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Construction and exploration of pollutant consumption oxygen equivalent treatment costs in municipal wastewater treatment plants

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ABSTRACT

The study of wastewater treatment costs is an important aspect of the operation and management of municipal wastewater treatment plants. People usually focus on the treatment cost per cubic meter of wastewater. However, this indicator is far too simple as it only considers the economics and so does not reasonably evaluate the operation conditions within the wastewater treatment plants. In view of this, this work considers two other measures, the pollutant consumption oxygen equivalent (PCOE), and the PCOE treatment cost (PCOETC). PCOETC not only reflects the total pollutant removal, but also how much the wastewater treatment costs. The feasibility and practicality of PCOETC usage is verified by the study of wastewater treatment costs in 18 wastewater treatment plants in southwest China. The obtained results show that PCOETC is a better indicator than the common statistical indicator (i.e. the treatment cost of per cubic meter of wastewater) for expressing the wastewater treatment cost.

Keywords: Municipal wastewater treatment plants; Pollutant consumption oxygen equivalent; Pollutant consumption oxygen equivalent treatment costs

1. Introduction

For several decades, wastewater treatment costs in China's municipal wastewater treatment plants (MWTPs) have been expressed in China's most authoritative statistical yearbook using treatment cost per cubic meter of wastewater as the statistical indicator [1,2]. This indicator is very useful and can meet the actual need for management and operation of MWTPs. However, it is too simple because it does not reflect the wastewater treatment costs of the MWTPs and the total pollutant removal. This latter factor is another important criterion for measuring the running costs of MWTPs.

To combine the overall running costs of MWTPs with the total pollutant removal, a theory of pollutant consumption oxygen equivalent (PCOE) and pollutant consumption oxygen equivalent treatment cost (PCOETC) is constructed in this research. This makes evaluating running costs of MWTPs much easier. The stimulus for the idea derives from our group's study of MWTPs in southwest China from 2010 to 2011 [3–7]. Firstly, the treatment costs per cubic meter of wastewater were referred to as "this pure economic indicator," which was "a fool indicator." The total operation costs

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are divided by the total influent form the treatment costs per cubic meter of wastewater of the MWTPs, and the calculation apparently expresses the entire concept. However, it only reflects the wastewater treatment costs of the MWTP—the total pollutant removal is not reflected. Secondly, the treatment costs per cubic meter of wastewater do not integrate high or low wastewater treatment costs with the level of wastewater discharge standards. For different emission standards under the same wastewater treatment process, the treatment costs per cubic meter of wastewater have a large price variance.

Hence, the indicator does not reflect how much wastewater treatment, costs the MWTPs. Taking these issues into account, the PCOETCs relating to the operation and management of MWTPs is constructed in this paper.

2. Definitions

PCOE is the total consumption of oxygen equivalent, added up over all the consumption oxygen equivalents of various pollutants. This is necessary because pollution indicators such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), ammonium nitrogen (NH_3–N), suspended solids (SS), and total phosphorus (TP) in wastewater in MWTPs are related to oxygen consumption. Thus, we must use oxygen consumption as an intermediate variable to express the consumption oxygen equivalent of each pollutant. The unit used is g O/m^3, i.e. the mass (g) of oxygen required to remove pollutants from unit volume ($1\,m^3$) of wastewater. In our calculation, the PCOE (Q) is the difference between the influent PCOE and the effluent PCOE for each MWTP.

Correspondingly, PCOETC is the ratio of the wastewater treatment cost per unit PCOE difference. PCOETC (C) has units of yuan/kg and can be calculated using:

$$C = P/(Q_i - Q_o) \tag{I}$$

where P is the wastewater treatment cost per cubic meter (yuan/m^3) and Q_i and Q_o are the PCOE of the influent and the effluent, respectively (g O/m^3).

