Int.).

= 45 mg-COD/L) during the later stage. Although the exact reason to explain for this response was not clear, it might be attributed to the too short calculation frequency in conjunction with no provision of data within each of the 1-hour interval. Despite that the data of influent S_B concentration attained in the fifth scenario (Com. Int. = 1.0) demonstrated a slight difference comparing to both measured and original-scenario result, this was acceptable due to the capability of matching the overall trend of the fluctuation in concentration. Similarly, in case of the S_{NHx} concentration, the result collected from the first scenario again demonstrated an appearance of unchanged values (S_{NHx} = 13.3 mg-N/L) during the later period (from 13h00 to 24h00). Although this result revealed a reasonable matching of calculated concentrations to those measured during the initial stage (from 0h00 to 12h00), most of the calculated concentrations were overestimated. A slight difference between the S_{NHx} concentration obtained from the fifth scenario and those from the measurement was also recognized.

To clarify the reason of mismatch, hourly calculated concentrations from each scenario were respectively compared to corresponding measured data based on the mean difference percentage attained from each singular difference. As shown in **Fig. 8**, the lowest value of calculation frequency (0.025 hours) resulted in the highest difference for both S_B (106%) and S_{NHx} (37%) whilst there was no significant difference between calculated and measured concentrations data under the setting of calculation frequency with 0.05, 0.1 and 0.2 hours respectively (the difference percentage ranged from 47% to 49% for S_B and ranged from 23% to 24% for S_{NHx}). It was noted that when the low value of the calculation frequency was set, the calculation speed was lowered. For instance, in case of calculation frequency was set at 0.05 hours with the time-step fixed at 1 hour, it was obviously realized that 20 numerical integrations per each pair of data plot have to be performed. However, when the calculation frequency was half decreased (0.025 hours) and the time-step still was fixed (1 hour), the number of numerical integrations performed per each pair of data plot was double resulting in lowered calculation speed. It was obvious that the more frequency of data updating obtained from the decrement of calculation frequency reasonably deteriorated the calculation process in terms of both time consuming and accuracy. From this analysis, the calculation frequency should be set in the range of 5 – 10 times less than the time-step but not lower than 0.05 hours.

Possibility of the alternative method and further application

Based on the above experimental results and computational analysis, the developed method in this study was thought to reasonably estimate the biodegradable materials in the influent, specifically the carbonaceous and nitrogenous fractions. With respect to the terms of cost and benefit, the working load of this developed method was compared to that of the conventional on-site sampling as listed in **Table 1**. According

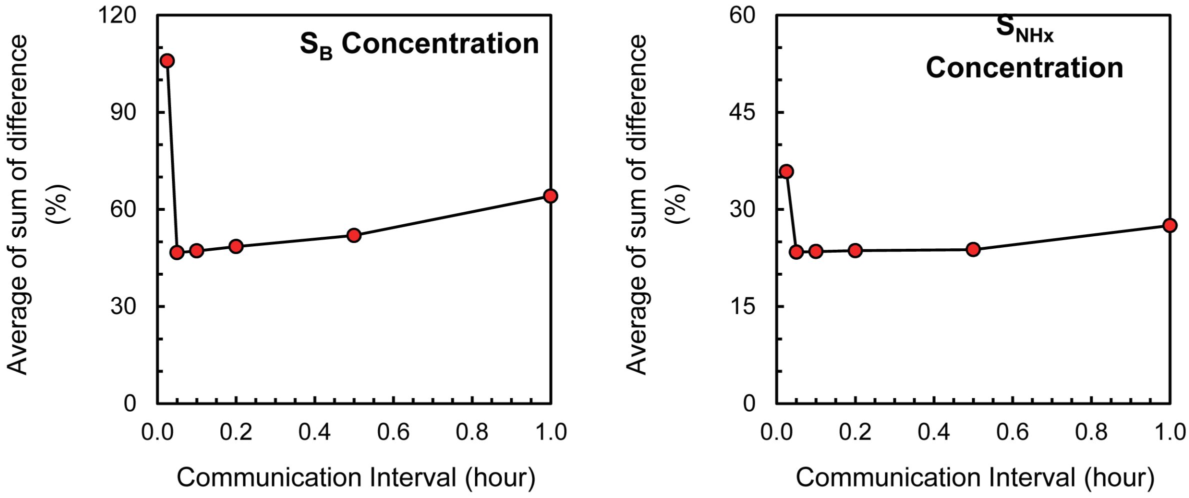

Fig. 8 The difference between the results obtained from each scenario and from measurement (Left: S_B concentration; Right: S_{NHx} concentration).

Table 1 List of requirements for analyzing the concentration influent biodegradable materials.

