Front. Environ. Sci. Eng. 2019, 13(6): 83
https://doi.org/10.1007/s11783-019-1167-7

RESEARCH ARTICLE

Characteristic and correlation analysis of influent and energy consumption of wastewater treatment plants in Taihu Basin

Luxi Zou[1], Huaibo Li[1], Shuo Wang (✉)[1,2,3], Kaikai Zheng[1], Yan Wang[1], Guocheng Du[4], Ji Li (✉)[1,2]

1 Jiangsu Key Laboratory of Anaerobic Biotechnology, School of Environment and Civil Engineering, Jiangnan University, Wuxi 214122, China
2 Jiangsu College of Water Treatment Technology and Material Collaborative Innovation Center, Suzhou 215009, China
3 Department of Civil Engineering, Schulich School of Engineering, University of Calgary, Calgary T2N 1N4, Canada
4 Ministry Key Laboratory of Industrial Biotechnology, School of Biotechnology, Jiangnan University, Wuxi 214122, China

HIGHLIGHTS

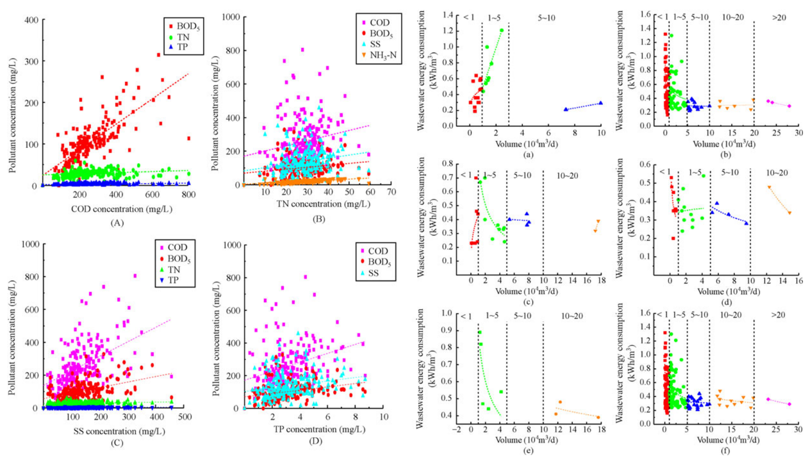
- Poor biodegradability and insufficient carbon source are discovered from influent.
- Influent indices presented positively normal distribution or skewed distribution.
- Average energy consumption of WWTPs in Taihu Basin was as high as 0.458 kWh/m^3.
- Energy consumption increases with the increase in influent volume and COD reduction.
- The total energy consumption decreases with the NH_3-N reduction.

ARTICLE INFO

Article history:
Received 27 June 2019
Revised 15 September 2019
Accepted 19 September 2019
Available online 29 October 2019

Keywords:
Taihu Basin
Wastewater treatment plant
Influent characteristics
Energy consumption evaluation
Specific energy consumption
SPSS correlation analysis

GRAPHIC ABSTRACT



ABSTRACT

The water quality and energy consumption of wastewater treatment plants (WWTPs) in Taihu Basin were evaluated on the basis of the operation data from 204 municipal WWTPs in the basin by using various statistical methods. The influent ammonia nitrogen (NH_3-N) and total nitrogen (TN) of WWTPs in Taihu Basin showed normal distribution, whereas chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), suspended solid (SS), and total phosphorus (TP) showed positively skewed distribution. The influent BOD_5/COD was 0.4%–0.6%, only 39.2% SS/BOD_5 exceeded the standard by 36.3%, the average BOD_5/TN was 3.82, and the probability of influent BOD_5/TP>20 was 82.8%. The average energy consumption of WWTPs in Taihu Basin in 2017 was 0.458 kWh/m^3. The specific energy consumption of WWTPs with a daily treatment capacity of more than 5×10^4 m^3 in Taihu Basin was stable at 0.33 kWh/m^3. A power function relationship was observed between the reduction in COD and NH_3-N and the specific energy consumption of pollutant reduction, and the higher the pollutant reduction is, the lower the specific energy consumption of pollutant reduction presents. In addition, a linear relationship existed between the energy consumption of WWTPs and the specific energy consumption of influent volume and pollutant reduction. Therefore, upgrading and operation with less energy consumption of WWTPs is imperative and the suggestions for Taihu WWTPs based on stringent discharge standard are proposed in detail.

1 Introduction

Taihu Basin, which is an important part of the Yangtze River Delta urban agglomeration, has a total area of 36500 km^2 and a population of approximately 34 million. The basin with less than 0.4% of the land area has

✉ Corresponding authors
E-mail: shuowang@jiangnan.edu.cn (S. Wang);
liji@jiangnan.edu.cn (J. Li)

Special Issue—China Urban Water Environment and Water Ecology (Responsible Editors: Shubo Deng & Huijuan Liu)

generated nearly one-eighth of the gross national product, which has become one of the most dynamic and open regions in China (Zhang et al., 2010). With the acceleration of industrialization and urbanization in Taihu Basin, industrial and domestic wastewater discharges have caused serious water environmental pollution problems (Cheng et al., 2016). In May 2018, Jiangsu Province issued a new local standard called "Discharge Limitation of Major Water Pollutants in Urban Wastewater Treatment Plants (WWTPs) and Key Industries in Taihu Region (DB32/ 1072-2018)" to reduce the ecological risks. Analyzing the influent water quality and energy consumption of WWTPs is imperative to promote upgrading of these plants, saving energy, and reducing consumption.

The concentration of pollutants in the effluent of WWTPs is not only an important basis for the design and operation of wastewater treatment processes but also a necessary condition for ensuring the stability of effluent to meet the treatment objectives (Caniani et al., 2015). Therefore, the characteristics of the influent water quality of WWTPs have been extensively studied to enhance contaminant removal and environmental protection. Shapiro–Wilk test and skewness coefficient could be used to analyze the water quality characteristics of WWTPs and concluded that the distribution of biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), suspended solid (SS), ammonia nitrogen (NH_3-N), total nitrogen (TN), and total phosphorus (TP) is positively skewed (Lu et al., 2019). Pearson correlation coefficient analysis was applied to systematically analyze the influent quality characteristics of WWTPs in a distributary drainage area of Kunming City, and the results showed a significant correlation between SS and BOD_5, TP, and COD in the distributary drainage area (Sun et al., 2013). Olsen et al. (2012) conducted principal component analysis to the influent water of WWTPs in the Illinois River Basin. The qualitative characteristics were investigated, and the results showed a correlation among several influent pollutants in these plants.

