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A comprehensive method for the evaluation of biological nutrient removal potential of wastewater treatment plants

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ABSTRACT

An evaluation method based on the supply and demand of carbon source in the biological nutrient removal (BNR) process, combined with an index of difficulty of nutrient removal (DNR), was put forward to achieve comprehensive assessment and analysis of the BNR potential of wastewater treatment plants (WWTPs). Twenty-five full-scale municipal WWTPs with different BNR processes were evaluated over a period of 12 months in Shanghai (China). Statistical analysis results showed that the DNR index had significant positive correlation ($r > 0.790$, $p < 0.01$) with total nitrogen, total phosphorus concentrations in the effluent, and yielded higher correlation coefficient with BNR efficiency than the C/N and C/P ratios that were conventionally used to estimate carbon source supply conditions. According to the WWTPs ranking by DNR evaluation, the number of WWTPs with low, medium, high, and extremely high DNR level was 8, 10, 6, and 1 among the 25 WWTPs, respectively. The developed method can evaluate and analyze the BNR potential scientifically and objectively, and the ranking results can be used to guide level-to-level management, upgrading, and optimization of WWTPs under different discharge standards.

Keywords: Wastewater treatment; Nutrient removal; Management; Potential; Evaluation

1. Introduction

The serious eutrophication of waters in China has prompted the creation of more stringent standards for the discharge of nutrient pollutants from wastewater treatment plants (WWTPs), and upgrading and optimization of existing WWTPs have been carried out substantively to achieve simultaneous removal of nitrogen and phosphorus [1]. In recent years, several biological nutrient removal (BNR) processes, such as anaerobic/anoxic/aerobic (AAO) [2–4], anoxic/anaerobic/aerobic (RAAO) [5], sequencing batch reactor (SBR) [6–8], and oxidation ditch (OD) [9], have been applied in full-scale WWTPs. Facing the BNR process with complicated configuration, the establishment of standardized evaluation method to estimate the BNR potential that meets requirements of different dis-

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charge standards has become a crucial problem for the upgrading, optimization, and management of WWTPs.

The BNR potential of wastewater is primarily a function of available organic carbon because the denitrification process and phosphorus release process by phosphorus accumulating organisms (PAOs) both require organic matters as electron donor [7,10]. Janssen [11] stated that suitable composition of wastewater, i.e. C/N (expressed as 5d biochemical oxygen demand (BOD_5)/total nitrogen (TN)) and C/P (expressed as BOD_5/total phosphorus (TP)) ratios, is one of the prerequisites for BNR processes. The influent C/N ratio usually limits the nitrogen removal efficiency and determines concentrations of nitrate and nitrite in anaerobic and anoxic stages of the BNR process [3,8,12], and thus also affects the biological phosphorus removal directly via the preferable competition for carbon source with PAOs [4,7]. The influent C/P ratios is an indicator for phosphorus removal since the anaerobic phosphorus release is usually limited by biodegradable carbon source available [2,6,13]. Therefore, the C/N and C/P ratio have been utilized by many researchers to evaluate the BNR potential of wastewater treatment processes [2,6–8,10,14].

Owing to the competition for carbon source between denitrification process and anaerobic phosphorus release process [10], evaluating BNR efficiency by independent C/N or C/P ratio might be deviated from actual values and was difficult to estimate the simultaneous conformity of effluent TN and TP with relevant discharge standards. Furthermore, the evaluation method by C/N or C/P ratio considers only carbon source available in the influent, but the influence of different requirements of discharge standards on the conformity of TN and TP concentrations in the effluents to limitations was unable to evaluate. In this study, a novel index for the evaluation of BNR potentials in WWTPs, difficulty of nutrient removal (DNR), was put forward and tested in 25 municipal WWTPs in Shanghai. We also aimed to rank the evaluated WWTPs by using DNR index based on different levels of Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002). The results are expected to provide ideas for the management and technical upgrade of WWTPs for nutrient removal.