PCOETC indicator together with PCOE was firstly proposed by our group in the world. So far, the research literature for PCOETC indicator has been not reported, but the research about equivalent in many fields has obtained some results. Lavoisier as early as in the eighteenth century proposed chemical equivalent [8]. Carbon equivalent was studied by Lebedev in 1969 [9]. CO_2 equivalent was used as Ruden researched on Diels-Alder reaction in 1975 [10]. In addition, there are many other equivalent indicators such as dose equivalent [11], snow water equivalent [12], TNT equivalent [13], and so on. In the field of sewage treatment, the literature of equivalent research is very little. The enterprise environmental pollutants' equivalent indicator established in 1985 by Hongguang Huang [14] is only found by us, but this indicator is an evaluation standard as government collecting sewage charges the enterprise and it is clearly different from PCOETC and PCOE indicators because it does not calculate oxygen consumption.

At the same time, PCOETC or PCOE is an integrated indicator considering all problems. It not only reflects the total pollutant removal, but also how much the wastewater treatment costs. Firstly, PCOE is unlike common single indexes such as BOD, COD, TN, and others from wastewater. Although those single-index indicators are very good and are often used, they cannot reflect the wastewater treatment costs of MWTPs. Secondly, they are also different from the pure economic indicators such as the treatment cost per cubic meter of wastewater, which does not include the level of wastewater pollutant removal. So, the construction of PCOETC and PCOE has a great significance for the analysis of the operation and management of MWTPs.

3. Formula derivation for PCOE

We use U, V, W, X, Y, and Z to denote the COD, BOD, SS, TN, NH_3–N, and TP per cubic meter of wastewater, respectively. Their consumption oxygen equivalents are correspondingly, denoted by UO, VO, WO, XO, YO, and ZO. Their units are mg/l or, equivalently, g/m^3. We consider each pollution indicator in turn.

3.1. COD and BOD

COD is the chemical oxygen demand and the COD consumption of oxygen equivalent is equal to the COD value. Thus, $U_o = U$. COD already contains BOD, and so the BOD oxygen equivalent value was no longer calculated.

3.2. SS

No oxygen precipitates because of the wastewater treatment process, thus there is $W_o = 0$.

3.3. TN and NH_3–N

Traditional theory holds that biological nitrogen removal is accomplished as a result of organic nitrogen ammonification, nitrification, denitrification, and microbial assimilation. Voet first proposed as early as 1975 a short cut nitrification-denitrification process when he found accumulation of HNO2 in nitrification process [15]. Following him, many domestic and overseas scholars subsequently carried out experimental research. The anaerobic ammonium oxidation principle means that ammonium nitrogen using NO_2^- and NO_3^- as an electron acceptor under anaerobic conditions can be converted to N_2. This was developed by the Kluyver Biotechnology Laboratory of Delft Technology University in the Netherlands [16]. In the wastewater treatment process, some nitrogen in the wastewater is assimilated as a part of microbial cells and microorganisms proliferate [17]. According to the theory of simultaneous nitrification and denitrification (SND), there are aerobic and anoxic environments at the same time in a reactor. Nitrification and denitrification occurs in the same reactor at the same time. So, SND is presented. The theory has been supported by research through discoveries such as the discovery of aerobic denitrification bacteria and heterotrophic bacteria, aerobic denitrification and heterotrophic denitrification. In practice it has been proved that SND does reduce the total time required for achieving complete nitrification and denitrification [18]. Based on the above results, the total reaction equation for biological nitrogen removal is:

$$NH_4^+ + 2O_2 \xrightarrow{\text{nitrifying bacteria}} NO_3^- + 2H^+ + H_2O \quad (\Delta H = 305 - 440\ \text{KJ/mol}) \tag{a}$$

According to Eq. (a), 1 g NH_4^+–N requires 4.57 g of oxygen for complete nitrification [19,20]. In the denitrification process by Eq. (b),

$$6NO_3^- + 5CH_3OH \xrightarrow{\text{denitrification bacteria}} 3N_2 + 5CO_2 + 7H_2O + 6OH^- \tag{b}$$

1 g of NO_3^-–N needs 2.47 g of methanol and BOD_5, which is 1.05 times of methanol. At the same time, 1 g of NO_3^-–N reduction leads to a cut of 2.6 g-BOD_5 (1.05×2.47). Calculating dissolved oxygen, 1 g of NO_3^-–N is equal to 2.6 g of oxygen produced in the denitrification process [19]. As NH_3–N oxygen consumption is only one part of TN consumption oxygen equivalent in the wastewater biological treatment process, only the TN consumption oxygen equivalent is calculated. So we deduce that, $X_0| = |4.57X| - |2.6X| = |1.97X$.