The energy of wastewater treatment is consumed mostly by power, chemical, and sludge treatment and disposal processes (Venkatesh and Brattebø, 2011a; Dąbrowski et al., 2017). Scientific and reasonable evaluation of energy consumption of WWTPs is the basis for realizing energy saving and consumption reduction of wastewater treatment. Bravo and Ferrer (2011) adopted lifecycle assessment to analyze the entire lifecycle energy consumption of a WWTP in Barcelona Metropolitan Area and proposed measures to improve its energy consumption. The performance of wastewater treatment process could be discovered according to the energy consumption, the use of economy, technology and management indices is feasible to evaluate the characteristics of wastewater treatment process (Hao et al., 2018), which could lay the foundation for the rationalization of wastewater treatment application.

The influent could not be well treated if the influent volume exceeded the designed flow rate of MBR process (Miyoshi et al., 2018), therefore, the capital and operational cost of WWTPs would further increase when stablishing regulation tank or adopting more membrane modules.

In the current study, 204 WWTPs with different processes and treatment capacities in Taihu Basin were investigated. The variation regularity and probability statistics of influent water quality characteristics of raw water from the plants were systematically analyzed. The correlation among organic matter, nitrogen, phosphorus, and suspended substances was also evaluated. The present situation of energy consumption and specific energy consumption in accordance with influent volume and contaminants reduction of WWTPs in Taihu Basin were explored. In addition, the relationship between contaminant reduction and energy consumption was constructed. Finally, the operational suggestions for enhancing contaminant removal by the optimization of WWTPs were proposed, thereby providing basic information for the upgrading of WWTPs in Taihu Basin.

2 Materials and methods

2.1 Data sources

In this study, 204 municipal WWTPs in Taihu Basin of Jiangsu Province were selected as the research objects. The distribution of these plants is shown in Table 1. The data were obtained from the information reported by the WWTPs in the municipal wastewater treatment management information system from the Ministry of Housing, Urban and Rural Construction, China. All the data were pretreated and screened to eliminate outliers, and random sampling survey was carried out to ensure the reliability of the data.

2.2 Evaluation index

The influent water quality analysis was based on the actual raw water quality data of the entire year in 2017. Normal distribution and regression analyses were conducted with six contaminant indicators of water quality, namely, COD, BOD_5, SS, NH_3-N, TN, and TP. Specific energy consumption analysis was also performed with COD and NH_3-N as contaminant indicators. The specific energy consumption based on treatment volume and contaminant removal was used to evaluate the energy consumption of WWTPs in Taihu Basin.

2.3 Data processing

The characteristics of influent quality and energy consumption of WWTPs were evaluated through statistical

Table 1 Distribution of WWTPs in Taihu Basin

Water treatment capacity (10^4 m^3/d)	Number				
	Nanjing	Wuxi	Changzhou	Suzhou	Zhenjiang
>20	0	2	1	1	0
10–20	0	5	2	5	0
5–10	1	5	3	17	2
1–5	2	34	11	55	8
< 1	12	5	15	8	10

analysis, including normal distribution, regression analysis, and cluster analysis in Statistical Product and Service Solutions (SPSS 22.0). The normal distribution used kurtosis, skewness and Shapiro-Wilk methods to test the normality of data. The regression analysis adopted the least square method to fit the actual operation data linearly, and obtained the regression equation and R^2 between the pollutants. K-Means fast clustering method was used in cluster analysis, and K = 3 was set and the number of iterations was 5 times for statistical analysis of data.

3 Results and discussion

3.1 Influent quality of WWTPs in Taihu Basin

3.1.1 Basic index analysis

The data analysis of 204 WWTPs in Taihu Basin in Table 2 reveals that the average influent COD concentration is 259.96 mg/L, BOD_5 concentration is 103.51 mg/L, SS concentration is 137.95 mg/L, NH_3-N concentration is 21.37 mg/L, TN concentration is 28.94 mg/L, and TP concentration is 3.16 mg/L. Compared with the average influent quality of typical WWTPs in China, the influent contaminant concentrations of WWTPs in Taihu Basin are remarkably lower than the average of national WWTPs except for COD and BOD_5 concentrations (Liao et al., 2015). The effluent contaminant concentrations of WWTPs in Taihu Basin are not only better than the first A discharge standard (GB18918-2002) but also are superior to those of water pollution discharge limits of the first and second protected areas in Taihu Basin. Among them, municipal WWTPs have the highest SS removal rate and the largest COD reduction; however, the reduction in TN and TP is significantly lower. The average value of BOD_5/TN is 3.58, and the average value of BOD_5/TP is 39.26, however, both of the values are insufficient for simultaneous biological removal of TN and TP.

3.1.2 Influent characteristics

The statistical results of COD, BOD_5, SS, NH_3-N, TN, and TP and the normality test analysis of the annual average influent quality indexes of Taihu Basin WWTPs in 2017 are shown in Table 3 that presents the Kolmogorov–Smirnov and Shapiro–Wilk statistics. The value of Shapiro–Wilk test is generally highly accurate when the sample size is less than 1000. In addition, the index is considered to obey normal distribution when the significance level is more than 0.05 (Guner et al., 2009). The Shapiro–Wilk test shows that the significant levels of NH_3-N and TN are more than 0.05 and obey normal distribution. By contrast, the significant levels of COD, BOD_5, SS, and TP are less than 0.05, respectively, which imply skewed distribution (Yang et al., 2017). The skewness and kurtosis coefficients of COD, BOD_5, SS, and TP indicators are above 0, which indicate that the data distributions of COD, BOD_5, SS, and TP indicators are positively skewed (Joanes and Gill, 1998; Hae-Young, 2013). The distribution law of influent contaminants of WWTPs in Taihu Basin were shown in Fig. 1. The average and typical representative values of influent contaminant concentrations of WWTPs in Taihu Basin are reflected. According to Figs. 1(a)–1(f), the influent COD concentration of WWTPs fluctuates from 59.31 mg/L to 804.51 mg/L in Taihu Basin, 50% of the influent COD of WWTPs is less than 228.09 mg/L, and 80% of the influent COD of WWTPs is less than

Table 2 Wastewater quality analysis of influent and effluent of WWTPs in Taihu Basin

Pollution	Influent (mg/L)	Effluent (mg/L)	Removal rate (%)	Reduction quantity (t)	National mean (mg/L)
BOD_5	103.51	5.05	95.12	1161.40	81.64
COD	259.96	26.28	89.89	2731.64	219.97
SS	137.95	6.49	95.30	1389.83	148.54
NH_3-N	21.37	1.02	95.23	234.39	22.83
TN	28.94	8.50	70.63	230.12	30.36
TP	3.16	0.18	94.30	37.92	3.70

