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Quantitatively updating sewage discharge standard of wastewater treatment plants: starting from the estimation of water environment capacity

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ABSTRACT

To protect aquatic environment and human health, determining the optimal sewage discharge standard for wastewater treatment plants (WWTPs) is important to reduce pollutant discharge into natural ecosystems. In this study, a novel quantitative assessment method combining water environment capacity (WEC) estimation and feasibility analysis was introduced for the selection of WWTP sewage discharge standard. A certain WWTP executing national Grade 1-B discharge standard in China's southern coast was selected as a case study. First of all, pollution sources of receiving water were investigated. More than 69.0% of nutrients (nitrogen, phosphorus) came from WWTP effluent, while non-point pollution contributed 58.3% of organic pollutants. Next, the WEC of receiving water was estimated via multiple mathematical models. It was speculated that the WEC of TP may be completely depleted by 2020 if still executing national Grade 1-B discharge standard. The maximum acceptable pollutant concentration of WWTP effluent are determined with chemical oxygen demand (COD) 86.05 mg/L, total nitrogen (TN) 19.38 mg/L, ammonium (NH_4^+-N)4.87 mg/L, and total phosphorus (TP) 0.67 mg/L to maintain water self-purification. Finally, after further economic/technical feasibility analysis, an optimal sewage discharge standard was recommended: 40 mg COD/L, 15 mg TN/L, 4.0 mg NH_4^+-N/L, and 0.3 mg TP/L.

Keywords: Wastewater treatment plant; Sewage discharge standard; Non-point pollution; Water environment capacity; Feasibility analysis.

1. Introduction

The development of sewage discharge standards is a very important topic in aquatic environment protection and water reclamation [1,2]. Wastewater treatment plants (WWTPs) has been required to enforce increasingly stringent sewage discharge standard with the implementation of relevant national standards and regulations in China, such as "Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB18918-2002)" and "National Urban Sewage Treatment and Recycling Facilities Construction in the Thirteenth Five-Year Plan" [3–5]. Nonetheless, the discharge standards implemented in most cities of China have still been low, with only 28% of WWTPs constructed after 2010 meeting national Grade 1-A Discharge Standard of Pollutants (GB18918-2002) [2]. The update of sewage discharge standards of WWTPs that still execute low discharge standard (i.e., Grade 1-B) should be raised special attention in order to balance urban economic development and environmental protection.

Relevant sewage discharge standards and regulations toward WWTPs in China have gradually been developed to guide the selection of sewage discharge standards when

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constructing or updating WWTPs [2,6]. However, different cities tend to differ significantly in terms of urban future planning, economic development level, and water function demand. Given that the situation of less-developed regions must be considered when setting national standards, the discharge standards seem to always lag behind for economically developed regions with high urbanization and industrialization, and it puts increasing pressure on frail water environments of these cities [6–8]. Therefore, it may be not enough to only meet requirements of national standards and regulations when updating the WWTP sewage discharge standards, and the actual urban situations, such as economic development and receiving water quality, should be considered to determine an optimal sewage discharge standard. The development of new assessment methods is urgently needed to help regulators flexibly update sewage discharge standards based on regional actual situations in the WWTP renovation.

Receiving water quality is a main influencing factor when setting a sewage discharge standard. The selected standard must ensure the normal self-purification capacity of receiving water, that is, the maximum amount of pollutants into receiving water should not exceed the water environment capacity (WEC) [6,9]. The limit of pollutant load into receiving water is crucial to maintain a safe WEC of water body and this can be regarded as a main guidance of selecting an appropriate WWTP sewage discharge standard. Additionally, the selected sewage discharge standard should also meet requirements of national regulations, economic development, and technique level. In this study, a quantitative assessment method combining WEC estimation and feasibility analysis was systematically introduced to determine the optimal WWTP sewage discharge standard and this result is expected to contribute to the WWTP renovation.

2. Materials and methods

2.1. The selected WWTP as the case study

A certain WWTP in China’s southern coast was selected as a case of discharge standard assessment and it still executes Grade 1-B discharge standard. The modified sequencing batch reactor (MSBR) that combines both anaerobic-anoxic-oxic and sequencing batch reactor is used to treat the wastewater in the WWTP. The receiving water of WWTP effluent is a relative enclosed water body and its water quality has become poor these days due to its weak self-purification capacity. Hence, the reevaluation of discharge standard for this WWTP is crucial to limit the pollutant load into the water body for environment protection.

2.2. Investigation and data collection

National/regional sewage discharge standards were referred for the selection of sewage discharge standard of study WWTP. Meanwhile, relevant laws and regulations for environment protection were also collected as an important guide. Additionally, the regional development planning was also considered in the determination of discharge standard.

Water quality characteristics of receiving water were analyzed combining the laboratory testing and data collection from environmental monitoring station. The sources of pollutants into the receiving water mainly include WWTP effluent, non-point pollution, shipping/transportation, marine aquaculture, and wastewater drainage without due approval. Therein, WWTP effluent and non-point pollution were main pollution sources that might deteriorate the receiving water based on practical investigation and literature research. Concentrations of pollutants, including chemical oxygen demand (COD), total nitrogen (TN),

Fig. 1. Location of study wastewater treatment plant (WWTP) and its surrounding terrain characteristics.

ammonium (NH_4^+-N), and total phosphorus (TP), were investigated from different land uses based on the analysis of road deposited substances and storm water runoff samples. Meanwhile, other WWTP information, including service area, running process, and raw/treated wastewater quality was also collected.