3.4. TP

The mechanisms of phosphorus removal from wastewater are mainly phosphorus adsorption removal, chemical phosphorus removal, and biological phosphorus removal. Biological phosphorus removal is really meant to improve activated sludge processes [21]. Anaerobic and aerobic environments combine to make the plot phosphorus bacteria absorb the excess phosphorus. In addition, biological nutrient removal technology is widely used because it is cheap and also removes C, N, and P at the same time [22]. Therefore, the biological phosphorus removal process was selected to calculate the consumption oxygen equivalent of phosphorus, as this has most meaning.

Early in the 1960s, it was found that excess absorption of phosphorus was closely related to microorganism metabolism. In these studies, in the theory governing the control of phosphorus released by redox potential [23], anaerobic release of phosphorus was a prerequisite for substantial absorption of phosphorus [24]. However, many people have studied in depth, the biochemical model of biological phosphorus removal due to physiological and biochemical processes. Although many metabolic pathways for them are not yet fully clear, the workers achieved some consensus that phosphorus removal process was divided into two stages [25–30]. In the anaerobic phase, organisms absorbed by phosphate accumulating bacteria stored polyhydroxyalkanoates (PHAs), degraded polyphosphate, and released orthophosphate at the same time. In the subsequent aerobic phase, aerobic growth of phosphate-accumulating bacteria absorb orthophosphate to synthesize polyphosphate by the use of the stored PHA for carbon and energy. Finally, through the emission of activated sludge in taking excessive phosphorus, phosphorus from wastewater was removed.

According to the theory developed by Tracy [26], the equation of degradation of polyphosphate was used in the anaerobic zone:

$$2C_2H_4O_2 + HPO_3\ (\text{phosphorus}) + H_2O = (C_2H_4O_2)_2\ (\text{stored organic matter}) + PO_4^{3-} + 3H^+ \tag{c}$$

And in the aerobic zone, the equation for accumulating phosphorus was shown to be the following [26]:

$$C_2H_4O_2\ (\text{organic}) + 0.16NH_4^+ + 1.2O_2 + 0.2PO_4^{3-} = 0.16C_5H_7NO_2 + 1.2CO_2 + 0.2HPO_3\ (\text{phosphate}) + 0.44OH^- + 1.44H_2O \tag{d}$$

As can be seen from Eqs. (c) and (d), in the biological phosphorus removal process, the removal of phosphorus in the anaerobic process does not require the participation of oxygen and nitrogen, but this is only in the aerobic process. When the phosphorus consumption of oxygen is calculated, we only need to consider the aerobic process. According to the stoichiometry in Eq. (c), removal of 1 g of phosphorus, consumes 6.19 g of oxygen, 9.68 g of $C_2H_4O_2$, and 0.36 g of nitrogen in the process. Also, the metabolism of $C_2H_4O_2$ generates carbon dioxide and water (via 10.33 g of oxygen, i.e. 16.52 g (6.19 g + 10.33 g) of $C_2H_4O_2 + 2O_2 = 2CO_2 + 2H_2O$), therefore 9.68 g of $C_2H_4O_2$ needs to consume oxygen and 0.36 g of nitrogen are involved in the whole process of phosphorus removal. In light of the above formula for nitrogen consumption of oxygen ($X_0| = |1.97X$), the consumption oxygen equivalent value of TP is $Z0 = |16.52Z| - |0.36X| = 16.52Z| - |0.36| \times |1.97Z| = 15.81Z$, where the amount of nitrogen produced was also calculated in TN.

In relation to (1) and (4) above, the PCOE formula has the form:

$$T = U_0 + V_0 + W_0 + X_0 + Y_0 + Z_0 \\ = U + 1.97X + 15.81Z \quad \text{(II)}$$

where T (mg/l or g/m^3) is the PCOE, U is the COD consumption oxygen equivalent, X is the TN consumption oxygen equivalent, and Z is the TP consumption oxygen equivalent.