Table 3 Statistical analysis and normality test of influent quality

Pollution	*N*	Average (mg/L)	Intermediate (mg/L)	Standard deviation (mg/L)	Skewness	Kurtosis	Kolmogorov–Smirnov Sig.	Shapiro–Wilk Sig.
BOD_5	204	103.51	97.21	52.98	1.341	2.963	0.000	0.000
COD	204	259.96	230.32	128.79	1.418	2.747	0.000	0.000
SS	204	137.95	122.17	72.81	1.127	2.021	0.000	0.000
NH_3-N	204	21.37	21.78	7.09	–0.085	–0.328	0.200	0.107
TN	204	28.94	29.13	8.25	0.257	0.614	0.200	0.195
TP	204	3.16	2.80	1.56	1.097	1.395	0.000	0.000

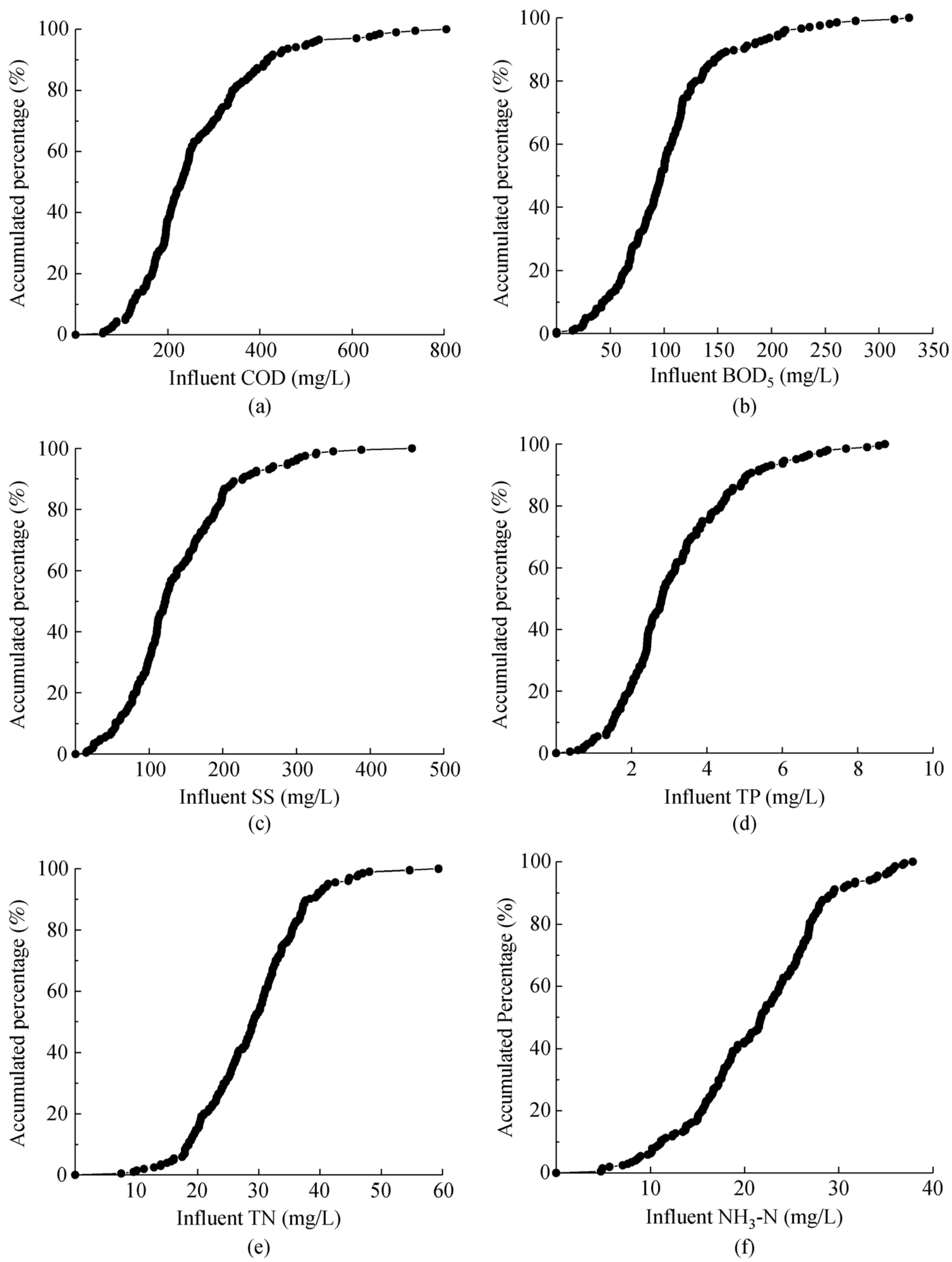


Fig. 1 Distribution law of influent pollutants in WWTPs at Taihu Basin: COD (a), BOD_5 (b), SS (c), TP (d), TN (e), NH_3-N (f).

340.02 mg/L. The influent BOD_5 fluctuates in the range of 0–327.95 mg/L, 50% of the influent BOD_5 of WWTPs is less than 96.52 mg/L, and 80% of the influent BOD_5 of WWTPs is less than 129.35 mg/L. Moreover, the influent SS fluctuates from 14.49 mg/L to 456.9 mg/L, 50% of the influent SS of WWTPs is less than 120.96 mg/L, and 80% of the influent SS of WWTPs is less than 190.38 mg/L. The influent NH_3-N fluctuates in the range of 4.74–37.86 mg/L, 50% of the WWTPs have influent NH_3-N < 21.71 mg/L, and 80% of the WWTPs have influent NH_3-N < 26.92 mg/L. The influent TN fluctuates in the range of 7.53–59.36 mg/L, 50% of the influent TN of WWTPs is less than 29.02 mg/L, and 80% of the influent TN of WWTPs is less than 35.41 mg/L. The influent TP fluctuates in the range of 0.37–8.72 mg/L, 50% of the effluent TP is less than 2.79 mg/L, and 80% of the effluent TP is less than 4.37 mg/L.

The data above indicate that influent COD and BOD_5 concentrations of WWTPs in Taihu Basin are low. This condition easily leads to insufficient carbon source in the influent water of WWTPs and can not effectively provide carbon source for efficient nitrogen and phosphorus removal of WWTPs (Zhao et al., 2018b). This situation is mainly due to the incomplete distribution of urban rainwater and wastewater in Taihu Basin, leakage of the underground pipeline network, and high level of groundwater (Zhao et al., 2013). Therefore, the WWTPs in Taihu Basin generally require additional carbon sources for the efficient removal of nitrogen and phosphorus from wastewater.