2. Materials and methods

2.1. *WWTPs for evaluation*

Twenty-five municipal WWTPs located in Shanghai were selected for the investigation. All WWTPs carry out conventional biological wastewater treatment with nutrient removal. In the 25 WWTPs for evaluation, no primary settler was used prior to the biological treatment, and no chemical phosphorus removal (CPR) measures were used as a pretreatment or simultaneous process during the investigation. The wastewater treatment process refers to AAO (10 WWTPs), RAAO (4 WWTPs), anoxic/aerobic (AO) (2 WWTPs), OD (6 WWTPs), and a series of SBR (3 WWTPs), including modified SBR (MSBR), Unitank, and intermittent cyclic extended activated sludge (ICEAS).

The characteristics of these plants, including the treatment process, population equivalent (PE) served, nominal capacity (NC), hydraulic retention time (HRT), and solid retention time (SRT), are summarized in Table 1. The evaluation of the WWTPs was

Table 1
Characteristics of the 25 WWTPs for BNR potential evaluation

WWTP	Process	PE (10^3 inhabitants)	NC ($10^3 m^3/d$)	HRT (h)	SRT (d)
1	Carrousel OD	100	30	14.2	13.0
2	AAO	350	120	17.6	17.1
3	Carrousel OD	40	4	14.5	25.0
4	RAAO	100	50	12	15.0
5	AAO	230	100	11	15.0
6	Carrousel OD	60	12	15	15.0
7	Carrousel OD	33	14	22.4	15.0
8	Carrousel OD	60	17	14.5	17.0
9	RAAO	350	70	14	17.0
10	AAO OD	453	120	15.3	15.0
11	AAO	100	35	14	15.0
12	AAO	300	138	15	12
13	AAO	150	50	13.2	16.8
14	RAAO	240	130	14.5	13.4
15	Unitank	700	400	15.9	17.3
16	AAO	200	12.5	16	15.0
17	AAO	600	100	11	13.0
18	AO	100	25	15.2	13.4
19	AAO*	320	75	15.4	7.2
20	AAO	270	50	14.4	15.0
21	RAAO	340	50	14.1	20.0
22	AAO	131	40	12	13.0
23	MSBR	220	70	7.7	15.0
24	AO	157	44	10.6	15.0
25	ICEAS	167	50	15.9	15.7

*A middle settling tank was inserted between the anaerobic tank and anoxic tank in WWTP 19.

carried out over a period of 12 months between January 2011 and December 2011 with monthly average data of influent and effluent.

2.2. Methodology for BNR potential evaluation

Besides environmental conditions, the efficiency of BNR is chiefly influenced by influent characteristics, treatment process, and operational parameters, and carbon source available in influent wastewater is an important factor for BNR potential evaluation of municipal WWTPs. In BNR process, the carbon source is typically one of the three sources [15,16]: (1) the biological soluble COD (BSCOD) in the influent wastewater; (2) the BSCOD produced during hydrolysis of particulate COD and endogenous decay of biomass; and (3) an external source such as methanol or acetate. In the evaluation of BNR potential, the carbon source consumed by oxygen and the other oxysalts was not taken into consideration, and the nitrogen and phosphorus removed by ordinary metabolic accumulation were also ignored because of their relatively small contribution to the overall removal in the BNR process [15].

In biological denitrification process, the carbon source requirement (CSR) for nitrogen removal (CSR_N) can be calculated by stoichiometric equation [15,16].

$$CSR_N = \frac{2.86 S_{NO,r}}{1 - 1.42 Y_n} \quad (1)$$

where $S_{NO,r}$ is reduced nitrate and nitrite nitrogen via denitrification (mg/L); Y_n is net biomass yield of denitrifying biomass (gVSS/gBSCOD), which can be calculated by Eq. (2).

$$Y_n = \frac{Y}{1 + k_{dn}SRT} \quad (2)$$

where Y is biomass yield of denitrifying biomass (gVSS/gBSCOD); k_{dn} is endogenous decay coefficient for denitrifying biomass (d^{-1}). The recommended value of Y and k_{dn} for the evaluation was 0.40 gVSS/gCOD and 0.15 gVSS/(g biomass·d), respectively [15].

The efficiency of biological phosphorus removal is also influenced by the amount of BSCOD available in the influent wastewater as most BSCOD will be converted to acetate in the short anaerobic HRT. According to the stoichiometry of biological phosphorus removal, owing to the low cell yield of the fermentation process, the yield of acetate is 1.06 g/gBSCOD as most of the COD fermented will be converted to volatile fatty acids. The cell yield and cell phosphorus content is 0.30 gVSS/g acetate and 0.30 gP/gVSS, respectively [15]. Therefore, the CSR for biological phosphorus removal (CSR_P) is:

$$CSR_P = 10.5 \times S_{PO,r} \quad (3)$$

where $S_{PO,r}$ is reduced phosphorus via biological storage mechanism (mg/L).