4. Theoretical analysis of PCOETC

4.1. Calculation

Using our group's statistical data on MWTPs in southwest China in 2010, the influent and effluent quality relating to COD, TN, and TP from 18 MWTPs can be collated (Table 1). For the treatment costs per cubic meter of wastewater in Table 1, the calculation was based on the theory given in *Water Supply and Drainage Design Manual* [31]. The depreciation of fixed assets and land occupation fees of MWTPs was not included.

According to Eq. (II), PCOE is equal to the sum of the total consumption oxygen equivalent of COD, TN and TP. PCOETC is the ratio of wastewater treatment costs to PCOE. Using the water quality data in Table 1, PCOE and PCOETC can be obtained (Table 2).

4.2. Feasibility analysis of PCOETC

Using Table 2, we can construct a graph to explore the relation between PCOE and PCOETC per cubic meter of wastewater (Fig. 1).

Firstly, the PCOE per cubic meter of wastewater (or unit PCOE) in the MWTPs in southwest China lies mainly from 180 to 500 g/m^3 (Fig. 1). PCOETC is mainly from 1.50 to 3.0 yuan/kg and its mean value is about 2.17 yuan/kg.

Secondly, according to the case study of 18 MWTPs in southwest China, a significant inverse

Table 1
The influent and effluent qualities and treatment cost per cubic meter of wastewater in MWTPs

MWTP	Treatment cost (yuan/m^3)	Influent COD (mg/l)	Effluent COD (mg/l)	Influent TN (mg/l)	Effluent TN (mg/l)	Influent TP (mg/l)	Effluent TP (mg/l)
1	0.67	191	17	24.15	11.15	2.69	0.30
2	0.44	198	28	50	38	3.01	0.35
3	0.51	179.55	26.80	15.70	7.99	1.84	0.97
4	0.90	424.4	32.77	7.39	3.00	9.93	5.83
5	0.53	260.59	24.02	32.87	14.60	3.60	0.22
6	0.57	239.78	32.01	35.35	12.91	3.92	0.59
7	0.69	353.87	37.99	37.42	16.70	4.84	1.22
8	0.69	731.85	26.47	62.93	15.17	17.29	0.44
9	0.76	243.31	18.26	23.74	10.81	5.08	0.35
10	1.03	353.17	26.39	37.99	9.60	7.19	0.17
11	0.56	244.06	40.03	39.1	11.61	2.32	0.08
12	0.63	297	55	29	15.8	4	0.72
13	0.44	137.55	32.7	30.9	18.6	0.76	0.51
14	0.44	175	36.3	25.18	12.40	2.56	0.77
15	0.57	253.00	16.78	35.30	13.28	2.63	0.35
16	1.35	353.1	26.2	54.4	10.8	4.3	0.30
17	0.92	231.6	14.1	27.4	8.9	3.2	0.7
18	0.63	261.21	27.23	26.35	13.84	2.86	0.67

Table 2
PCOEs in MWTPs

MWTPs	Treatment cost (yuan/m^3)	Influent PCOE (mg/l)	Effluent PCOE (mg/l)	PCOE of per liter of water (mg/l)	PCOE of per cubic meter of wastewater (g/m^3)	PCOETC (yuan/kg)
1	0.67	281.10	43.71	237.40	237.40	2.82
2	0.44	344.09	108.39	235.69	235.69	1.87
3	0.51	239.57	57.88	181.69	181.69	2.81
4	0.90	595.95	130.85	465.10	465.10	1.94
5	0.53	382.31	56.27	326.04	326.04	1.63
6	0.57	371.32	66.77	304.55	304.55	1.87
7	0.69	504.03	90.16	413.87	413.87	1.67
8	0.69	1129.24	63.38	1065.86	1065.86	0.65
9	0.76	370.40	45.12	325.28	325.28	2.34
10	1.03	541.74	48.00	493.74	493.74	2.09
11	0.56	357.77	64.17	293.60	293.60	1.91
12	0.63	417.37	97.51	319.86	319.86	1.97
13	0.44	210.44	77.41	133.03	133.03	3.31
14	0.44	265.08	72.90	192.18	192.18	2.29
15	0.57	364.04	48.47	315.57	315.57	1.81
16	1.35	528.25	52.22	476.03	476.03	2.84
17	0.92	336.17	42.70	293.47	293.47	3.13
18	0.63	358.34	65.09	293.25	293.25	2.15