3.1.3 Proportional relationship of influent nutrients

In general, BOD_5/COD is used to evaluate the biodegradability of influent from WWTPs and reflects the ratio of biodegradable organic matter to total organic matter from influent. Wastewater is unsuitable for biological treatment when BOD_5/COD is lower than 0.1; refractory biodegradable pollutants are present in wastewater when BOD_5/COD ranges from 0.2 to 0.4; the biodegradability of wastewater is good when BOD_5/COD is between 0.4 and 0.6 (Samudro and Mangkoedihardjo, 2010). As shown in Fig. 2(a), BOD_5/COD fluctuates between 0.07 and 1.44 and has an average value of 0.42 and a median value of 0.39. A total of 39.2% of the WWTPs have BOD_5/COD between 0.4 and 0.6, and 7.4% of them have a BOD_5/COD ratio higher than 0.6. The results show that the influent of WWTPs in Taihu Basin is suitable for biological treatment. However, the overall biodegradability of the influent is relatively poor and leads to low capacity of biological treatment. The reason may be due to leakage of the underground pipeline network and the dilution of groundwater.

SS/BOD_5 mainly reflects the effect of influent SS on sludge yield and activity (Spérandio et al., 2013). The bioactivity of activated sludge decreases with the increase in influent SS/BOD_5, thereby affecting the efficiency of contaminant removal. The denitrification capacity of WWTPs will decrease when SS/BOD_5 is higher than 1.2. The reason is that high SS/BOD_5 leads to the low utilization rate of carbon source in denitrification stage. The denitrification effect will worsen when the carbon source is largely consumed for the growth of activated sludge (Boltz et al., 2012). Figure 2(b) shows that SS/BOD_5 of WWTPs in Taihu Basin ranges from 0.13 to 7.14 and has an average value of 1.52 and a median value of 1.33. A total of 42.2% of the WWTPs have a SS/BOD_5 ratio lower than 1.2, and 36.3% of them have a SS/BOD_5 ratio higher than 1.5. Only 21.5% of the WWTPs have SS/BOD_5 in the optimal range of 1.2–1.5. The results show that most of the WWTPs in Taihu Basin are responsible in reducing the microbial activity of activated sludge, which affects the efficient nitrogen and phosphorus removal of these plants.

C/N ratio is an important limiting factor that affects denitrification (Quan et al., 2018). Sufficient organic matter should be provided to increase the removal performance of TN for enhancing the denitrification capacity in anoxic tank. Nitrate can be effectively reduced to nitrogen gas when the influent BOD_5/TN ratio is higher than 2.86. However, the influent carbon source is considered adequate when the influent ratio is higher than BOD_5/TN>4 (Zhang et al., 2017; Ding et al., 2018). Figure 2(c) shows that the average value of BOD_5/TN is 3.82 and the median value is 3.33. A total of 33.8% of WWTPs have a BOD_5/TN ratio higher than 4, whereas 43.14% of WWTPs have a BOD_5/TN ratio lower than 3. Therefore, most WWTPs in Taihu Basin require additional carbon sources to improve denitrification capacity and facilitate effluent TN for meeting the discharge standard.

The effect of biological phosphorus removal is principally determined by the ratio of energy production from substrates and the total amount of phosphorus (López-Vázquez et al., 2008). The BOD_5/TP ratio is usually used to evaluate the feasibility of biological phosphorus removal (Wang et al., 2011). In general, the influent BOD_5/TP ratio higher than 20 can achieve good biological phosphorus removal; the energy produced by phosphorus-accumulating organisms in anaerobic tank can be stored as polyhydroxyalkanoates, which significantly enhance phosphorus uptake process in aerobic tank (Bru et al., 2017; Müller et al., 2017; Sun et al., 2017). The analysis of Fig. 2(d) reveals that the distribution of BOD_5/TP in the effluent of WWTPs in Taihu Basin ranges from 0 to 190.05, the average value is 39.26, and the median value is 31.02. A total of 82.8% of the influent BOD_5/TP ratio is higher than 20 from WWTPs in Taihu Basin. Therefore, the effluent of WWTPs in Taihu Basin can meet the requirements of biological phosphorus removal.

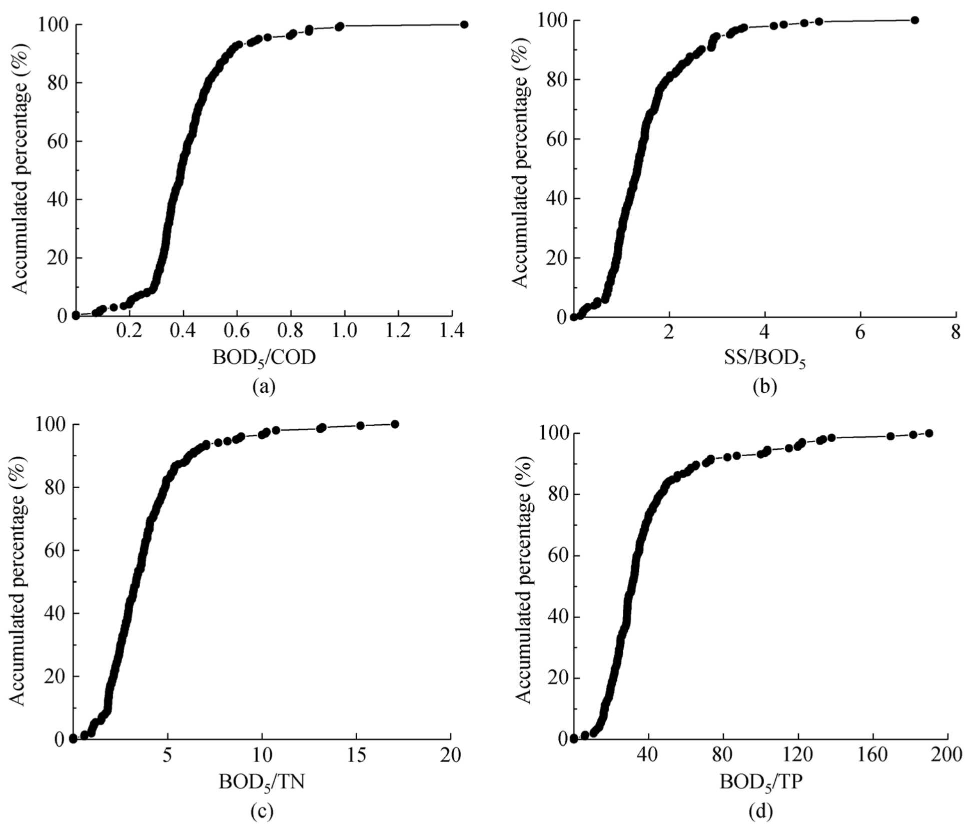


Fig. 2 Proportional relationship of nutrients in influent water: BOD_5/COD (a), SS/BOD_5 (b), BOD_5/TN (c), BOD_5/TP (d).