Most of nitrogen removed in the biological treatment process is firstly converted to nitrite and nitrate via nitrification, and then denitrified to gaseous nitrogen [17]. Therefore, the $S_{NO,r}$ in Eq. (1) is equivalent to the TN removed in the wastewater treatment process, and $S_{PO,r}$ in Eq. (2) can also be replaced by the TP removed as most phosphorus is removed via biological storage mechanism. The CSR for biological nitrogen and phosphorus removal can be expressed as:

$$CSR = \frac{2.86(TN_i - TN_S)}{1 - 1.42 Y_n} + 10.5(TP_i - TP_S) \quad (4)$$

where TN_i and TP_i are TN and TP concentrations in influent wastewater (mg/L), respectively; TN_S and TP_S are TN and TP concentrations regulated in relevant discharge standards (mg/L), respectively.

Because, relatively long SRT (10 ~ 25 d) is required for nitrification in WWTPs [15], the colloidal and particulate components in the biological COD could be hydrolyzed to BSCOD, and thus BOD_5, a routine monitoring index in municipal WWTPs, is used to approximately replace the BSCOD for the evaluation of BNR potential. Therefore, in a BNR process, CSR and BOD_5 represents carbon source demand of BNR and supply in the wastewater, and the CSR/BOD_5 ratio can reflect the difficulty of BNR.

$$DNR = \frac{CSR}{BOD_{5,i}} \quad (5)$$

where $BOD_{5,i}$ is BOD value in the influent wastewater (mg/L). The DNR value higher than 1.0 represents the demand of carbon source of BNR which overweighs the supply in the wastewater.

3. Results and discussion

3.1. Characteristics of influent and effluent of the WWTPs

Table 2 shows characteristics of influents and effluents of the 25 WWTPs. The total flow rate of the evaluated WWTPs was $1.81 \times 10^6\ m^3/d$ and corresponded to a PE of 5.77×10^6 inhabitants

Table 2
Characteristics of influents and effluents of the 25 WWTPs (Unit: mg/L)

	Influent						Effluent					
WWTP	COD	BOD_5	SS	NH_4–N	TN	TP	COD	BOD_5	SS	NH_4–N	TN	TP
1	399.8	220.5	320.3	13.86	19.47	2.16	39.4	4.3	7.9	1.58	9.64	0.19
2	517.3	190.1	243.3	20.46	25.86	2.04	42.5	16.3	18.6	3.31	10.58	0.35
3	284.4	124.1	120.0	16.1	21.41	1.91	26.0	3.1	6.1	1.12	6.87	0.07
4	275.4	84.8	115.5	16.91	18.07	2.20	38.8	6.1	24.2	4.76	8.84	0.61
5	411.4	200.6	217.7	13.58	25.28	4.23	30.5	12.2	25.1	1.26	12.46	0.40
6	247.2	107.6	151.7	15.09	20.45	2.84	29.4	3.4	14.3	3.21	11.42	0.16
7	423.3	226.4	194.2	21.28	29.45	4.39	36.1	10.9	10.7	2.08	9.60	0.27
8	257.1	112.5	164.0	31.19	21.61	3.07	26.6	3.2	7.9	1.12	10.38	0.11
9	392.0	188.9	210.2	32.39	33.73	5.22	40.1	3.5	8.1	3.69	11.46	0.43
10	334.2	154.1	167.9	20.83	28.18	5.19	40.5	3.4	17.1	2.27	10.87	0.76
11	288.9	135.8	118.7	24.25	29.73	3.69	34.5	3.6	13.2	2.14	11.43	0.79
12	424.9	171.3	250.5	30.12	36.24	4.76	29.2	3.2	6.6	1.66	12.39	0.94
13	265.5	171.9	194.1	25.05	38.88	4.17	30.3	10.2	11.5	4.19	12.92	0.65
14	392.5	217.4	273.9	19.8	40.4	7.04	34.4	11.4	18.8	4.18	12.11	0.74
15	357.5	212.1	248.3	31.43	49.11	4.01	39.5	4.3	15.8	1.32	9.98	0.99
16	427.7	190.9	184.8	29.82	35.8	7.37	36.3	8.8	14.6	5.23	16.51	0.56
17	469.5	198.7	165.7	34.93	49.43	6.70	41.5	8.3	19.5	4.01	12.99	0.95
18	264.7	97.1	289.0	28.9	36.55	2.13	28.9	1.8	10.3	1.34	10.52	0.76
19	327.4	146.4	127.0	34.52	45.92	4.25	32.5	8.8	11.1	9.02	16.32	1.02
20	205.2	118.1	98.6	23.51	40.95	4.08	37.9	3.5	11.6	4.73	13.68	0.95
21	293.4	105.9	260.3	28.52	40.48	4.36	34.6	7.4	19.9	1.69	12.32	1.35
22	510.0	177.1	293.0	38.93	58.78	7.35	22.8	6.6	11.5	9.28	16.79	1.03
23	484.8	181.8	360.3	32.01	51.97	11.23	46.0	16.6	12.7	9.69	20.36	1.48
24	333.2	127.7	155.8	30.82	53.37	4.56	34.1	9.7	11.2	5.33	16.15	1.08
25	518.1	210.2	222.4	26.31	48.47	26.40	49.2	14.1	14.7	7.81	16.96	2.10

