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Research Article

The Use of Simulation Modelling for Optimisation of Phosphorus Removal in Sewage Treatment under Varying Influent Loading

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Abstract: A validated ASM2 model (STOAT) for the Changzhou WWTP was used to evaluate operational problems encountered in most wastewater treatment plants, during the transitional period from winter to summer. Favourable operating conditions which can achieve both TN and TP effluent concentrations under varying influent loading without the use of either chemical polishing or external carbon sources were established. Further, the use of 1.5 h wastage pump run time and 4.5 h cycle time was found better than the 3 h wastage pump run time and the 6 h cycle time as practiced in most WWTPs, as the latter is sufficient to allow second TP release, whereas the former is found to improve effluent TP by approximately 73%. The model was applied to troubleshoot another WWTP successfully. The finding in this study will improve the management of wastewater treatment plants for better and consistent effluent quality at a reduced capital cost.

Keywords: Cycle time, operational problems, transitional period, wastage pump run time, wastewater treatment plant

INTRODUCTION

Optimization benefits are well documented (Parker *et al*., 2000; Harleman, 1990; Buris, 1981; Griborio *et al*., 2008), ranging from improving treatment efficiency, optimization of chemical and energy utilization, capital and operational savings of the existing wastewater treatment plants while meeting the new or more stringent effluent quality limits for parameters of concern, such as, total phosphorus and total nitrogen. As part of Changzhou WWTP, it is required to reduce the TP and TN loading discharged from the treatment plant, because of its strategic location to many sources of rivers which are used for water supply. In view of the variation in the influent loadings and the effect of temperature on the general performance of the treatment plants, a detailed optimization study of the WWTP is necessary in order to achieve a consistent effluent quality during summer and winter period. Therefore, proper control strategy and a thorough understanding of the system are required.

Phosphorus removal can be accomplished in WWTP's by chemical or biological methods. A combination of these methods can be used to achieve very low effluent TP. However, biological method is favoured over the use of chemical precipitation because of its sustainability, cost effectiveness (Wood, 2004) and environmental friendliness. The phosphorus removal treatment plant can either be P deficient or carbon deficient (Randall *et al*., 1992). According to Sedlak (1991), a carbon deficient treatment plant cannot achieve a complete phosphorus removal, whereas, the phosphorus deficient systems can achieve a near-complete phosphorus removal. Randall *et al*. (1992) and Grady *et al*. (1998) reported that 40 mg/L and 20 mg/L are the requirement for COD/TP and BOD/TP ratios, respectively for phosphorus deficient WWTP. Additionally, WEF and ASCE (2006), Neethling *et al*. (2005) and Barnard (2006), reported 40-45 mg/L, 20 mg/L, 4-16 mg/L and 10-16 mg/L as the minimum ratios for COD/TP, BOD/TP, VFA/TP and readily biodegradable COD to TP ratios (rbCOD/TP), respectively for a plant to achieve total phosphorus effluent concentration of less than 1 mg/L.

Nevertheless, the design and operation of biological nutrient systems which involves both TN and TP removal is tilted in favour of TN. This is because chemical polishing is view as a good alternative to the TP removal. However, the use of chemical polishing creates inhibition problems, depending on the point at which the chemical is dosed into the system. Further, the residual effect of chemicals on the environment and the receiving water bodies is another persistent problem apart from the chemical being an extra operating cost.

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This study aimed at meeting the effluent TP and TN criteria at a reduced cost through operational strategy. The control of cycle time and pump run time are vital strategy in achieving this aim.