2.3. Mathematical models

2.3.1. Non-point pollution load

Event mean concentration (EMC) is a statistical parameter commonly utilized in storm water studies as characteristics for runoff concentrations. This is defined as the total mass load of a pollutant from a site during a storm divided by the total runoff water volume discharged during the storm [10]. EMC-based empirical model was used to estimate the non-point pollution load [Eq. (1)] [11,12]. EMC values at different land uses were determined according to sampling analysis and literature research (Table S2).

$$W = \sum_{i=1}^{n} EMC_i \times A_i \times \psi_i \times P \tag{1}$$

where W is pollution load, t·a^{-1}; i presents the land use; n is the number of land uses (roof, grass, road, hill, and harbor); EMC is the event mean concentration of i land use, mg·L^{-1}; A is the area of i land use, km^2; ψ is the runoff coefficient of i land use; P is the rainfall, mm·a^{-1}.

2.3.2. The estimation of WEC

The WEC of organic pollutants was estimated based on Eq. (2) [13]:

$$V\frac{dC}{dt} = Q_{in} \cdot \mathrm{C}_{in} + \mathrm{S}_c - Q_{out} \cdot C_{out} - k \cdot C \cdot V \tag{2}$$

where V is the water quantity, m^3; dC/dt is the change rate of pollutant concentration, mg·L^{-1}·a^{-1}; Q_{in} is the inflow water quantity, m^3·a^{-1}; C_{in} is the pollutant concentration of inflow water, mg·L^{-1}; S_c is the external pollution source or the drain, mg·a^{-1}; Q_{out} is the outflow water quantity, m^3·a^{-1}; C_{out} is the pollutant concentration of outflow water, mg·L^{-1}; k is the pollutant degradation coefficient, a^{-1}; and C is the pollutant concentration in the water body, mg·L^{-1}.

The receiving water of WWTP effluent is a relatively closed bay with poor water exchange capacity. Hence, both OECD model [Eq. (3)] and Hetianjia's model [Eq. (4)] were coupled to estimate the WEC of nutrients and the average of these two models was applied [14,15]:

$$C = \frac{C_i}{1 + 2.27(V/Q_{\mathrm{out}})^{0.586}} \tag{3}$$

$$C = \frac{L}{Z \cdot (Q_{out}/V + 10/Z)} \tag{4}$$

where C_i is the flow-weighted concentration of inflow pollutant, mg·L^{-1}; Z is the average depth, m; and L is the allowed load per unit area, g·m^{-2}·a^{-1}.

3. Results and discussion

3.1. Investigation of WWTP operating characteristics

3.1.1. Present sewage treatment capacity of WWTP

The effluent quality of WWTP (i.e., COD, TN, NH_4^+-N, TP) during 2016 was investigated in Fig. 2. As shown in Figs. 2a–c, COD, TN, and NH_4^+-N could be efficiently removed with the effluent quality up to national Grade 1-A discharge standard. This elucidates that the practical removal capacity of WWTP toward carbon and nitrogen could meet the executing discharge standard (Grade 1-B). However, there was still a poor removal of phosphorus, and the effluent concentration of TP variable was even higher than the limit of national Grade 1-B discharge standard in the early spring, which may have a great threat to the receiving water (Fig. 2d). Hence, it is urgent to update the study WWTP and its sewage discharge standard must be redrawn based on current sewage treatment characteristics.

3.1.2. The estimation of sewage disposal load in the future

In the future, the population of service area of WWTP will gradually increase [16] and the WWTP faces an increasing sewage treatment task. The relative concentration index (*RCI*) can reveal the relationship between port regions and their related human settlements [17]. Given that there was an obvious port-city characteristic in Yantian (Fig. S1), the *RCI* index was used to predict the future resident population in Yantian [17] and it can be calculated according to Eq. (5).

$$RCI = \frac{X_i}{\sum X} / \frac{Y_i}{\sum Y} \tag{5}$$

where X_i is the container throughput of i port city during one year; $\sum X$ is the total container throughput of study area which i port city belongs to; Y_i is the resident population of i port city; and $\sum Y$ is the total resident population of study area which i port city belongs to.

As shown in Table S1, the port container throughput and regional service population increased gradually from 2010 to 2016 in Shenzhen and Yantian. The *RCI* value was up to 25.64 in 2016. It is hypothesized that the *RCI* value will become relatively constant finally and it was selected as 26.0 to estimate the resident population of Yantian in 2020. By 2020, there will be approximately 12 million people in Shenzhen, and container throughputs of Shenzhen and Yantian are estimated to be approximately 29.5 million and 14.5 million twenty-foot equivalent unit (TEU) respectively [16]. Therefore, the resident population in 2020 could be estimated with approximately 226.8 thousand based on the *RCI* method. Additionally, there will be a certain number of floating populations in Yantian due to the vigorous development of tertiary industry (tourism and transportation) (Fig. S1) [18]. In this study, the floating population was considered as approximately eleven thousand according to the population movement in 2016. Moreover, the reduction coefficient of 1.05 was considered due to the discharge of certain amount of industrial wastewater. Overall, the amount of sewage into WWTP is approximately 124.9 thousand m^3/day by 2020.