(designed value). Based on these data, the volume of wastewater produced per person was estimated at 313 L/d. The amount of BOD_5, COD, suspended solids (SS), ammonium nitrogen (NH_4–N), TN, and TP produced per person was 112.4, 50.8, 64.0, 8.4, 12.0, and 1.9 g/d, respectively. The average COD and BOD_5 in the influents were 369.5 ± 104.3 and 168.5 ± 46.4 mg/L, respectively; the average BOD_5/COD ratio was 0.46 ± 0.08, indicating high biodegradability of the 25 WWTPs.

The average removal efficiency of COD, BOD_5, and SS was, respectively, 89.8 ± 2.6, 95.5 ± 2.3, and 92.5 ± 4.0%, indicating the stable and efficient removal of organic and particulate pollutants in the 25 WWTPs. The highest concentrations of SS were found in the effluents from WWTP 4 and 5, probably due to the lower efficiency of secondary settler. The average removal efficiency of NH_4–N, TN, and TP was 85.1 ± 8.4, 63.2 ± 8.7, and 84.3 ± 8.9%, respectively. The higher deviation (26.7%) of NH_4–N removal efficiencies among the evaluated WWTPs was probably attributed to different operational variables (dissolved oxygen, SRT) [18,19] and the extremely high sensitivity of nitrifying biomass to environmental factors and toxic compounds [20,21]. The highest deviation of removal efficiencies among the 25 WWTPs was found for TN (35.5%) and TP (32.1%) with concentrations in the effluents ranged in 6.87 ~ 20.36 and 0.07 ~ 2.10 mg/L, respectively.

3.2. BNR potential evaluation by C/N and C/P ratios

Based on the BOD_5, TN, and TP values given in Table 2, C/N and C/P ratios were calculated and varied in the range of 2.4 ~ 11.3 $gBOD_5/gN$ and 8.0 ~ 102.1 $gBOD_5/gP$, respectively. The recommended threshold value of C/N and C/P for nitrogen and phosphorus removal was 4 $gBOD_5/gN$ and 17 $gBOD_5/gP$ [15], respectively. In the evaluated WWTPs, the C/N ratios of WWTP 1 ~ 17 and WWTP 25 were all higher than 4.0 $gBOD_5/gN$, while the C/P ratios of WWTP 1 ~ 22 and WWTP 24 were all higher than 17.0 $gBOD_5/gP$, indicating higher removal efficiencies of nitrogen or phosphorus could be observed in these WWTPs. Nevertheless, high TP concentrations (>1.0 mg/L) were found in the effluents of WWTPs 19, 21, 22, and 24 with C/P ratios higher than 24.1 $gBOD_5/gP$, which was probably owing to the