MATERIALS AND METHODS

Description of the WWTP: The WWTP is located in Changzhou, Jiangsu province People Republic of China (PRC). It consists of two parallel plug-flow bioreactors and two secondary sedimentation tanks (clarifiers) operated in a 3-stage pho-redox process configuration (Anaerobic, Anoxic and Oxic). The volumes of the anaerobic, anoxic and aerobic tanks are; 1143 m^3, 3440.8 m^3 and 9179 m^3, respectively for the first lane and 1465.8 m^3, 4408.53 m^3 and 11759.7 m^3, respectively, for the second lane. The flow streams are combined before entering the two secondary sedimentation tanks. The surface area of the clarifier is 1252 m^2, which comes from a 40 m diameter, excluding the area occupied by the centre well and a 3 m depth. There are two screens and two vortex grit chambers for pre-treatment. The influent wastewater stream from the reservoir to the reactor is divided into two with each lane receiving one stream. The plant is designed to treat 50,000 m^3/d of mainly domestic wastewater. Influent wastewater is collected in a reservoir and pumped through the screens and grit chambers before it is finally distributed to the reactors. The WWTP was designed to treat the following influent concentrations: BOD = 180, COD = 400, NH3-N = 35, SS = 250, TP = 4 and TN = 45, all in mg/L. It is expected to produce the following effluent concentrations: BOD≤10, COD≤50, NH3-N≤5, TN≤15, TP≤0. 5 and SS≤10, all in mg/l. Although the observed effluent TP and TN concentrations of the Changzhou WWTP meets the target discharge effluent concentrations, however, acetate is added to the anaerobic reactor to facilitate Phosphorus Accumulating Organisms (PAO) activity and Al_2 (SO4) $_3$ is used for chemical polishing for the removal of TP. The addition of acetate and Al2 (SO4) 3 is an extra cost that needs to be optimized and possibly eliminated.

Evaluation of the Changzhou WWTP historical data: The available historical data for Changzhou WWTP was evaluated. The average total COD, average BOD_5 and the COD/TP ratio and BOD/TP ratio were determined.

The analysed results for 2010 and 2011 (two years) historical data are shown in Fig. 1a to d and 2a to d, respectively.

Figure 2a to d shows a decreasing COD/TP and BOD/TP ratios in 2011 compared to 2010. However, the 40 mg/L and 20 mg/L COD/TP and BOD/TP ratios, respectively, as observed by Grady *et al*. (1998) and Randall *et al*. (1992) as a requirement for a phosphorus deficient system are met. Further, Fig. 1a to d shows a similar trend between 2010 and 2011 in terms of COD and BOD influent loading at different season of the year. A thorough examination of the results from these two seasons, with different temperatures and COD concentrations in the influent suggests the division of the operational settings of this treatment plant into two, based on the historical influent loadings of the two seasons.