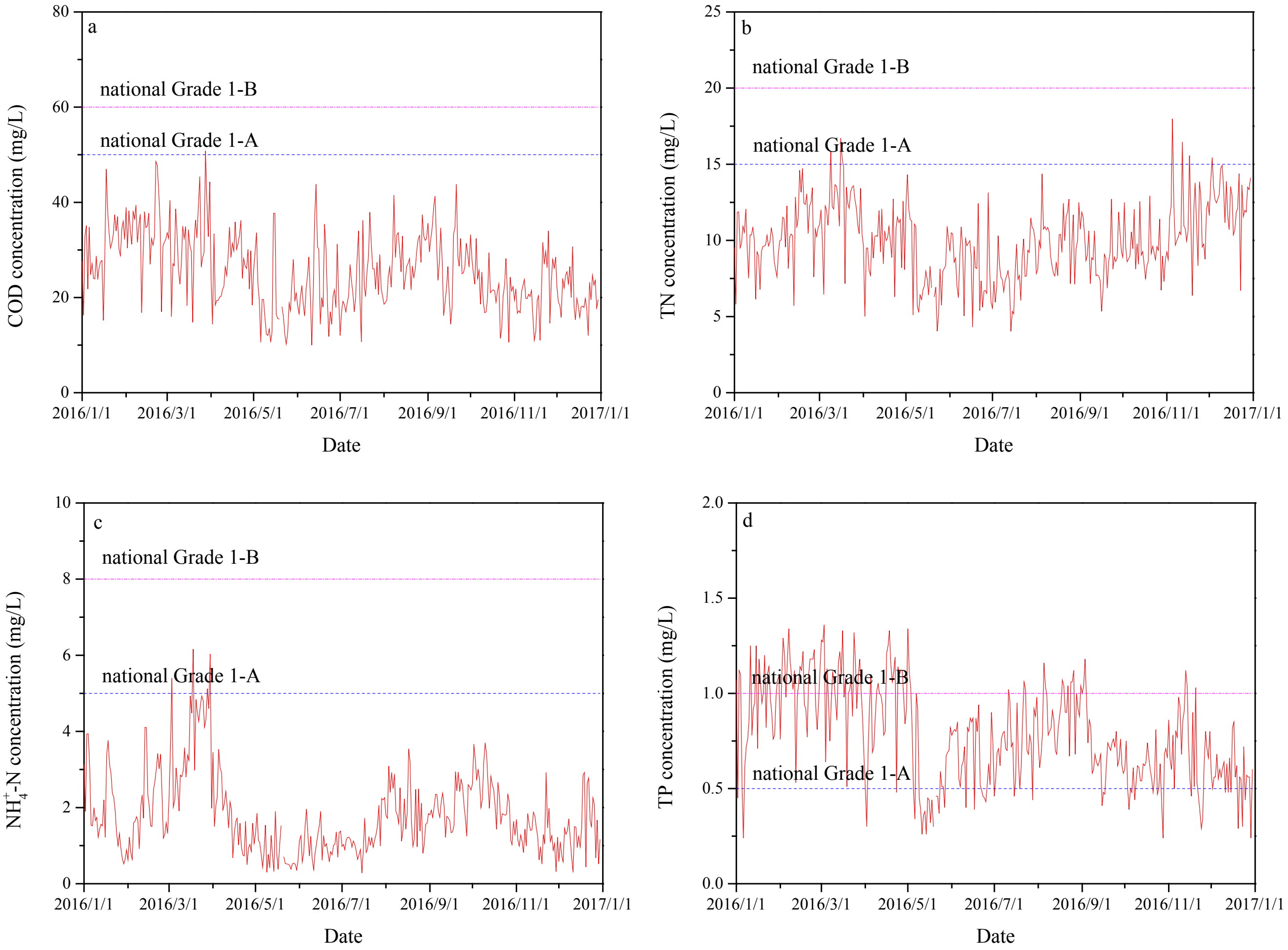

Fig. 2. Effluent water quality of study wastewater treatment plant during 2016 (mg/L): a) chemical oxygen demand (COD), b) total nitrogen (TN), c) ammonium (NH_4^+-N), and d) total phosphorus (TP).

In order to estimate the annual effluent discharge into receiving water, it was hypothesized that the amount of treated sewage of WWTP would evenly increase year by year from 2016 to 2020. As shown in Fig. 3a, due to the difference of water consumption in different seasons, the amount of daily sewage treatment differed certainly with season variation. The mean in 2016 was 88.8 thousand m^3/d and it was regarded as the basis of following calculation. Fig. 3b shows the predicting sewage discharge in 2016–2020 based on the previous hypothesis.