Items	This study	Conventional method
Sampling and analytical material	Activated sludge	Wastewater
On-site experimental apparatus	Activated sludge reactors	Auto-sampler equipped with refrigerator
Sampling and monitoring frequencies	Only one time (within a day)	Every hour (within a day)
Analysis for readily biodegradable substrate	DO concentration (automatic) and specific decay rate of heterotroph	Soluble C-BOD_{30}
Analysis for soluble ammonium nitrogen	DO, nitrate concentration (automatic) and specific growth rate of autotroph	Soluble N-NH_4^+
Duration of the test	30 days for start-up + net evaluation period	Net evaluation period + 30 days for incubation of BOD_{30}

to recommendation from CH2 M Gore and Storrie Ltd [22], an installation of an auto-sampler equipped with refrigerator was required when performing on-site water sampling. In addition, Nguyen [6] also pointed out that total organic carbon concentration in the municipal wastewater was decreased by 20–30% after 2-day storage at 4°C, therefore daily sampling might be required even availability of 1-day delivering at the experimental site.

Moreover, it was also mentioned a huge number of analytical items for measuring C-BOD_{30} and ammonium nitrogen in laboratory could be saved by the developed method although a few items had to additionally analyzed (*i.e.* b_{OHO}, μ_{max_NAO} and K_La) and monitored (*i.e.* DO and nitrate). In case of 1-day conducting experiment with 1-hour interval of data updating, the conventional method would require 48 analyses (24 analyses for each parameter) whilst this developed method only required totally 6 analyses (2 analyses for kinetic parameters, 2 analyses for aeration intensity and 2 analyses for target variables).

This developed method was supposed to be applicable to measuring not only the pollutants concentrations but also the load of oxygen demand in storm water for combined sewerage systems. In fact, at the beginning of rain or storm event, pollutant concentration would rapidly increase due to the washing out of materials on the ground and then flew into the sewerage system. Over the time, the concentrations of pollutants reached the peak followed by a significant decrease during the later stage as a result of dilution by rain/storm water. Tran [21] also point out the dilution of influent wastewater in rainy season in Hue, Vietnam. Furthermore, from the continuous monitoring of DO concentration, the peak of pollutant load and its frequency could be detected. These one is considered as crucial factors for designing the capacity of air blower, which could be obtained from the utilization of this developed method. For instance, from the data shown in **Fig. 6**, the daily average value of influent oxygen demand was estimated at approximately 108 mg-O_2/L. In addition, the hourly peak recorded within a day was approximately 175 mg-O_2/L; the appearance frequency of values, which was higher than the average value from 1.5 to 1.75 time, was estimated to be 5 time per day. Based on the above data analysis, the maximum capacity of air blower can be easily estimated to be around 200% of the daily average value of influent oxygen demand. In the same manner, by performing the intensive analysis for longer period (within a month, a quarter and a year) or specific time (dry and wet season), the more peak of pollutant load and its appearance frequency can be obtained to utilize for more precise designing of blower capacity.

CONCLUSIONS

An alternative method to back-calculate influent wastewater concentrations from the responses of the activated sludge process in the sampling field was evaluated using IWA ASM1. The following conclusions were obtained in this study.

(1) From the kinetic parameters of activated sludge, the operational conditions of the activated sludge module and the DO and nitrate concentrations, the influent concentrations for readily biodegradable organics and ammonia could be estimated in a dynamic manner. The hourly estimated concentrations of influent materials were comparable to those measured in the 1-day intensive sampling.

(2) The appropriate time-step using in the dynamic parameter estimation method was set to the same value of the data collection frequency whilst the calculation frequency was 5 ~ 10 times less than the time-step but not lower than 0.05 hours. In case that the time-step was set at 1 hour, the 0.1 or 0.2-hour calculation frequency can be utilized without a huge difference, which was respectively 47% and 49% of difference for S_B and was 24% of difference for S_{NHx}.

(3) The developed method only required 6 analytical items including OUR, b_{OHO}, μ_{max_NAO}, K_La, DO and nitrate per 1-day field test to estimate the concentrations of influent biodegradable carbonaceous and nitrogenous materials, comparing to 48 analytical items including 24 items for each measurement of S_B and S_{NHx} of conventional method of on-site water sampling, indicating that the working load of the analysis could be significantly saved.

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REFERENCES

[1] World Bank: Vietnam – Urban wastewater review (Vol 2): Performance of the wastewater sector in urban areas: a review and recommendations for improvement. Public Report, Washington DC, 2013.

[2] Nguyen VA: On-site wastewater treatment in Vietnam. Workshop on On-site domestic wastewater treatment in Asia, Tokyo, Japan, 2013.