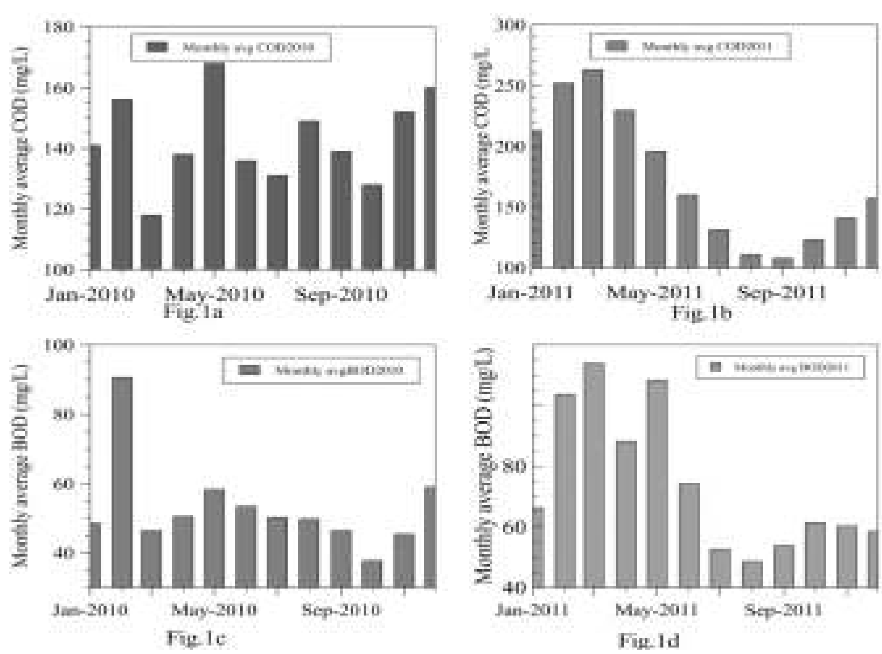

Fig. 1: a-d averages COD and BOD for 2010 and 2011 for Changzhou WWTP

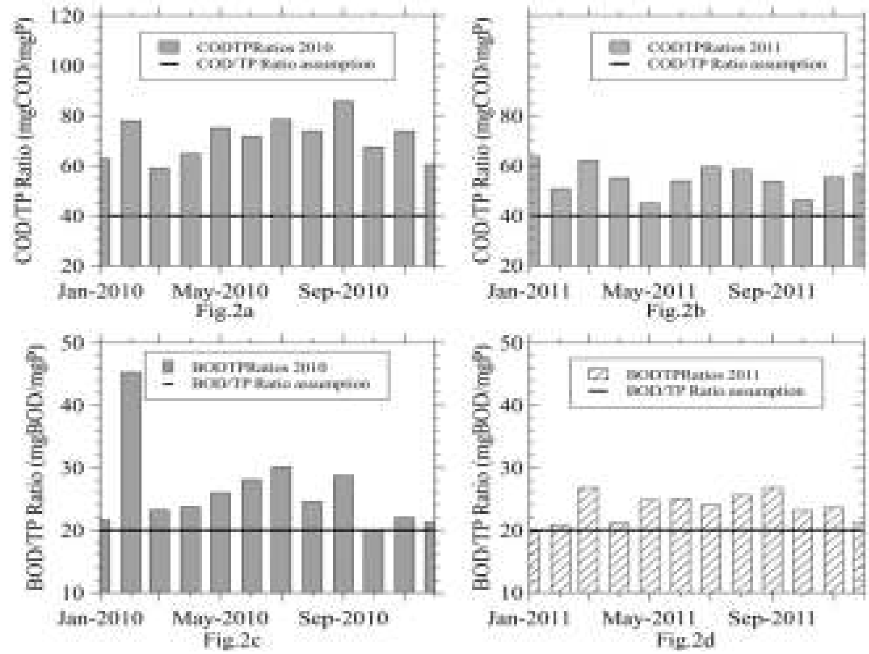

Fig. 2: a-d COD/TP and BOD/TP ratios for 2010 and 2011

Table 1: Operating parameters and influent wastewater characteristics for Changzhou WWTP, September/October, 2011

Parameter	Unit	Mean	SD	Min	Max
Flow rate	m^3d^{-1}	42401	3249	37096	48070
SRT	d	14	0.4	13	16
RAS flow rate	m^3d^{-1}	17695	600	16692	18650
Temperature	^OC	26.2	1	24.5	28.6
pH	-	7.2	-	-	7.2
VSS	mg/L	168	19.5	115	227
BOD_5	mg/L	48.6	15.2	42.7	71
CODtot	mg/L	123	22.3	76	178
CODi-sol	mg/L	34.6	2.1	21.8	39
VFA	mg/L	12.4	0.9	5.2	18.7
TP	mg/L	2	0.4	1.32	2.62
SPO_4	mg/L	0.94	0.1	0.53	1.16
TN	mg/L	26	2.5	22	28.1
TNi-sol	mg/L	23.7	1.4	18.9	25.2
N-NH3	mg/L	16.6	2.48	14.2	22.5
$N\text{-}NO_3$	mg/L	0.4	0.21	0.1	1.25
$N\text{-}NO_2$	mg/L	0.14	0.1	0.1	0.52