Table 4 Relevance and regression analysis of wastewater quality indicators

Water Quality Index	COD	SS	TN	NH_3-N	TP
BOD_5	$y = 0.2994x + 26.09$ $R^2 = 0.5397$	$y = 0.3276x + 58.75$ $R^2 = 0.2064$	$y = 0.9107x + 77.584$ $R^2 = 0.0205$	$y = 0.9557x + 83.509$ $R^2 = 0.0167$	$y = 9.3509x + 74.378$ $R^2 = 0.0774$
COD		$y = 0.8661x + 140.48$ $R^2 = 0.2397$	$y = 2.7144x + 181.41$ $R^2 = 0.0205$	$y = 2.5296x + 205.89$ $R^2 = 0.0194$	$y = 26.31x + 176.79$ $R^2 = 0.1017$
SS			$y = 1.7042x + 88.637$ $R^2 = 0.0373$	$y = 2.5228x + 84.029$ $R^2 = 0.0605$	$y = 10.04x + 106.22$ $R^2 = 0.0464$
TN				$y = 0.809x + 11.646$ $R^2 = 0.4840$	$y = 2.3775x + 21.423$ $R^2 = 0.2024$
NH_3-N					$y = 2.2134x + 14.378$ $R^2 = 0.2372$

3.1.4 Correlation of influent contaminants

On the basis of the average values of influent COD, BOD_5, SS, NH_3-N, TN, and TP indices of Taihu Basin WWTPs in 2017, the least square method was adopted to linearly fit the actual operation data. The correlation among influent contaminants was obtained. The corresponding regression equation and correlation coefficient (R^2) are shown in Table 4 and Fig. 3. Figure 3(a) shows that the linear fitting between COD and BOD_5 is good ($R^2 = 0.5397$), and the linear fitting degree with TP is general ($R^2 = 0.1017$). By contrast, no linear relationship exists between COD and TN ($R^2 = 0.0205$). The correlation analysis of COD and BOD_5 indicates that COD and BOD_5 are proportional, and COD concentration increases with the increase in BOD_5. As a result, the BOD_5/COD value decreases and contaminant removal is poor. Figure 3(b) shows that the correlation between TN and NH_3-N is evident ($R^2 = 0.484$), but no evident linear relationship exists with COD, BOD_5, and SS. Therefore, controlling influent NH_3-N and enhancing nitrification and denitrification efficiency are necessary to achieve efficient total nitrogen removal in WWTPs. Figure 3(c) shows that a certain linear relationship exists among SS, COD, and BOD_5, whereas SS index has nearly no linear relationship with TP and TN. Therefore, particles of COD and BOD_5 are formed in the influent of WWTPs in Taihu Basin. The influent SS concentration evidently affects the concentration of COD and BOD_5. TP and TN perform in dissolved state, and the influent SS slightly affects the concentrations of TP and TN. As shown in Fig. 3(d), the correlation between TP and COD, BOD_5, and SS is evident. Therefore, controlling the BOD_5/TP value of influent water is important to improve the efficiency of phosphorus removal.

3.2 Energy consumption analysis of WWTPs in Taihu Basin

3.2.1 Energy consumption status of WWTPs in Taihu Basin

Statistical results of energy consumption characteristic values of WWTPs in Taihu Basin in 2017 are shown in Table 5. At present, the energy consumption in Taihu Basin is mainly distributed between 0.2 and 0.5 kWh/m^3, which is higher than the average value of WWTPs in China (Tang et al., 2017). The Shapiro–Wilk test shows that the significant level of the total energy consumption index in Taihu Basin is more than 0.05, which obeys normal distribution.

K-means fast clustering was used to study the energy consumption distribution of 204 WWTPs. Under the condition of K = 3 and 5 iterations, the data of three final class centers are 0.34, 1.08, and 0.68, respectively. The ascending order of the data sets shows that the energy consumption of 149 WWTPs is lower than 0.51 kWh/m^3, whereas the energy consumption of 12 WWTPs is higher than 0.86 kWh/m^3. The results show that the energy consumption level of WWTPs in Taihu Basin is relatively uniform, and the energy consumption value of 0.51 kWh/m^3 can be used as a warning upper limit for the operation performance of these plants in Taihu Basin.

The average energy consumptions of WWTPs in

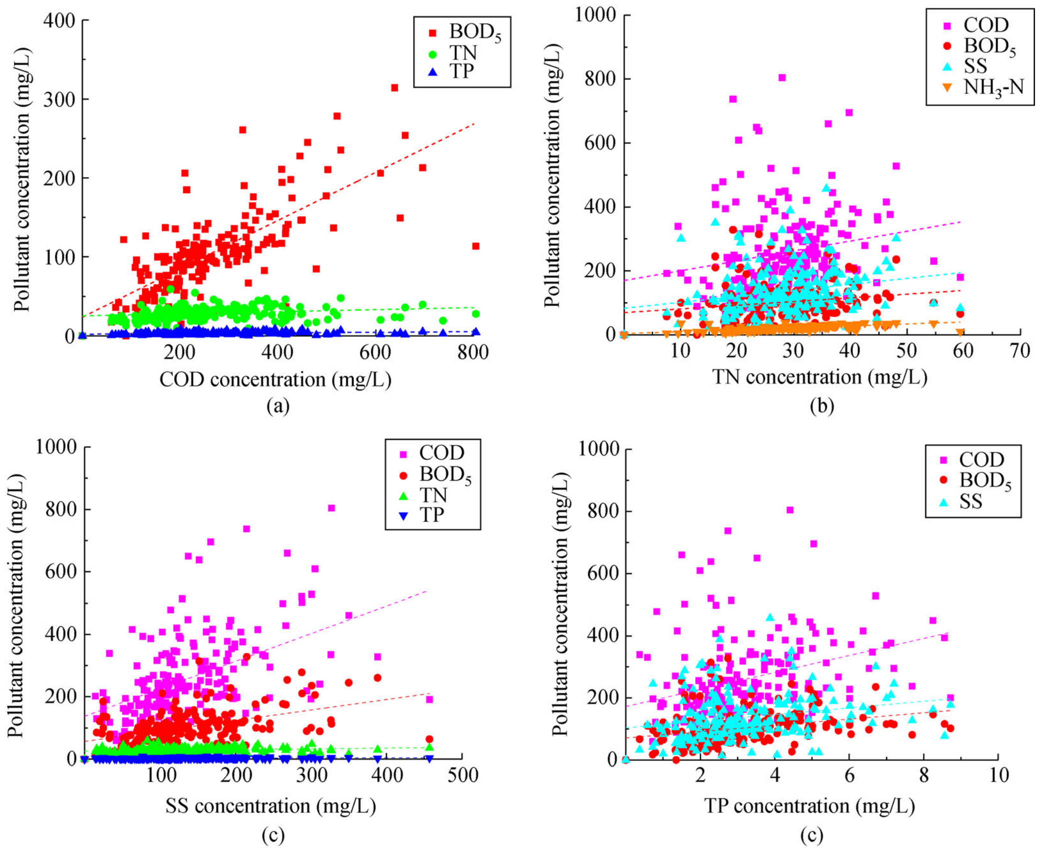


Fig. 3 Relevance of water quality indicators in influent Water: COD (a), TN (b), SS (c), TP (d).