3.2. Pollution characteristics of receiving water and its source apportionment

Recently, the receiving water of WWTP (Fig. 1) becomes poor because of its weak water exchange capacity and continuous input of external pollutants. According to the environmental quality bulletin [19], its water quality has been degraded from marine Grade I standard in 2012 to marine Grade II standard in 2016. In August and October, some variables (nitrogen and phosphorus) were even inferior to marine Grade VI standard. Overall, the water quality of receiving water has gradually been deteriorated with the rapid economic development. It is essential to decrease the input of land-sourced pollutants into the receiving water. The worst water characteristic was regarded as background values for the WEC estimation of receiving water in this study and it is shown in Table 1.

According to the investigation of regional industrial structure, pollutants of receiving water mainly come from WWTP effluent, non-point pollution, shipping/transportation, aquaculture, and so on [20,21]. Given that primary industry accounted for a lower proportion of 0.008% in 2016 (Fig. S1), the aquaculture was ignored in this study. Shipping/transportation as an important component of regional agriculture will generate a certain amount of sewage and it was estimated by converting container throughput into population equivalent, with the load of 20.00 t COD, 6.16 t TN, 1.33 t NH_4^+-N, and 0.27 t TP in 2016. Based on Figs. 2 and 3a, the pollution load of WWTP effluent into receiving water in 2016 was calculated with 810.93 t COD, 310.87 t TN, 56.10 t NH_4^+-N, and 24.35 t TP. EMC-based empirical model as a general prediction method of non-point pollution load was used based on different land uses (Tables 2 and 3), and pollutants generated from non-point pollution

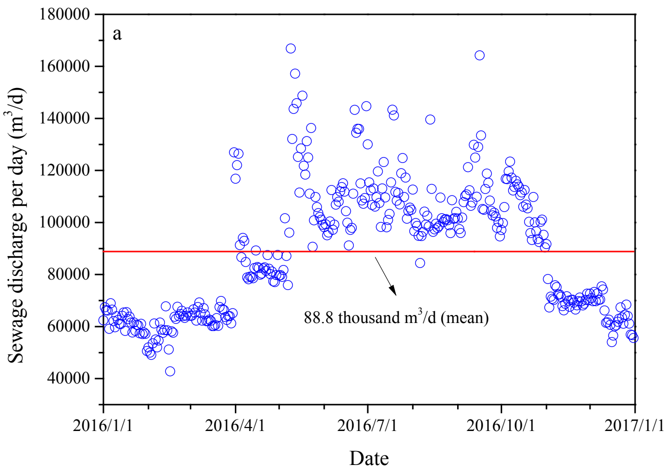

Fig. 3. Sewage discharge per day of study wastewater treatment plant (m^3/d): a) sewage discharge in 2016, and b) sewage discharge prediction in 2016–2020.

Table 1
The background values of main pollutants (chemical oxygen demand (COD), total nitrogen (TN), ammonium (NH_4^+-N), and total phosphorus (TP)) in receiving water

Pollutants	Background (mg/L)
COD	0.30
TN	0.417
NH_4^+-N	0.125
TP	0.082

Table 2
Runoff water quality (chemical oxygen demand (COD), total nitrogen (TN), ammonium (NH_4^+-N), and total phosphorus (TP)) at different land uses for non-point pollution prediction

Land uses	COD mg/L	TN mg/L	NH_4^+-N mg/L	TP mg/L
Roof	70	2.5	1.5	0.2
Grass	60	2.0	1.0	0.6
Road	90	2.5	1.5	0.4
Hill	15	1.0	0.8	0.1
Harbor	80	2.5	1.5	0.4

Table 3
The area of different land uses measured by Google Earth™ and the stormwater runoff coefficient for non-point pollution prediction

Land uses	Roof	Grass	Road	Hill	Harbor
Area (km^2)	4.2	1.1	1.8	15.1	3.1
Stormwater runoff coefficient	0.85	0.15	0.85	0.1	0.85

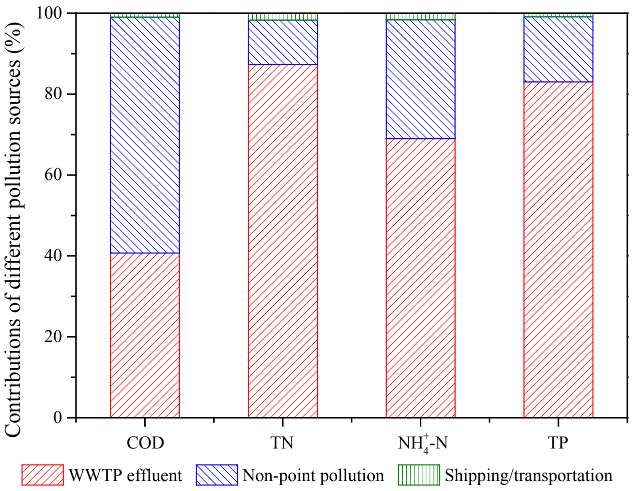

Fig. 4. Contributions of different pollution sources (WWTP effluent, Non-point pollution, and Shipping/transportation) to the pollution load of receiving water in 2016. COD: chemical oxygen demand, TN: total nitrogen, NH_4^+-N: ammonium, and TP: total phosphorus.

in 2016 were approximately 1161.58 t COD, 38.99 t TN, 23.89 t NH_4^+-N, and 4.71 t TP.