Analytical methods: Two weeks intensive sampling was performed in September 26-October 6, 2011. A 2-hourly composite data for 24 h daily and some days 1-hourly grab samples were used to characterize the influent. Influent characterization was determined according to the STOWA method (Stowa, 1999; Meijer *et al*., 2001). The samples were analyzed based on Chemical Oxygen Demand (COD) of non filtered (total COD) and filtered through 0.45 μm and 1.2 μm diameter pores (COD influent soluble, filtered, flocculated), Biochemical Oxygen Demand (BOD) of non filtered and filtered, Volatile Fatty Acids (VFA), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total Kjeldahl nitrogen (TKN), total phosphorus (TP), ortho-phosphate (PO_4^3), Total Suspended Solids (TSS) and volatile suspended solids (VSS) concentrations. The experiment was conducted in the Changzhou WWTP laboratory in accordance with the standard methods (Standard Methods5220, 5210, 4500-NH3, 4500-Nitrogen, 4500-P, 2540-D and 2540-E, respectively) (APHA, American Water Works Association, Water Environment Federation, 1995) (Table 1).

Model application: The validated ASM2 model (O.O.James, unpublished data) was applied to the data collected during September/October, 2011 to verify the model's suitability for optimization and operational strategies under varying influent loadings. This becomes necessary because of the seasonal variations in temperatures and the influent concentrations between when the model was first calibrated (January, 2011) and validated (April, 2011) and the effect of temperature on the general performance of the treatment plants.

A simplified schematic flow diagram of the Changzhou WWTP biological reactors is shown in Fig. 3.

The simulation was performed using the validated model parameter (O.O.James, unpublished data) and the operating parameters. After the first simulation, the results were compared with the measured data to evaluate the disparity between the measured and simulated results (Gujer *et al*., 1995). The modeller adjusted one parameter (in this case, the operating parameter because the model has been calibrated and validated already) at a time until a reasonable match