Table 5 Energy consumption characteristics of WWTPs in Taihu Basin in 2017

Sample (*N*)	Minimum (kWh/m^3)	Maximum (kWh/m^3)	Average (kWh/m^3)	Standard Deviation (kWh/m^3)	Intermediate (kWh/m^3)	Kolmogorov-Smirnov Sig.	Shapiro-Wilk Sig.
204	0.16	1.32	0.458	0.225	0.385	0.158	0.051

developed countries are 0.20, 0.26, and 0.32 kWh/m^3 in the United States, Japan, and Germany, respectively (Mizuta and Shimada, 2010; Venkatesh and Brattebø, 2011b). The energy consumption is currently 0.306 kWh/m^3 in Strass WWTP (Austria), with the designed inflow rate of 1.7 × 10^4–3.8 × 10^4 m^3/d and adsorption–biodegradation process. Carbon neutralization operation mode is used in Strass WWTP, and the energy consumption is approximately 0.106 kWh/m^3. The average energy consumption of WWTPs in Taihu Basin in 2017 is 0.458 kWh/m^3, which there is still a relatively larger energy-saving space for the WWTPs in Taihu Basin.

3.2.2 Influent volume specific energy consumption

The treatment process of WWTPs in Taihu Basin can be divided into five common types: anoxic–oxic (AO), anaerobic–anoxic–oxic (AAO), oxidation ditch (OD), sequencing batch reactor (SBR), and membrane bioreactor (MBR) processes. Under the same treatment process, the influent volume of WWTPs can be divided into five grades: lower than 1 × 10^4, 1 × 10^4–5 × 10^4, 5 × 10^4–1 ×

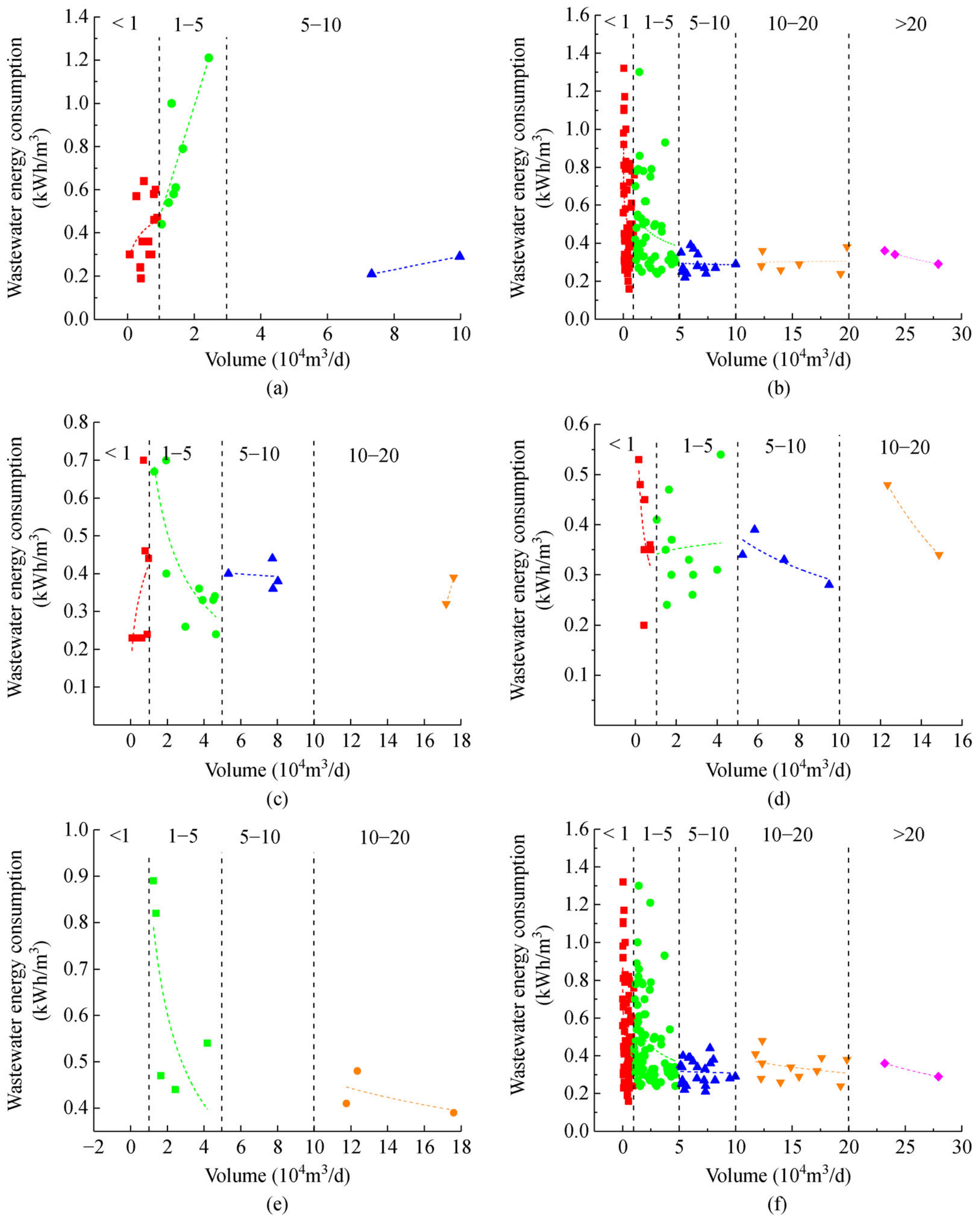


Fig. 4 Relation between energy consumption and wastewater treatment volume: A/O process (a), AAO process (b), Oxidation ditch process (c), SBR process (d), MBR process (e), All (f).

10^5, and 1×10^5–2×10^5 m^3/d and higher than 2×10^5 m^3/d. As shown in Figs. 4(a)–4(e) and Table 6, a power function relationship exists between the influent volume and the specific energy consumption in WWTPs of different scales. The specific energy consumption decreases with the increase in influent volume in AAO and MBR processes. However, the specific energy consumption increases with the increase in influent volume in AO process, OD process with influent volumes lower than 1×10^4 and 1×10^5–2×10^5 m^3/d, and SBR process with an influent volume of 1×10^4–5×10^4 m^3/d.