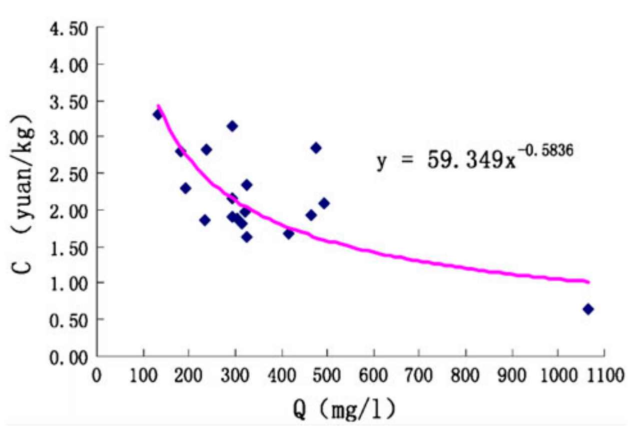

Fig. 1. The relation between PCOE (Q) and PCOETC (C) per cubic meter of wastewater.

relation is found between unit PCOE and PCOETC in the MWTPs (Fig. 1). The higher the unit PCOE's value, the lower the PCOETC's value, and *vice versa*. On fitting the data, the PCOETC model we obtained is $C = 59.349Q^{-0.5836}$.

The inverse relation between unit PCOE and PCOETC gives full proof that the PCOETC parameter is reasonable and correct. Also, it *can* be used as a parameter for the evaluation of the running costs of MWTPs.

4.3. PCOETC application principles

The wastewater treatment costs in MWTPs have been popularly expressed using the treatment cost per cubic meter of wastewater. However, high or low treatment costs per cubic meter of wastewater cannot directly evaluate the good or bad nature of the running costs of the MWTPs, because the amount of wastewater pollutants removed is not determined. For example, if a plant has high treatment costs per cubic meter of wastewater but removes large amounts of wastewater pollutants, we can identify that the MWTP runs well. On the contrary, if high treatment costs per cubic meter of wastewater are associated with low removal of wastewater pollutants, these MWTPs' running costs are unreasonable. Using the treatment cost per cubic meter of wastewater means that the running costs of the MWTP cannot be best evaluated because of the large differences in the influent and effluent quality and the wastewater pollutant removal levels of the MWTPs. Hence, PCOETC is introduced to judge the rationality of the running costs. Two steps are considered when using PCOETC to evaluate the running costs of MWTPs.

In the first step, before applying the PCOETC parameter to evaluate the running costs of the MWTP, Eq. (I) is first simplified to the form of Eq. (III),

$$C = P/Q \tag{III}$$

where C is the PCOETC (yuan/kg); P the treatment cost per cubic meter of wastewater (yuan/m^3); and Q is the PCOE (g O/m^3). The later is the difference between the influent PCOE and the effluent PCOE for each MWTP.

In the second step, the treatment costs per cubic meter of wastewater (P) and PCOE (Q) on the basis of Eq. (III) is divided into nine kinds, in order to explain how to apply the new parameter—PCOETC (Table 3).

In the third step, the change of P and Q is determined by the values of P_m and Q_m, which are the average values of P and Q. The value of P and Q is obtained through regional or national statistical MWTP operational data. The standard of small, medium, and large P and Q value, according to the $\frac{P-P_m}{P_m} \times 100\%$ and $\frac{Q-Q_m}{Q_m} \times 100\%$ respectively, is determined by the statistical data from local MWTPs. In light of our research, $\pm 20\%$ of the calculation value by above formulas is considered as cut off value of the evaluation criterion for small, medium, and large values of P and Q in mountainous cities (Table 4), but $\pm 10\%$ of *that* is required for Plain Area. On this basis, if the treatment cost per cubic meter of wastewater (P) and PCOE (Q) change in the same direction, then the running cost of the MWTP is reasonable by judgment. Otherwise, the opposite behavior is unreasonable. In the corresponding calculation, the value of P and Q is first obtained by the statistical operating data from a number of regional or national MWTPs.