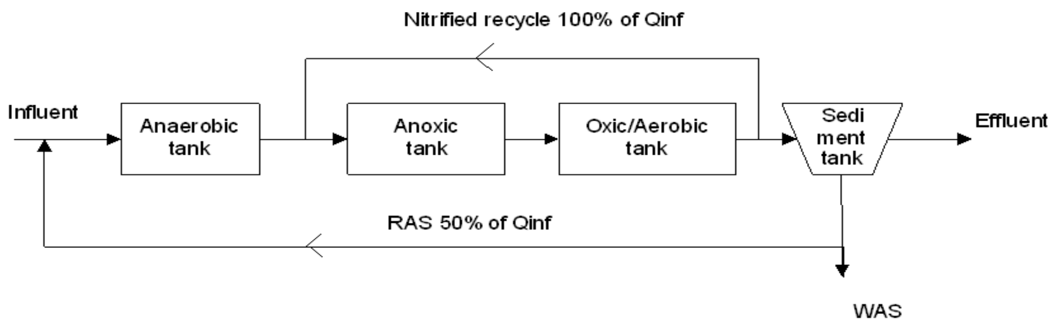

Fig. 3: Changzhou WWTP simplified schematic flow diagram

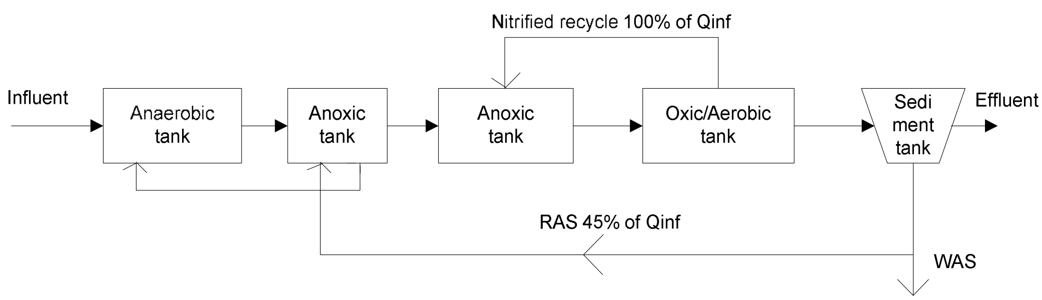

Fig. 4a: Nanjing WWTP simplified schematic flow diagram

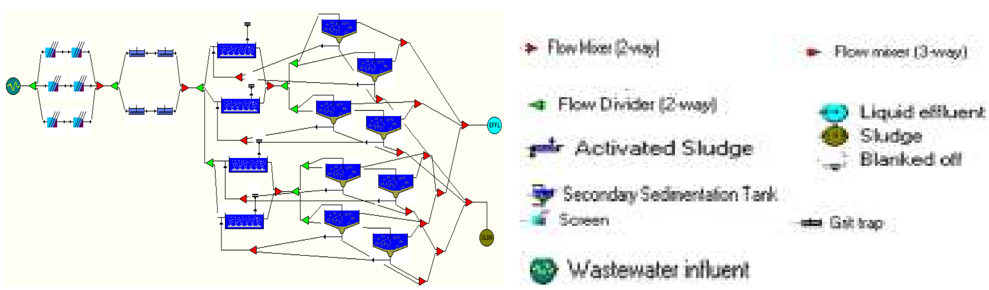

Fig. 4b: STOAT configuration of Nanjing WWTP

Table 2: Operating parameters and influent wastewater characteristics for the Nanjing WWTP, October, 2012

Parameter	Unit	Mean	SD	Min	Max
Flow rate	m^3d^{-1}	127556	10969	112717	150655
SRT	d	10	0.3	8	12
RAS flow	m^3d^{-1}	59477	5211	50723	67795
Temperature	^{O}C	13.2	-	-	13.2
pH	-	7.3	-	-	7.3
SS	mg/L	212	40.7	122	264
BOD_5	mg/L	86	16.1	60	113
CODtot	mg/L	268	38.8	188	319
CODi-sol	mg/L	109	12	69	148
TP	mg/L	4.2	0.36	3.14	4.61
SPO_4	mg/L	1.9	0.4	1.5	2.4
TN	mg/L	43.6	4.38	35.5	50.4
N-NH3	mg/L	37.5	3.8	29.2	43.5

between the measured data and the model prediction was achieved. It should be noted that during the calibration and the validation of the model, 100% and 70% were used for nitrified recycle and RAS, respectively, in addition to the stochiometric parameter that was used (O.O.James, unpublished data).

Nanjing WWTP: To demonstrate the value of modelling, the model was applied to the Nanjing WWTP using the calibrated and validated parameters from Changzhou WWTP. The simplified schematic flow diagram of the biological reactors of Nanjing WWTP is shown in Fig. 4a and the STOAT configuration of the Nanjing WWTP is shown in Fig. 4b respectively. The WWTP consists of four parallel bioreactors and eight secondary sedimentation tanks (clarifiers) with two clarifiers connected to one bioreactor operated in the modified University of Cape Town (UCT) process configuration. The volumes of the anaerobic, 1st anoxic, 2nd anoxic and aerobic are; 3430 m^3, 1320 m^3, 5100 m^3 and 16840 m^3 respectively. The surface area of each clarifier is 1380 m^2, which comes from a 42 m diameter, excluding the area occupied by the centre well and a 3.5 m depth. Additionally, there are six screens and four vortex grit chambers for pre-treatment. The influent wastewater is collected in a reservoir and pumped through the screens and grit chambers before it is finally distributed to the bioreactors. Influent wastewater from the reservoir to the bioreactors is divided into three equal volumes. The bioreactor lanes are numbered A-D, with lane A and B each receiving their volume, while the third volume is further sub-divided into two equal volumes with lane C and D each receiving half. The plant receives averagely 168,000 m^3/d mainly domestic wastewater, about 5 to 10% of industrial wastewater contributions.