Figure 4(f) shows that the specific energy consumption of small WWTPs with an influent volume less than 5×10^4 m^3/d is dispersed, and many small WWTPs possess relatively low specific energy consumption. However, 42% of small WWTPs have higher specific energy consumption than the average value in Taihu Basin. In addition, the specific energy consumption is close (0.33 kWh/m^3) when the influent volume is larger than 5×10^4 m^3/d. The scale of influent volume and treatment process are not the key affecting factors of the specific energy consumption of WWTPs. The specific energy consumption of WWTPs may be related to the design and actual operation level of WWTPs.

3.2.3 COD specific energy consumption

COD removal in wastewater depends on the metabolism of heterotrophic bacteria in aerobic tank (Yin et al., 2017). COD in wastewater can be divided into two categories: degradable and refractory CODs. Degradable COD is generally removed at the forepart of aerobic tank, whereas refractory COD is gradually removed in aeration with the extension of hydraulic retention time (Xia et al., 2018).

The effluent COD concentration is divided into five zones: 15, 15–20, 20–30, 30–40, and 40–50 mg/L. The relationships between COD reduction and specific energy consumption are shown in Figs. 5(a)–5(f). The power function correlation between COD reduction and COD specific energy consumption is established. With the increase in COD reduction of WWTPs, the specific energy consumption for COD removal decreases first and then gradually stabilizes. This result is mainly due to the lack of precise aeration control strategy in WWTPs in Taihu Basin. The aeration system does not adjust the aeration volume in accordance with the actual influent COD concentration. Excessive aeration aggravates the waste of electric energy and thus increases the specific energy consumption of COD. With the increase in COD reduction, the specific energy consumption for COD removal maintains a stable value.

Table 7 describes the specific energy consumption for COD removal in different effluent COD concentration ranges. When the effluent COD ranges from 40 mg/L to 50 mg/L and from 30 mg/L to 40 mg/L, the average COD specific energy consumptions are 1.77 and 1.78 kWh/kg, respectively. However, the average COD specific energy consumption significantly increases when the effluent COD is lower than 30 mg/L. COD reduction of WWTPs is only correlated to COD specific energy consumption, and COD specific energy consumption largely depends on the energy consumption of aeration system.

3.2.4 NH_3-N specific energy consumption

The removal of NH_3-N in wastewater depends on the bioactivity of nitrifying bacteria in activated sludge by obtaining carbon source from CO_2 and energy from inorganic oxidation (Ding et al., 2013). The results show that heterotrophic bacteria are more competitive than nitrifying bacteria in substrate (O_2). Thus, the removal of NH_3-N is subjected to dissolved oxygen (DO) and further influences the conversion from NH_3-N to nitrate.

Therefore, the specific energy consumption of COD should not be used as the single index to evaluate the energy consumption of WWTPs. The specific energy consumption for NH_3-N removal may be suitable to reflect the energy consumption of WWTPs through nitrification. The effluent NH_3-N concentration can be divided into three intervals: 1, 1–3, and 3–5 mg/L. The relationship

Table 6 Functional relation between influent volume and specific energy consumption

Scale (10^4 m^3/d)	AO	AAO	OD	SBR	MBR
< 1	$y = 0.436x^{0.1642}$ $R^2 = 0.0917$	$y = 0.4013x^{-0.141}$ $R^2 = 0.132$	$y = 0.3809x^{0.2475}$ $R^2 = 0.351$	$y = 0.2896x^{-0.279}$ $R^2 = 0.2275$	
1–5	$y = 0.4675x^{1.0759}$ $R^2 = 0.6668$	$y = 0.5203x^{-0.253}$ $R^2 = 0.0747$	$y = 0.7683x^{-0.644}$ $R^2 = 0.6504$	$y = 0.3388x^{0.0163}$ $R^2 = 0.0009$	$y = 0.7922x^{-0.4}$ $R^2 = 0.3717$
5–10	$y = 1.372x^{0.9959}$ $R^2 = 1$	$y = 0.2917x^{-0.01}$ $R^2 = 0.0001$	$y = 0.4488x^{-0.066}$ $R^2 = 0.0226$	$y = 0.7525x^{-0.426}$ $R^2 = 0.6747$	
10–20		$y = 0.3035x^{-0.007}$ $R^2 = 0.0001$	$y = 1.1595x^{0.9562}$ $R^2 = 1$	$y = 51.245x^{-1.858}$ $R^2 = 1$	$y = 0.92x^{-0.295}$ $R^2 = 0.3601$
>20		$y = 12.754x^{-1.137}$ $R^2 = 0.9965$			