As shown in Fig. 4, the WWTP effluent was the main sources of nitrogen and phosphorus in receiving water with the contribution of more than 60%. Because the nitrogen and phosphorus were significant pollution factors of receiving water, the WWTP may play an important role in the deterioration of water quality. It is essential to reevaluate the sewage discharge standard for the update of WWTP. Additionally, the non-point pollution made a certain contribution to nitrogen and phosphorus pollution and contributed more to organic pollution than WWTP effluent. The early rain water should be intercepted because a large amount of pollutants will be carried by runoff on the effect of first-flush [22].

3.3. The calculation of the WEC of receiving water

To estimate the WEC of receiving water, it was hypothesized that water self-purification mainly attributed to water exchange and microbial degradation [23,24]. Moreover, to delineate the range of accepting pollutants discharged from WWTP, some factors, such as discharge outlet, terrain characteristics, and administrative division were considered. The volume of receiving water was approximately 8.7 × 10^7 m^3. Additionally, according to the future functional orientation of receiving water, the marine Grade III standard was considered as the upper limit of receiving water. Based on these hypothesis, multiple mathematical models were combined to estimate the WECs of organic and nutrients (nitrogen and phosphorus) [Eqs. (2)–(4)], and the remaining WEC can be obtained by deducting the background of receiving water and the pollutants from water exchange process.

As shown in Fig. 5, the WEC of receiving water was approximately 13154.99 t COD/a, 1604.00 t TN/a, 481.00 t NH_4^+-N/a, and 110.00 t TP/a, however, more than or nearly half of WEC has been used up these days with rapid economic development. Considering the potential increase of land-sourced pollutants into water body, the carrying capacity of receiving water towards pollutants will be further weakened if still executing national Grade 1-B discharge standard. This may potentially damage the aquatic environment so as to reduce biological diversity and hinder the development of related industries (tourism and aquaculture). It was hypothesized that only 5% of pollutants imported into receiving water would be remaining after water exchange and microbial degradation each year between 2016–2019 [20,25]. Therefore, by 2020, the remaining WEC will become approximately 5565.39 t COD/a, 1003.22 t TN/a, 271.01 t NH_4^+-N/a, and 35.39 t TP/a. However, the total pollution loads from WWTP effluent, non-point pollution, and shipping/transportation into receiving water will attain to 2326.51 t COD, 483.70 t TN, 104.41 t NH_4^+-N, and 39.28 t TP in 2020 (Table S3). The amount of TP into receiving water will possibly exceed the acceptable limit of water body during some periods which means a potential risk of water environment damage. Once the aquatic ecosystem is completely destroyed, it will be difficult to recover to the initial situation of water body in a short time. Reducing pollution discharge of WWTP must be paid special attentions to maintain a certain self-purification capacity of water body.

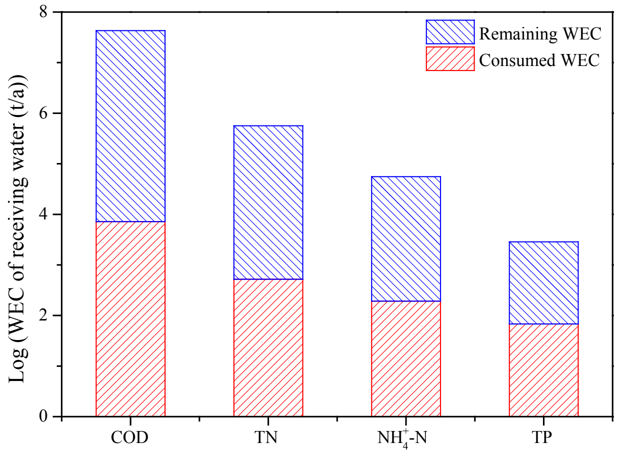

Fig. 5. Remaining and consumed water environment capacity (WEC) of receiving water by 2016 based on multi-models analysis (t/a). COD: chemical oxygen demand, TN: total nitrogen, NH_4^+-N: ammonium, and TP: total phosphorus.

3.4. Determining the optimal sewage discharge standard for study WWTP

Based on the WEC estimation and pollution source apportionment of receiving water discussed above, the maximum acceptable pollutant concentration of WWTP effluent was determined by backward inference method, and this can be regarded as an important quantitative basis for the selection of new sewage discharge standards (Table 4). As shown in Table 4, the maximum acceptable concentrations of TN, NH_4^+-N, and TP are all below the limit of national Grade 1-B discharge standard. This elucidates that national Grade 1-B discharge standard is really not suitable as the implemented standard of study WWTP for aquatic ecosystem protection. Moreover, national Grade 1-A discharge standard can not also meet the requirement of NH_4^+-N limit, therefore,the study WWTP should execute a stricter discharge standard than national Grade 1-A.