Cinar *et al*. (1998) applied the calibrated model parameters from one WWTP to other WWTPs to check the model validity and achieved the desired result in one and failed to produce desired results in two out of the three WWTPs. This failure was attributed to perhaps, poor reactor hydraulics characterization. However, it should be noted that in engineering, there are no two structures that are the same and in terms of complex reactions involves in WWTP and wastewater characteristics, different reactor configurations, varying operating conditions and environmental factors, it necessitates the need to recalibrate the model for specific WWTP in most cases. Similar to Cinar *et al*. (1998) experience, Nanjing WWTP simulation results did not yield a good match in terms of the WWTP trend when the Changzhou WWTP parameters were used, hence necessitating some change in the model parameter. Thus, in addition to yield coefficient for heterotrophic biomass (Y_H 0.67) which was transferred from the Changzhou WWTP, the oxygen half-saturation constant for autotrophic organisms (K_{OA}) was reduced from the default value of 0.5 to 0.4 at the NWWTP. This change is in accordance with Petersen *et al*. (2003) and Dudley *et al*. (2002). Table 2 presents the operating parameters and the wastewater characteristics of the Nanjing WWTP (Table 2).

RESULTS AND DISCUSSION

The effect of cycle time and wastage pump run time on the effluent TP quality: The interval between wastage events defines the cycle time and is equal to the sum of pump on plus off times. A sensitivity analysis was performed to evaluate the effect of cycle time, wastage pump run time and the internal recycle ratios. An examination of the result revealed that, the longer the cycle time the greater the risk and possibility of second TP release in the sedimentation tank, the shorter the cycle time the less the risk of second TP release (Fig. 5a). When the wastage pump was on for 3 h and then off for 6 h, was simulated (3 h 6 h), there was approximately 73% increase in the effluent TP concentrations compared to when the wastage pump was on for 1.5 h and then off for 4.5 h, was simulated (1.5 h 4.5 h). This phenomenon is due to deflocculation of the floc in the sedimentation tanks causing cell lysis and the release of stored poly-phosphate into the water phase, consequently, increasing TP concentrations in the effluent.

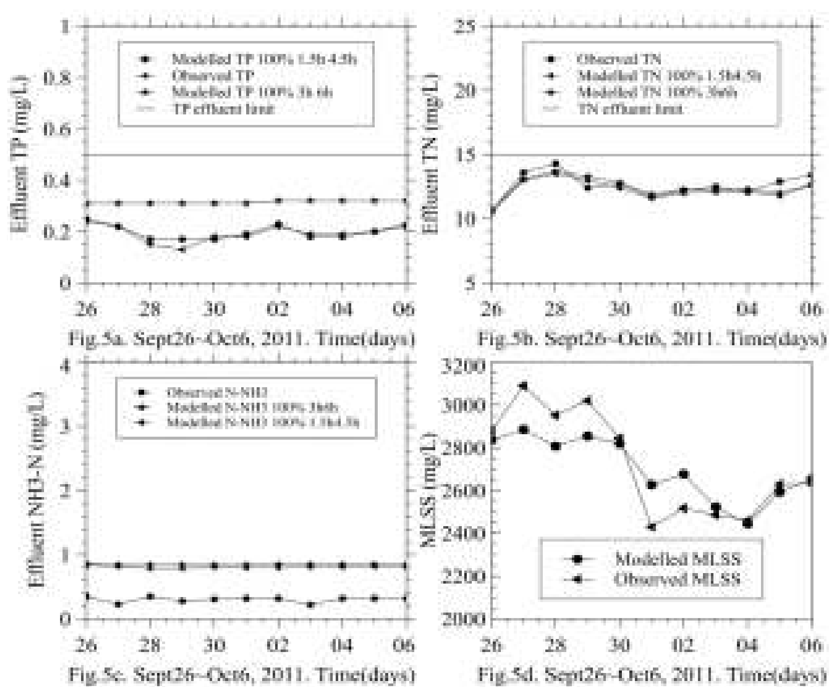

Fig. 5: a~d Effluent TP, TN, N-NH3 concentrations and MLSS concentration in the tank; 100% 1.5 h 4.5 h = 100% internal recycle with the wastage pump on for 1.5 h and then off for 4.5 h 100% 3 h 6 h = 100% internal recycle with the wastage pump on for 3 h and then off for 6 h