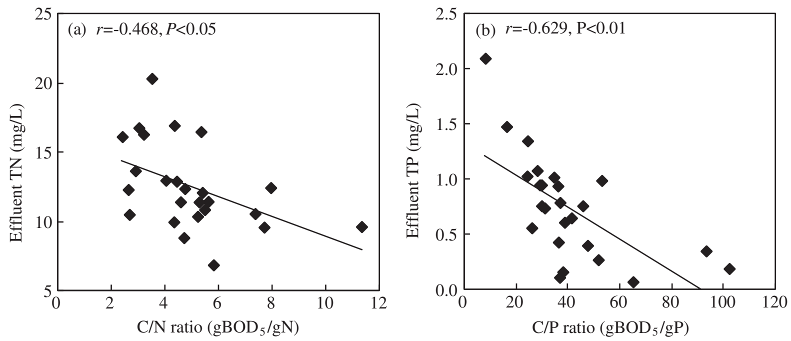

Fig. 1. Relationship between effluent TN, TP, and influent C/N, C/P ratios of the 25 WWTPs.

lower C/N ratio in these WWTPs (<3.2 $gBOD_5/gN$), since the competition of carbon source by denitrification is unable to be reflected by the C/P ratio.

The scatter diagram for the relationship between nutrient concentrations in the effluents and C/N, C/P ratios in the influents are shown in Fig. 1. TN and TP concentrations in the effluents are decreased with C/N and C/P ratios in the influent, but the dispersed data points (especially in Fig. 1(a)) indicates little correlation between the variables within Fig. 1. Therefore, more reliable index to comprehensively consider carbon source requirements of simultaneous nitrogen and phosphorus removal is required for BNR potential evaluation.

3.3. BNR potential evaluation by DNR

The standard values of Grade 1B (Class B Grade 1) (TN ≤ 20 and TP ≤ 1.0 mg/L) and 1A (Class A Grade 1) (TN ≤ 15 and TP ≤ 0.5 mg/L) in GB 18918-2002 were employed for the calculation of DNR values. In China, Grade 1A is the basic requirement of the effluent of municipal WWTPs used as reclaimed water and landscape water, while Grade 1B is executed for municipal WWTPs with effluent discharged into water bodies hospitable for aquiculture. Fig. 2 illustrates the monthly mean DNR values and its constitute (DNR_N and DNR_P) for the 25 WWTPs under Grade 1B and 1A in the year 2011. The minimum DNR value under Grade 1B and 1A was, respectively, 0.075 and 0.149, which were both observed in the WWTP 1. In the other word, this plant had the most abundant carbon supply and the lowest difficulty for simultaneous nitrogen and phosphorus removal, and the low TN and TP concentrations (9.64 and 0.19 mg/L) in the effluent of WWTP 1 proved the inference. The WWTP 25 had the highest DNR value (1.74 and 1.84 under Grade 1B and 1A, respectively) among the 25 WWTPs, and DNR_P values of WWTP 25 under Grade 1 B and 1A were both higher than 1.25, which is the main reason for its higher TP concentrations in the effluent (2.10 mg/L).

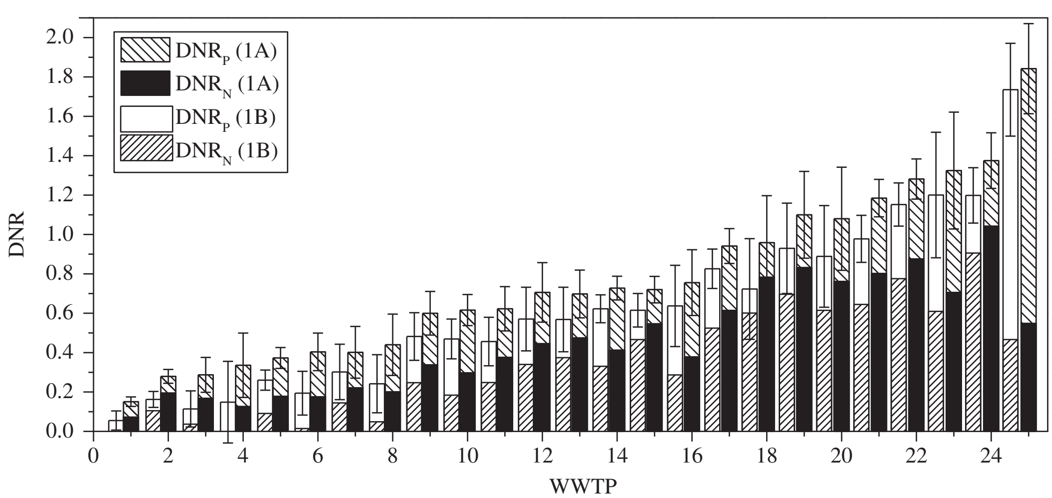

Fig. 2. DNR index of the 25 evaluated WWTPs under different discharge standards.