[3] Harada H, Dong NT, Matsui S: A measure for provisional-and-urgent sanitary improvement in developing countries: septic-tank performance improvement. *Water Sci. Technol.*, **58**(6), 1305–1311, 2008. PMID:18845871 doi:10.2166/wst.2008.715

[4] Harada H, Matsui S, Dong NT, Shimizu Y, Fujii S: Incremental sanitation improvement strategy: comparison of options for Hanoi, Vietnam. *Water Sci. Technol.*, **62**(10), 2225–2234, 2010. PMID:21076207 doi:10.2166/wst.2010.508

[5] Anh TNQ, Harada H, Fujii S, Anh PN, Lieu PK, Tanaka S: Preliminary analysis of phosphorus flow in Hue Citadel. *Water Sci. Technol.*, **73**(1), 69–77, 2016. PMID:26744936 doi:10.2166/wst.2015.463

[6] Nguyen Duong QC, Le VT, Tran VQ, Liu B, Terashima M, Nguyen TH, Le VC, Harada H, Yasui H: An alternative method to estimate influent concentration using on-site lab-scale activated sludge reactors. *J. Water Environ. Technol.*, **15**(6), 220–232, 2017. doi:10.2965/jwet.17-015

[7] Henze M, Gujer W, Mino T, van Loosdrecht MCM: Activated Sludge Models ASM1, ASM2, ASM2D and ASM3. *IWA Scientific and Technical report No.9*, IWA publishing, London, UK, 2000.

[8] Thua Thien Hue Center for Preventive Medicine: Statistics on On-site Sanitation System in Hue City. Thua Thien Hue Province, Vietnam, 2013. [in Vietnamese]

[9] HEPCO (Hue Urban Environment, Public Works State Limited Company): Current Status of Drainage System in Hue City and Orientation toward Future Urban Drainage System for Thua Thien Hue province. Thua Thien Hue Province, Vietnam, 2013. [in Vietnamese]

[10] Kappeler J, Gujer W: Estimation of kinetic parameters of heterotrophic biomass under aerobic conditions and characterization of wastewater for activated sludge modelling. *Water Sci. Technol.*, **25**(6), 125–139, 1992. doi:10.2166/wst.1992.0118

[11] Ramdani A, Dold P, Déléris S, Lamarre D, Gadbois A, Comeau Y: Biodegradation of the endogenous residue of activated sludge. *Water Res.*, **44**(7), 2179–2188, 2010. PMID:20074768 doi:10.1016/j.watres.2009.12.037

[12] Torretta V, Ragazzi M, Trulli E, De Feo G, Urbini G, Raboni M, Rada E: Assessment of biological kinetics in a conventional municipal WWTP by means of the oxygen uptake rate method. *Sustainability*, **6**(4), 1833–1847, 2014. doi:10.3390/su6041833

[13] Tsai YP, Wu WM: Estimating biomass of heterotrophic and autotrophic bacteria by our batch tests. *Environ. Technol.*, **26**(6), 601–614, 2005. PMID:16035653 doi:10.1080/09593330.2001.9619500

[14] Garcia-Ochoa F, Gomez E: Bioreactor scale-up and oxygen transfer rate in microbial processes: An overview. *Biotechnol. Adv.*, **27**(2), 153–176, 2009. PMID:19041387 doi:10.1016/j.biotechadv.2008.10.006

[15] Kim GC: 8 − The oxygen transfer rate and overall volumetric oxygen transfer coefficient. In: Kim GC (ed.): Bioprocess Engineering, Woodhead Publishing Limited, Cambridge, UK, pp.147–170, 2013.

[16] Corominas L, Rieger L, Takács I, Ekama G, Hauduc H, Vanrolleghem PA, Oehmen A, Gernaey KV, van Loosdrecht MCM, Comeau Y: New framework for standardized notation in wastewater treatment modelling. *Water Sci. Technol.*, **61**(4), 841–857, 2010. PMID:20182062 doi:10.2166/wst.2010.912

[17] Hydromantis Environmental Software Solutions, Inc.: Optimizer − Technical reference in GPS-X ver. 7.0, Hydromantis Environmental Software Solutions, Inc., Hamilton, Canada, pp.398–438, 2017.

[18] APHA-AWWA-WEF: Standard Methods for the Examination of Water and Wastewater, 22nd edition. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA, 2012.

[19] Makinia J: Mathematical Modelling and Computer Simulation of Activated Systems. IWA publishing, London, UK, 2010.

[20] Su YM, Makinia J, Pagilla KR: Estimation of autotrophic maximum specific growth rate constant--experience from the long-term operation of a laboratory-scale sequencing batch reactor system. *Water Environ. Res.*, **80**(4), 355–366, 2008. PMID:18536487 doi:10.2175/106143007X221436

[21] Tran Nguyen QA: Characterization of domestic wastewater discharge and its impact on material flows in urban Hue, Vietnam. PhD thesis, Course in Environmental Management, Kyoto University, Japan, 2016.

[22] CH2 M Gore and Storrie Ltd.: Guidance manual for sewage treatment plant process audits. Ottawa − Ontario, Canada, 1996.