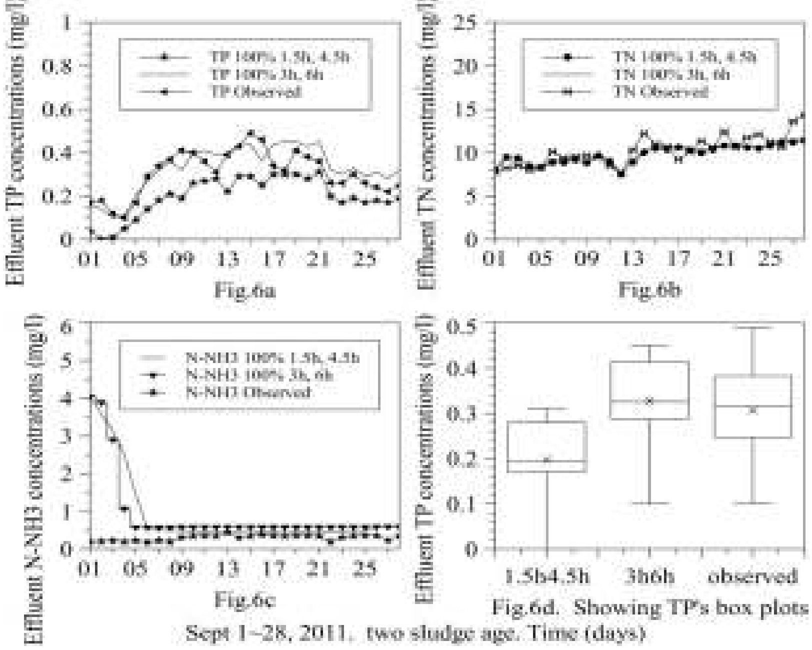

Fig. 6: a~d Effluent TP, TN and N-NH3 concentrations for two sludge age; 100% 1.5 h 4.5 h = 100% internal recycle with the wastage pump on for 1.5h and then off for 4.5 h 100% 3 h 6 h = 100% internal recycle with the wastage pump on for 3 h and then off for 6 h)

Table 3: Average observed and modelled values for Changzhou WWTP, September, 2011

Month	TP	TN	NH3-N
September observed	0.31	12.6	0.3
Modelled 100% 1.5 h 4.5 h	0.19	11.9	0.84
Modelled 100% 3 h 6 h	0.32	11.8	0.88

100% 1.5 h 4.5 h = 100% internal recycle with the wastage pump on for 1.5 h and then off for 4.5 h100% 3 h 6 h = 100% internal recycle with the wastage pump on for 3 h and then off for 6 h

Table 4: Average observed and modelled values for Nanjing WWTP, October, 2012

Month	TP	TN	NH3-N	CODtot
October, 2012 observed	0.65	11	1.95	27.4
Modelled 100% 1.5 h 4.5 h	0.38	9.7	1.2	24.8
Modelled 100% 3 h 6 h	0.67	10	1.24	25

100% 1.5 h 4.5 h = 100% internal recycle with the wastage pump on for 1.5 h and then off for 4.5 h 100% 3 h 6 h = 100% internal recycle with the wastage pump on for 3 h and then off for 6 h

To confirm that the high TP observed was not as a result of rising sludge resulting in undesired denitrification in the secondary clarifier (Ekama *et al*., 1997; Henze *et al*., 1993), the results of the N-NH3, NO3-N and TN were evaluated in view of comparing the disparity in the N-NH3, NO3-N and TN effluent concentrations under the same scenario; however, there is no visible differences in the TN concentrations (Fig. 5b), a negligible improvement in the N-NH3 concentrations (Fig. 5c), as well as a negligible increase in the NO3-N concentration (result not shown), thus crediting the increase in the TP effluent concentrations to a possible cell lysis resulting in the second TP release due to longer cycle time. (Fig. 5d) presents the observed and simulated MLSS concentrations in the aeration tank; the model equally depicts the trend quite well.

In order to observe the long term phenomenon, the simulation was performed for two sludge ages, as shown in Fig. 6a to d. The graphs presents a repeated trend as observed earlier and thus, confirmed that the 1.5 h 4.5 h is better than 3 h 6 h respectively.