Fig. 6 shows the box-plot of effluent quality of WWTP on the basis of current operation process. The effluent concentration of COD can be controlled below 40 mg/L during

Table 4
The proposed sewage discharge standard of study wastewater treatment plant (WWTP) and related reference standards. COD: chemical oxygen demand, TN: total nitrogen, NH_4^+-N: ammonium, and TP: total phosphorus

Pollutants		COD mg/L	TN mg/L	NH_4^+-N mg/L	TP mg/L
Maximum acceptable discharge concentration of WWTP for water protection		86.05	19.38	4.87	0.67
Reference standards	National special discharge limits	30	15	3.0	0.3
	National Grade 1-A discharge standard	50	15	5.0	0.5
	National Grade 1-B discharge standard	60	20	8.0	1.0
	Guangdong Province discharge limits	40	–	10	–
	Beijing B standard	30	15	1.5	0.3
The proposed standard in this study		40	15	4.0	0.3

Note: The temperature of receiving water exceeds 12°C for most time in Shenzhen.

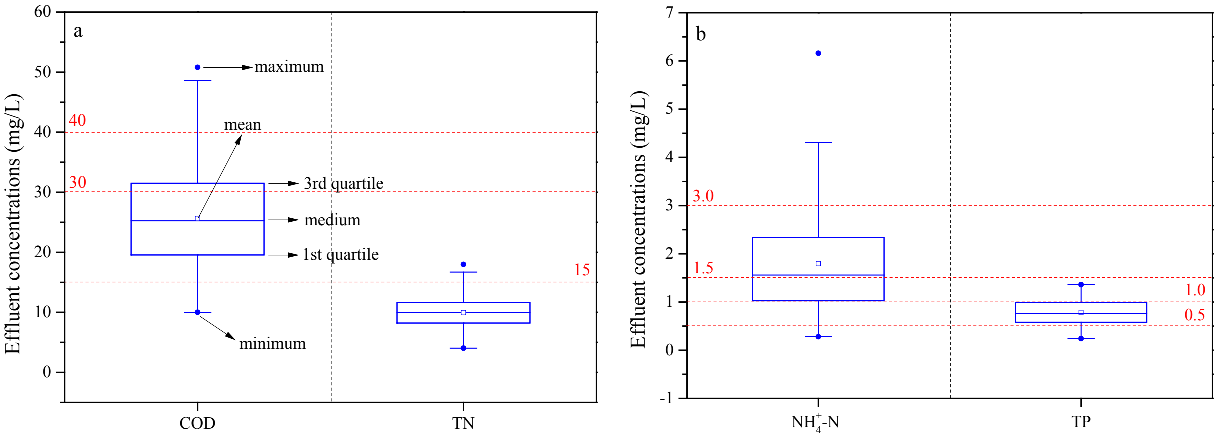

Fig. 6. Box-plot of water quality of study wastewater treatment plant (WWTP) effluent in 2016 (mg/L): a) chemical oxygen demand (COD) and total nitrogen (TN), b) ammonium (NH_4^+-N) and total phosphorus (TP).

approximately 96.2% time of one year and it can just fit to the requirement of Guangdong Province discharge limits (Fig. 6a and Table 4). The WWTP has a relatively strong treatment capacity of TN with < 15 mg/L during approximately 97.8% time of one year (Fig. 6a). Hence, 15 mg/L can be selected as the limit of effluent TN and it is in line with the permissive limit of receiving water and related national/regional standards (Table 4). As for NH_4^+-N, the discharge limit at least below 4.87 mg/L should be selected to protect the aquatic ecosystem considering the rapid economic development of study city. The effluent NH_4^+-N concentration can be controlled below 4.0 mg/L during approximately 95.3% time of one year (Fig. 6b) and the effluent limit of 4.0 mg NH_4^+-N/L may be a good choice for study WWTP that can ensure the purification capacity of receiving water without any WWTP process change. Specially, the effluent TP concentration during more than 63% time of one year exceeded 0.67 mg/L (Fig. 6b) and it is imperative to develop advanced treatment process for strengthening phosphorus removal. Considering the powerful economic development potential of Shenzhen as an international metropolis, more pollutants may be drained into the receiving water in the future and a stringent discharge limit of TP for WWTP should be selected to realize society sustainable development. Referring to national special discharge limits and Beijing B standard, 0.3 mg/L was selected as the TP limit of WWTP effluent that can be easily attained based on existing advanced treatment technology, such as rear filters [26,27], new adsorbents [28], membrane bioreactor [29,30].

Overall, the proposed sewage discharge standard of study WWTP was 40 mg COD/L, 15 mg TN/L, 4.0 mg NH_4^+-N/L, and 0.3 mg TP/L.

3.5. Implications for WWTP upgrading

3.5.1. Renovation proposals of the study WWTP

The current MSBR process of study WWTP can fully meet the treatment requirements of COD, TN, and NH_4^+-N. Given that the effluent concentration of NH_4^+-N was below 3.0 mg/L during approximately 87.8% time of one year, the removal of NH_4^+-N for the WWTP still has a great increasing potential and more stringent discharge limit of 3.0 mg/L can also be achieved by slight adjustment of current process parameters, such as dissolved oxygen, hydraulic retention time, and sludge concentration [31–33]. Additionally, advanced treatment technologies should be supplemented into current treatment process for the removal of phosphorus so as to balance economic development and aquatic ecosystem protection. Overall, the partial renovation of study WWTP on the basis of maintaining the treatment capacity of current MSBR process is enough to ensure an eligible water quality of WWTP effluent.