In the fourth step, the running costs of the MWTPs are further analyzed. This result includes reasonableness and unreasonableness. For the MWTP whose running costs are reasonable, we further determine which category it belongs to, such as C_1, C_2, and C_3. However, for the MWTPs with unreasonable running costs, we can accurately analyze the reasons for the high or low values of the treatment costs per cubic meter of wastewater using Table 3; we also further determine which category they belong to, such as C_4, C_5, C_6, C_7, C_8, and C_9.

Table 4
The standard definitions of small, medium, and large values of P and Q

	$H < \mid -20\%$	$-20\% \mid \leqslant \mid H \leqslant \mid 20\%$	$H > \mid = \mid 20\%$
P	Small	Medium	Large
Q	Small	Medium	Large

The four-step method above is the whole process which used to evaluate the running costs of the MWTPs. Finally, the results obtained will help to objectively judge the running cost of the MWTP. This can also help us decide the corresponding measures to take for the MWTPs running badly, to solve their problems and thus improve future operations and management of the MWTP.

5. Application of PCOETC

For further explanation, the statistical data from the previously considered 18 MWTPs in southwest China in 2010 is used again as the research sample. Because the southwest region of China is mountainous, construction and investment there, as well as operation, is more complex. This causes the treatment costs per cubic meter of wastewater there to have larger differences. In this article, $\pm 20\%$ of H is considered as the value for the evaluation standard of small, medium, and large values of P and Q, where H represents $\frac{P-P_m}{P_m} \times 100\%$ and $\frac{Q-Q_m}{Q_m} \times 100\%$ (see Table 4).

In view of the statistical data, the average values of P (P_m) and Q (Q_m) of the 18 MWTPs China in 2010

Table 3
The application of PCOETC

PCOETC classification (C)	Treatment cost per m^3 of wastewater (P) is relative to the mean of statistical sample (P_m)	PCOE (Q) is relative to the mean of statistical sample (Q_m)	Judgment result	MWTP running cost
C_1	Large or↑	Large or ↑	Reasonable	Normal
C_2	Medium	Medium	Reasonable	Normal
C_3	Small or ↓	Small or ↓	Reasonable	Normal
C_4	Large or ↑	Medium	Unreasonable	High
C_5	Medium	Small or ↓	Unreasonable	High
C_6	Large or ↑	Small or ↓	Very unreasonable	Very high
C_7	Small or ↓	Medium	Unreasonable	Low
C_8	Medium	Large or ↑	Unreasonable	Low
C_9	Small or ↓	Large or ↑	Very unreasonable	Very low

Table 5
The evaluation results of applying PCOETC

MWTP	Judgment result of wastewater treatment cost, P (yuan/m^3)		Judgment result of PCOE, Q (g/m^3)		Evaluation result of PCOETC, C	Judgment result of running cost of MWTP
	$0.55 < P_m = 0.69 < 0.82$		$282.94 < Q_m = 353.68 < 424.41$			
1	0.67	Medium	237.40	Small	Unreasonable	High
2	0.44	Small	235.69	Small	Reasonable	Normal
3	0.51	Small	181.69	Small	Reasonable	Normal
4	0.90	Large	465.10	Large	Reasonable	Normal
5	0.53	Small	326.04	Medium	Unreasonable	Low
6	0.57	Medium	304.55	Medium	Reasonable	Normal
7	0.69	Medium	413.87	Medium	Reasonable	Normal
8	0.69	Medium	1065.86	Large	Unreasonable	Low
9	0.76	Medium	325.28	Medium	Reasonable	Normal
10	1.03	Large	493.74	Large	Reasonable	Normal
11	0.56	Medium	293.60	Medium	Reasonable	Normal
12	0.63	Medium	319.86	Medium	Reasonable	Normal
13	0.44	Small	133.03	Small	Reasonable	Normal
14	0.44	Small	192.18	Small	Reasonable	Normal
15	0.57	Medium	315.57	Medium	Reasonable	Normal
16	1.35	Large	476.03	Large	Reasonable	Normal
17	0.92	Large	293.47	Medium	Unreasonable	High
18	0.63	Medium	293.25	Medium	Reasonable	Normal