The effect of internal recycles on the effluent TP quality: Contrary to the effect of cycle time and wastage pump run time, the internal recycles have insignificant effect on the TP effluent concentrations. The 200~400% internal recycle results (not shown) resulted in improving the TN effluent concentrations, a small improvement on the ammonium concentrations, but it has no obvious improvement on the TP effluent concentrations. However, the use of 300~400% internal recycle is not economically prudent as it requires 3~4 times energy consumption compared to a 100% internal recycle, thereby increasing the operating costs (Baeza *et al*., 2003). Moreover, an increase in nitrate load to the anoxic reactor indicates a higher COD removal in this reactor, but in this present study, the influent COD concentrations is low and therefore, a higher internal recycle is not necessary. Besides, the use of a 100% internal recycle prevented the possibility of excess dissolved oxygen been introduced into the anoxic reactor which might have a negative effect on its denitrification capacity. The average observed and modelled values for Changzhou WWTP are presented in the Table 3.

The effect of RAS on the effluent TP quality: A sensitivity analysis was performed starting with a 25% and ending with a 100% proportional RAS flow ratio to determine which ratio will yield the desired result. From an examination of the sensitivity analysis, a 45% proportional RAS flow ratio produced the best and the most desired results for the Nanjing WWTP. Ratios above 45% resulted in higher TP and ammonium concentrations in the effluent. The lower RAS ratio employed here could have played an important role in reducing the amount of nitrate introduced into the anaerobic reactor, which minimizes nitrate effect and thus facilitates micro-organism activities.

Furthermore, the use of a 45% RAS ratio could be likened to the principle of feast-famine, as observed by Chudoba *et al*. (1973b). According to Chudoba (1989) heterotrophic bacteria may not consume or use sufficient food when returned to the bioreactor without attaining starvation conditions per pass through the aeration tank. The decreased in RAS ratio tends to create feast/famine conditions by increasing the solid detention time to maintain the accumulation capability of the heterotrophic bacteria. Table 4 presents the averaged observed and modelled values of the Nanjing WWTP.

The disparity in TP values between 100% 1.5 h 4.5 h and 100% 3 h 6 h as shown in Table 3 and 4 is very obvious, is approximately 73%.

CONCLUSION

This study investigated the effect of cycle time and wastage pump run time on the effluent TP quality in two full-scale WWTPs. It was found that in all the cases simulated, the TP effluent concentrations were better at shorter cycle times. This phenomenon is attributed to the possible cell lysis at longer cycle time thereby resulting in the release of stored poly-phosphate into the water phase causing high concentrations of TP in the effluent. It was observed that, the concentrations of both the influent COD and BOD should be considered when determining the % RAS. Higher RAS means more numbers of active micro-organism returns into the tank. Thus, there is a possibility of introducing more competitive active micro-organism into the anaerobic tank when there is no sufficient food to support their activities, if for instance a 70% RAS were to be used in this present study given the low influent COD and BOD concentrations. Similarly, lower RAS means less numbers of active micro-organism returns into the tank. Hence, there is also a likelihood of introducing less micro-organism into the tank when there is surplus food beyond their uptake capability and thus might resulted in having not completely taken up the nutrients. This principle is employed in this study as can be seen in Fig. 1a to d, the COD and BOD concentrations in the month of January to April is higher than the COD and BOD concentrations in the month of September and October, therefore, 70 and 50% RAS were used respectively. The essence is to prevent the formation of nutrient deficient floc particles which may result in the loss of settle ability. Soluble BOD is not degraded under nitrogen and phosphorus deficiency, its rather stored within the floc particles as an exocellular polymer-like material, this material interferes with floc settle ability. This situation can be prevented with the use of low RAS under low influent concentrations. Overall, the control of cycle time and wastage pump run time are paramount in meeting consistent effluent TP concentrations, as this has been shown to reduce the risk of second TP release and possibly prevent biomass washout.

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