3.5.2. A quantitative assessment method of sewage discharge standard of WWTPs

Fig. 7 summarized the selection process of sewage discharge standard combining WEC estimation and feasibility analysis. In this novel assessment method, it is a priority to protect the receiving water and its WEC value is firstly estimated as a quantitative reference for the selection of WWTP sewage discharge standard. Furthermore, feasibility analysis including national/regional discharge limits, actual operation conditions of WWTP, urban economic development, and technique level are also considered to help determine the optimal sewage discharge standard. The study WWTP in China's southern coast was considered as a case for a detailed introduction of this quantitative assessment method and it is expected to contribute to the selection of sewage discharge standard for other WWTPs in different regions using this method based on their actual situations.

4. Conclusions

Pollutants of receiving water mainly came from WWTP effluent and non-point pollution. WWTP effluent contributed more than 69.0% load of nutrients (nitrogen and phosphorus) to receiving water, while non-point pollution may play a relatively important role in organic pollution with 58.3% contribution compared with WWTP effluent. The reduction of land-sourced pollutants should be paid special attentions to protect the aquatic ecosystem.

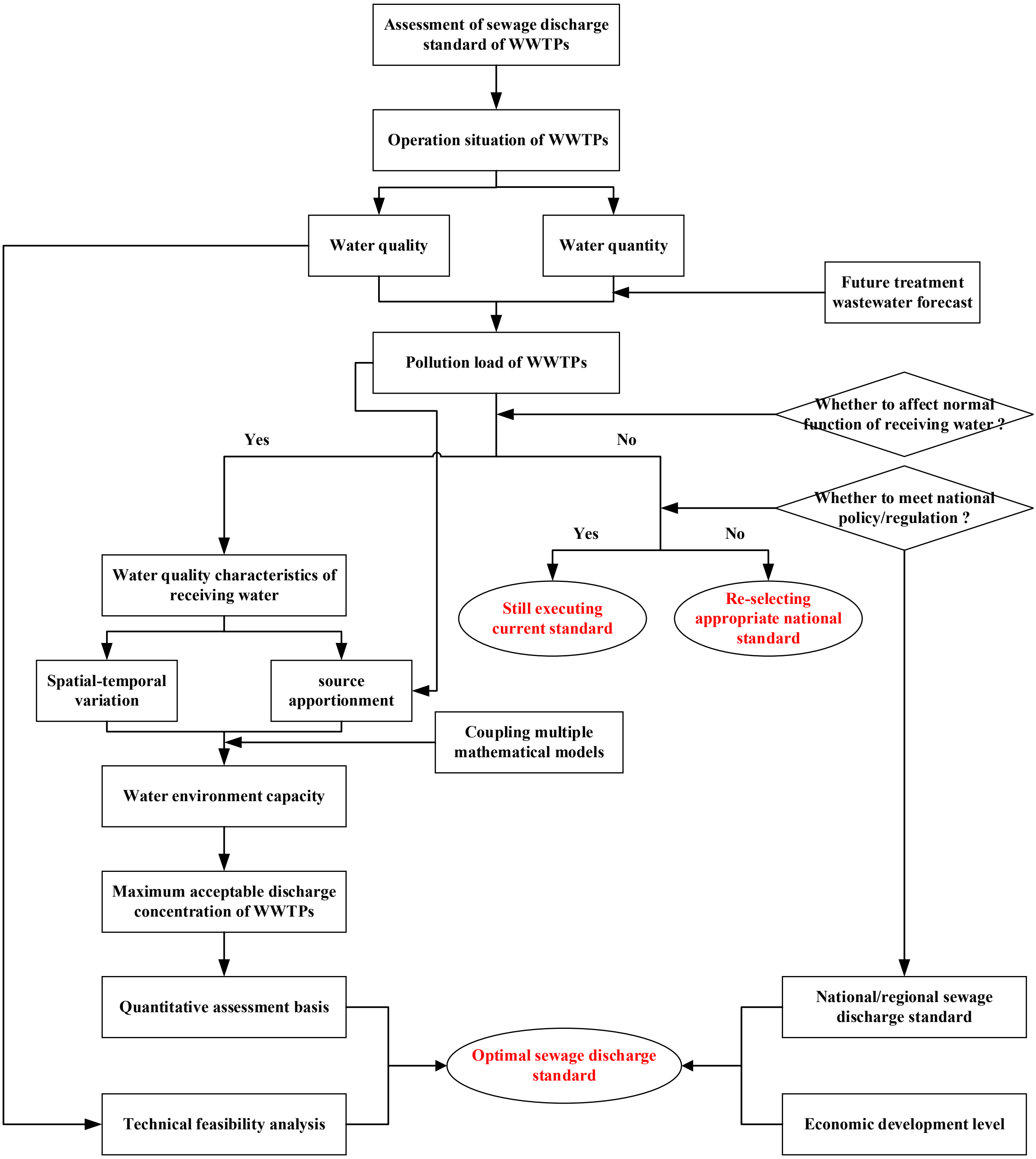

Fig. 7. Flow chart of quantitatively determining new sewage discharge standard for wastewater treatment plants (WWTPs) combining water environment capacity (WEC) estimation and feasibility analysis.