are 0.69 yuan/m^3 and 353.68 g/m^3, respectively. In light of Tables 3 and 4, the running costs of the MWTPs are evaluated by PCOETC. ±20% of the treatment costs per cubic meter of wastewater (P_m) and PCOE (Q_m) are considered as the value for the evaluation standard of small, medium, and large values. The results show that the treatment costs per cubic meter of wastewater of 14 of the MWTPs is normal, that of two of them is low, and two of them is high (Table 5).

6. Conclusions

This paper demonstrates that the treatment costs per cubic meter of wastewater have been irrationally used as a statistical indicator for MWTPs in China because it cannot reflect the total pollutant removal. Therefore, two new concepts, PCOE and PCOETC, are constructed. They reflect both the total pollutant removal and wastewater treatment costs in the MWTPs.

The PCOE formula is deduced by using the fact that wastewater pollutant indicators such as COD, BOD, SS, NH_3–N, TN, and TP have some relation to oxygen consumption. Thus, the PCOE formula is derived as: $T| = U + |1.97X| + |15.81Z$. On this basis, we further build the mathematical model for PCOETC ($C| = |59.349Q^{-0.5836}$). The results show that PCOE (Q) and PCOETC (C) have a significant inverse relation based on the study of practical examples from 18 MWTPs in southwest China (Fig. 1). Overall, the higher the PCOE value, the lower the PCOETC value, and *vice versa*. This proves that PCOETC is a reasonable and correct parameter to use, and that it can be used as the evaluation parameter for the running costs of MWTPs.

Finally, the running costs of 18 MWTPs are evaluated according to the PCOETC theory. The results obtained show that the treatment costs per cubic meter of wastewater of 14 MWTPs are normal, that of two are low, and that of two are high. PCOETC can effectively evaluate the running cost of a MWTP together with PCOE and the treatment costs per cubic meter of wastewater. This method is much more scientific than the commonly used statistical indicator (i.e. the treatment cost per cubic meter of wastewater). This has important significance in the operation and management of MWTPs.