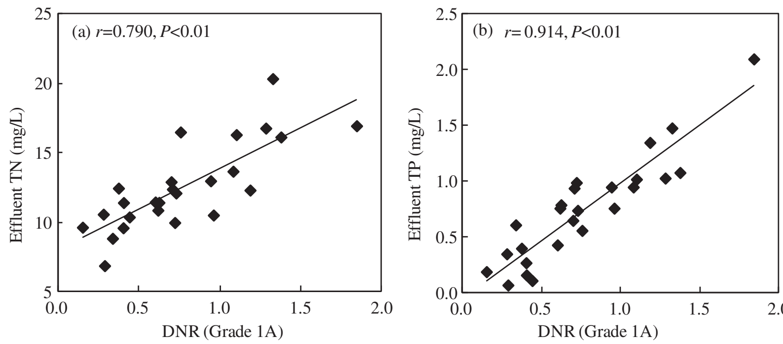

Fig. 3. Relationship between effluent TN(a), TP (b), and DNR of the 25 WWTPs.

Table 3
Pearson correlations coefficient for the evaluation of BNR potential of WWTPs

Index	C/N	C/P	DNR (1A)	DNR (1B)	Effluent TN	Effluent TP
C/N	1	0.742**	−0.726**	−0.676**	−0.468*	−0.612**
C/P	0.742**	1	−0.728**	−0.711**	−0.629**	−0.652**
DNR (1A)	−0.726**	−0.728**	1	0.995**	0.790**	0.914**
DNR (1B)	−0.676**	−0.711**	0.995**	1	0.807**	0.923**
Effluent TN	−0.468*	−0.629**	0.790**	0.807**	1	0.690**
Effluent TP	−0.612**	−0.652**	0.914**	0.923**	0.690**	1

*Correlation is significant at the 0.05 level (two-tailed).
**Correlation is significant at the 0.01 level (two-tailed).

The relationship between DNR values under Grade 1A and nutrient concentrations in the effluents are shown in Fig. 3. The Pearson's coefficients r_P of effluent TN and TP concentrations with DNR, C/N, and C/P values are summarized in Table 3 by using SPSS statistical analysis method. From Table 3, it can be seen that the correlation of C/N ratio with TN concentration in the effluents is less significant than the other r_P values. The correlation of C/P ratio with TP concentration in the effluents is significant at 0.01 level, but the correlation coefficient r_p is only 0.612. Nevertheless, the r_P values between DNR and TN, TP concentrations in the effluents are all higher than 0.790 ($p < 0.01$), which confirms that the DNR is a more reliable indicator for evaluating BNR potential of WWTPs. The correlation coefficient between DNR (1A) and TN, TP concentrations is slightly higher than DNR (1B) as only 3 among the 25 WWTPs were designed under Grade 1A. Compared to TP concentrations, TN concentrations in the effluents have lower r_P with the DNR values, which might be attributed to the low nitrification efficiency of some WWTPs (e.g. 19, 22, and 23). In these WWTPs, low nitrification efficiency in the effluents resulted in high TN but low nitrate concentrations in the effluent, and the low nitrate concentration caused the low-efficiency utilization of carbon source for denitrification. In these cases, the TN removal was not limited by carbon source supply, and thus should not be related to the DNR values.

3.4. DNR ranking of WWTPs

Looking at the distribution of DNR values across individual WWTPs, four levels may be distinguished: (i) low difficulty, when the DNR value does not exceed 0.5; (ii) medium difficulty, when the DNR value is between 0.5 and 1.0; (iii) high difficulty, when the DNR value is between 1.0 and 1.5; and (iv) extremely high difficulty, when the DNR value exceeds 1.5. Fig. 4 shows these four groups of WWTPs under Grade 1A. *C* and *Cs* in Fig. 4 represent measured concentrations in the effluents and regulated concentrations under Grade 1A for TN and TP. The percentage of WWTPs with low, medium, high, and extremely high DNR level among the 25 WWTPs under Grade 1A was 32, 40, 24, and 4%, respectively.