The remaining WEC of receiving water estimated via mathematical models was approximately 5988.94 t COD/a, 1084.00 t TN/a, 289.00 t NH_4^+-N/a, and 42.00 t TP/a by 2016. If still executing national Grade 1-B discharge standard for this WWTP, the amount of pollutants (i.e., TP) into receiving water will exceed the remaining WEC in 2020.

The remaining WEC can be regarded as a quantitative basis for the selection of WWTP sewage discharge standard. The quantitative assessment method combining WEC estimation and feasibility analysis was introduced in detail to determine the optimal sewage discharge standard. The proposed sewage discharge standard of study WWTP was 40 mg COD/L, 15 mg TN/L, 4.0 mg NH_4^+-N/L, and 0.3 mg TP/L.

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Supplementary information

Table S1
Container throughput and service population of study city/region for the prediction of future service population based on relative concentration index (*RCI)* value

Year		2010	2011	2012	2013	2014	2015	2016
Container throughput (×10^4 TEU)	Shenzhen	2250.96	2257.09	2294.13	2327.84	2403.74	2420.46	2397.93
	Yantian	1013.4	1026.44	1066.67	1101.23	1167.28	1216.57	1169.64
Regional service population (×10^4)	Shenzhen	891.23	1046.74	1054.74	1062.89	1077.89	1137.89	1190.84
	Yantian	20.91	21.10	21.26	21.39	21.65	22.12	22.65
RCI		19.19	22.56	23.07	23.51	24.18	25.86	25.64

Table S2
Urban storm water runoff quality in China. COD: chemical oxygen demand, TN: total nitrogen, NH_4^+-N: ammonium, and TP: total phosphorus

No.	City	Land uses	COD mg/L	TN mg/L	NH_4^+-N mg/L	TP mg/L	References
1	Shenzhen	Hill	16.47	1.09	0.76	0.09	This study
2		Harbor	81.62	1.74	1.45	0.27	
3		Harbor	64.43	2.45	1.52	0.48	
4		Road	115.95	2.30	1.81	0.30	
5		Road	66.04	1.42	1.13	0.43	
6		Road	85.31	1.28	0.98	0.22	
7		Road	77.18	2.85	2.02	0.39	
8	Changzhou	Road	38.5–90	2.16–3.79	0.12–0.6	0.38–1.18	[1]
9	Beijing	Roof	140.13	8.21			[2]
10		Grass	120.37	6.80		0.74	
11		Road	140.18	6.89		0.61	
12	Chongqing	Roof	54.4–59		2.7–2.9	0.04–0.05	[3]
13		Grass	23		1.6	0.21	
14		Road	33–76.3		2.8–3.7	0.08–0.24	
15	Changsha	Roof	10–316	0.05–8.60		0.01–0.034	[4]
16		Grass	4–26.88				
17		Road	50–638.40	0.67–4.80		0.04–0.065	
18	Xiamen	Grass	60.48		0.88	0.44	[5]
19	Macau	Grass	165.77		0.92	0.96	
20	Neijiang	Roof	86	3.63	2.03	0.13	[6]
21		Road	209–215	4.06–4.37	2.29–2.55	0.35–0.40	
22	Guangzhou	Roof	31–87	1.02–5.96		0.10–0.47	[7]
23		Grass	48–181	1.56–2.31		0.46–1.89	
24		Road	42–193	0.95		0.15–0.30	
25	Cili	Hill		0.7	0.1	0.2	[8]
26	Lin’an	Hill	1.569	0.085	0.023	0.034	[9]

Table S3
The total amount of pollutants into the receiving water in 2020 based on Grade 1-B discharge standard. WWTP: wastewater treatment plant, COD: chemical oxygen demand, TN: total nitrogen, NH_4^+-N: ammonium, and TP: total phosphorus

Pollutants		COD	TN	NH_4^+-N	TP
Sources	WWTP effluent (t/a)	1140.14	437.07	78.87	34.24
	Non-point pollution (t/a)	1161.58	38.99	23.89	4.71
	Shipping/transportation (t/a)	24.79	7.64	1.65	0.33
Total (t/a)		2326.51	483.70	104.41	39.28

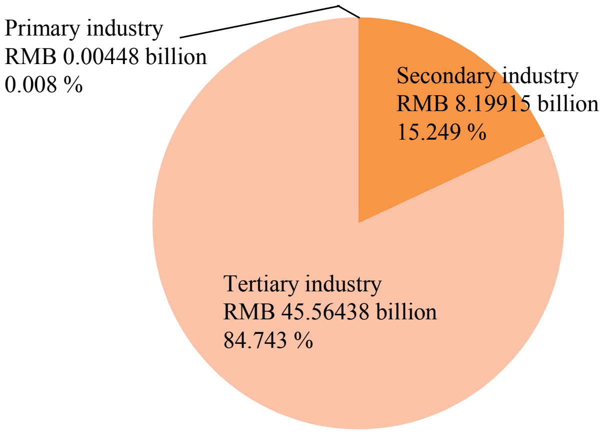

Fig. S1. Industrial structure of the service area of study wastewater treatment plant in 2016.

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