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References

[1] National Bureau of Statistics of China, China Statistical Yearbook, China Statistics Press, Beijing, 2011.
[2] Environmental Protection Department and National Bureau of Statistics of China, China Environment Statistical Yearbook, China Statistics Press, Beijing, 2011.
[3] B. Rao, B. Han, W. Jiang, Z. Zhang, Q. Zhang, Discussion on the management strategy for Chongqing urban rivers: Using the Taohuaxi River as an example, Chongqing Archit. 8 (2009) 20–23 [in Chinese].
[4] H. Ning, Q. Zhang, H. Li, Analysis on economic indices of wastewater treatment plants and refuse disposal facilities in western small towns, China Water Wastewater 12 (2009) 7–11 [in Chinese].
[5] Q. Zhang, B. Yang, S. Pan, Z. Zhi, Research progress on treatment of high strength ammonia-nitrogen wastewater by MAP, Sichuan Environ. 5 (2010) 93–97 [in Chinese].
[6] P. Wu, Y. Chen, Z. Zhang, H. Liu, Q. Zhang, Discussion on applicable wastewater treatment processes for the small town sewage in Chongqing, Environ. Eng. 1 (2011) 58–61 [in Chinese].
[7] H. Huang, Q. Zhang, B. Fu, A comparative study of the investment program of WWTP based on LCC theory, China Water Wastewater 1 (2013) 101–104.
[8] P. Huang, X. Zhang, Chemical equivalent, Pop. Sci. 12 (1950) 202–203 [in Chinese].
[9] B.D. Lebedev, Question of carbon equivalent, Weld. Prod. 2 (1969) 1–2.
[10] R.A. Ruden, R. Bonjouklian, Carbon-dioxide equivalent for Diels-Alder reaction, J. Am. Chem. Soc. 23 (1975) 6892–6893.
[11] B.M. Whetley, Dose equivalent estimation in health physics instrumentation, Phys. Med. Biol. 3 (1965) 431–437.
[12] E.L. Peck, V.C. Bissell, E.B. Jones, Evaluation of snow water equivalent by airborne measurement of passive terrestrial gamma radiation, Water Resour. Res. 5 (1971) 1151–1153.
[13] X. Qiao, Y. Hu, J. Peng, W. Chen, C. Zhang, J. Hui, TNT equivalence of a rock emulsion explosive, Explos. Mater. 6 (1998) 5–8 [in Chinese].
[14] H. Huang, X. Tang, Discussion on the establishment of enterprise environmental pollutants equivalent indicators, China Environ. Manage. 4 (1985) 16–18 [in Chinese].
[15] L. Yan, D.C. Peng, Z.Y. Wang, Shortcut nitrification-denitrification biological nitrogen removal technique, China Water & Wastewater 16 (2000) 29–31.
[16] A. Mulder, Anaerobic ammonium oxidation, US Patent Documents, 427849 (507884), 1992.
[17] X. Zheng, Y. Li, Technology of Nitrogen and Phosphorus Removal from Wastewater, China Architectural Press, Beijing, 1998 [in Chinese].
[18] X. Wan, Y. Peng, S. Wang, Sustainable urban wastewater biological treatment technology, Water Treat. Technol. 30 (2004) 106–109 [in Chinese].
[19] J. Lou, S. Xie, S. He, Principle and Application of Biological Nutrient Removal, National University of Defense Technology press, Changsha, 2002.
[20] F. Zhang, Biological Nitrogen Removal Technology, China Environmental Science Press, Beijing, 1992.
[21] P. Timmermans, A. Van Haute, Denitrification with methanol: Fundamental study of the growth and denitrification capacity of *Hyphomicrobium* sp., Water Res. 17(10) (1983) 1249–1255.
[22] S. Li, Z. Qin, Application of nitrogen and phosphorus removal process in municipal wastewater treatment plants, China Resour. Compr. Utilization 28 (2010) 61–62 [in Chinese].
[23] J.L. Barnard, Biological nutrient removal without the addition of chemicals, Water Res. 9 (1975) 485–490.
[24] Z. Zhang, Mechanism and microorganisms of biological phosphorus removal, J. Anhui Agric. Sci. 38 (2010) 4205–4207, 4211, [in Chinese].
[25] T. Mion, T. Matsuo, Basic mechanism of biological phosphorus removal process, Water Pollut. Res. 10 (1984) 605–609.

[26] K.D. Tracy, A. Flammino, Advances in Water Pollution Control: Biological Phosphate Removal from Wastewater, Pergamon Press, Oxford, 1987, pp. 15–26.
[27] N. Jardin, H.J. Pöpel, Behavior of waste activated sludge from enhanced biological phosphorus removal during sludge treatment, Water Environ. Res. 68(6) (1996) 965–973.
[28] T. Kuba, M.C.M. Van Loosdrecht, J.J. Heijnen, Phosphorus and nitrogen removal with minimal COD requirement by integration of denitrifying dephosphatation and nitrification in a two-sludge system, Water Res. 30(7) (1996) 1702–1710.
[29] M.S.M. Jetten, S.J. Horn, M.C.M. van Loosdrecht, Towards a more sustainable municipal wastewater treatment system, Water Sci. Tech. 35(9) (1997) 171–180.
[30] T. Mino, D.C. San Pedro, S. Yamamoto, T. Matsuo, Application of the IAWQ activated sludge model to nutrient removal process, Water Sci. Tech. 35(8) (1997) 111–118.
[31] Shanghai Municipal, Design Manual of Water Supply and Drainage, No. 10 Technical and Economic, 2nd ed., China Building Industry Press, Beijing, 2000.