The DNR level is a good factor for the management of WWTPs under different levels of requirements. As shown in Fig. 4, the average TN concentrations in the effluents were increased from 9.97 ± 1.66 mg/L under low difficulty to 16.96 mg/L under high difficulty,

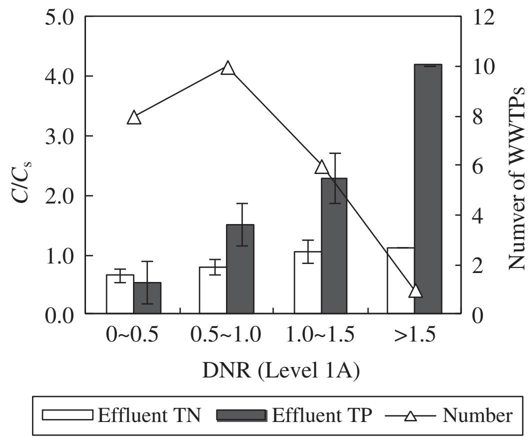

Fig. 4. DNR ranking of the 25 WWTPs.

while the average TP concentrations were increased from 0.27 ± 0.18 to 2.10 mg/L. Therefore, the requirement of TN and TP concentrations in the effluents should be varied with the DNR values, and more stringent discharge standard could be put forward for WWTPs with low level of DNR. The operational cost of WWTPs for BNR should also be estimated by the DNR level, and different subsidy policies for the operation of WWTPs could be advanced by taking the difficulty of nitrogen and phosphorus removal in consideration. Furthermore, for the WWTPs with DNR > 1.0, the discharge of industrial wastewater with high concentrations of TN and TP should be restricted to reduce the load of nutrient pollutants.

The DNR level can also be used to estimate the carbon supply conditions for process upgrading of WWTPs. The levels of average DNR for the 25 WWTPs under Grade 1B and 1A were both medium, with values of 0.682 and 0.832, respectively. The results indicated the supply of carbon source was relatively abundant, and the additional requirement of carbon source for BNR upgrade of WWTPs from Grade 1B to 1A was equivalent to 15% of BOD_5 in the influent. As for the process upgrading from Grade 1B to 1A, DNR levels of WWTP 4, 8, 10, and 11 will increase from low to medium, and WWTP 19, 20, and 21 will increase from medium to high.

The DNR value and its constitute are also a favorable indicator for treatment process selection of WWTPs. Because denitrifying bacteria have more competition for carbon source than PAOs [7], the increment of effluent TP is higher than that of TN with the increase of DNR values (Fig. 4). For the WWTP with extremely high or high difficulty (DNR > 1.0), it is suggested that CPR measures be taken to ensure TP concentration in the effluent meeting relevant discharge standards by adding aluminum or ferric salt to effluent or mixed liquor, but the inhibitory effects of chemicals on microbial activities should be estimated if chemicals are added into the mixed liquor [22].

The addition of external carbon source is also an effective measures for simultaneous nitrogen and phosphorus removal [23,24], especially for WWTPs with higher DNR_N (e.g. WWTP 24 with DNR_N (1A) > 1.0 in Fig. 2), and the critical dose of external carbon source (m_c) can be estimated by the DNR value.

$$m_c = \mathrm{CSR} - \mathrm{BOD}_{5,i} \qquad (6)$$

4. Conclusions

As a new comprehensive method for the evaluation of BNR potential of WWTPs, the DNR index was established based on the supply-demand relationship of carbon source in the BNR process, and was superior to C/N and C/P ratios, since it considers the competition of carbon source between denitrification and anaerobic phosphorus release. The statistical analysis of 25 WWTPs in Shanghai showed that the DNR values had significant positive correlation ($r > 0.790$, $p < 0.01$) with TN and TP concentrations in the effluents. According to the WWTPs ranking based on DNR evaluation, the number of WWTPs with low, medium, high, and extremely high difficulty for nutrient removal level was 8, 10, 6, and 1 among the 25 WWTPs, respectively. The developed method can evaluate and analyze the BNR potential scientifically and objectively, and the DNR ranking results can be used to guide management, upgrading, and optimization of WWTPs.

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