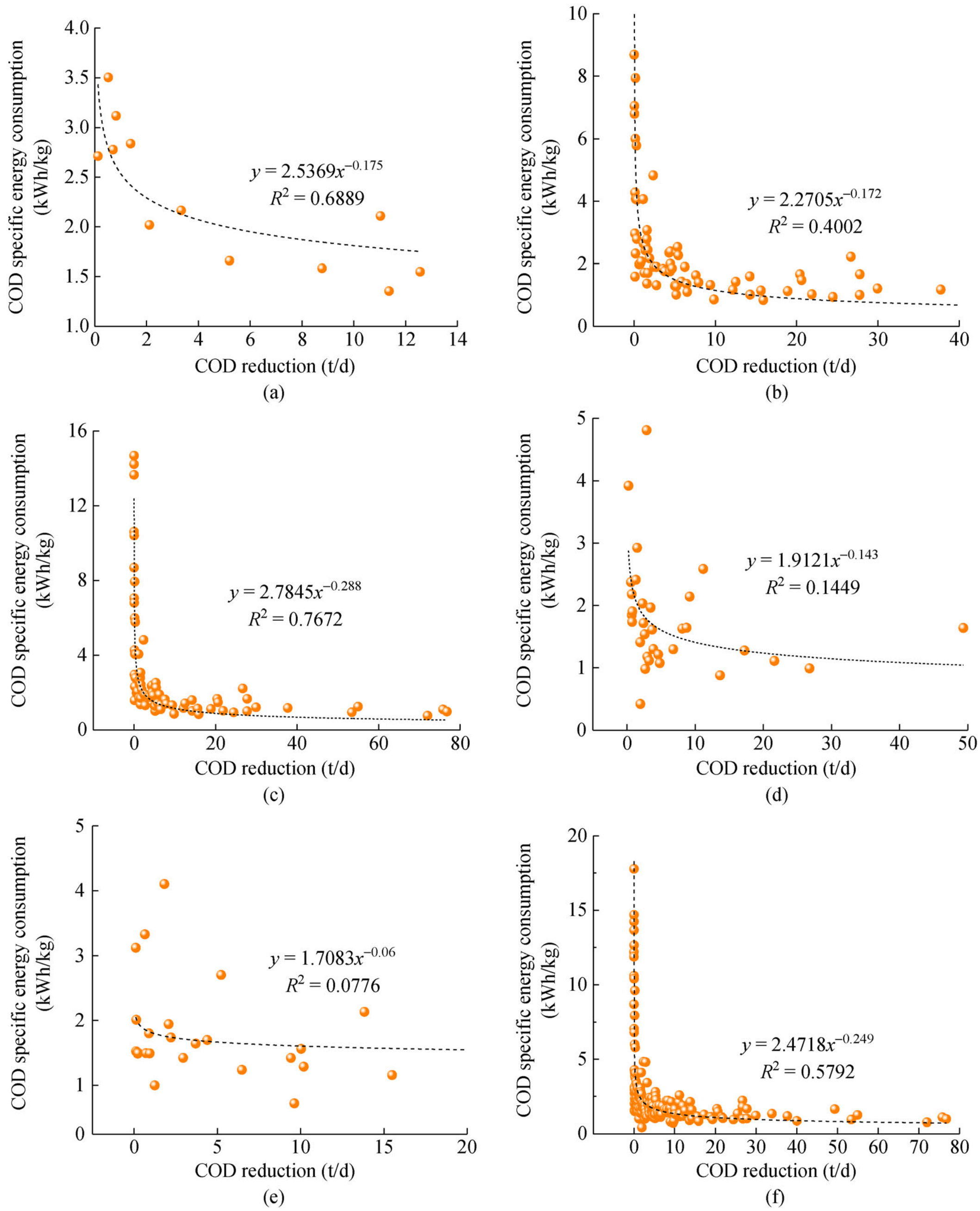


Fig. 5 Relation between COD specific energy consumption and COD reduction: < 15 mg/L (a), 15–20 mg/L (b), 20–30 mg/L (c), 30–40 mg/L (d), 40–50 mg/L (e), All (f).

between contaminant reduction and specific energy consumption in different intervals was analyzed. The results are shown in Figs. 6(a)–6(d). When the effluent NH_3-N is less than 1 mg/L, the correlation between NH_3-N reduction and NH_3-N specific energy consumption is good (R^2 = 0.5265). However, no correlation exists between NH_3-N reduction and NH_3-N specific energy consumption when effluent NH_3-N is 1–3 and 3–5 mg/L. With the increase in NH_3-N reduction, specific energy consumption decreases gradually first and then stabilizes owing to the poor control of aeration in WWTPs.

Table 8 lists the specific energy consumption of different effluent NH_3-N concentrations. When effluent NH_3-N ranges from 3 mg/L to 5 mg/L, the average NH_3-N specific energy consumption is 21.35 kWh/kg. However, the average NH_3-N specific energy consumption evidently increases when effluent NH_3-N is lower than 3 mg/L. Although the reduction in NH_3-N in WWTPs is correlated

Table 7 Relationship between effluent COD concentration and specific energy consumption

Effluent (mg/L)	COD specific energy consumption (kWh/kg)		
	Average	Minimum	Maximum
< 15	2.28	1.35	3.50
15–20	2.19	0.81	9.62
20–30	2.97	0.76	14.69
30–40	1.78	0.42	4.80
40–50	1.77	0.72	4.10

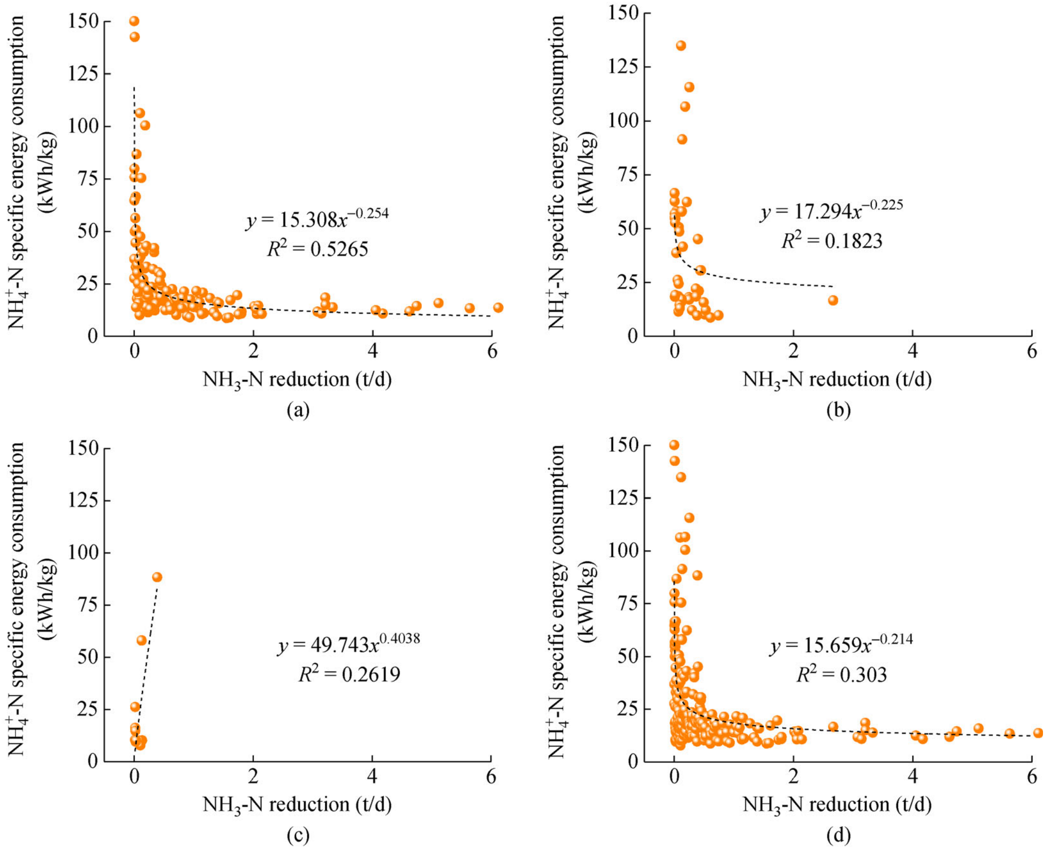


Fig. 6 Relation between NH_3-N specific energy consumption and NH_3-N reduction: (a) < 1 mg/L, (b) 1–3 mg/L, (c) 3–5 mg/L, (d) All.

with the specific energy consumption of NH_3-N, excessive aeration in WWTPs leads to relatively high energy consumption.

3.2.5 Relation between energy consumption and influent volume and contaminant removal

The energy consumption of WWTPs in Taihu Basin can be divided into two parts (Sid et al., 2017): wastewater lifting and aeration. Increasing the aeration rate to remove contaminants will increase the energy consumption from the aeration system. Therefore, influent volume and contaminant reduction were adopted to reflect the energy consumption of WWTPs. Regression analysis was used to quantify the relationship of WWTPs in Taihu Basin. The regression linear equation is shown in Eq. (1).

$$Y = 1480.1242 + 2221.7457X_1 + 0.5378X_2 - 1.9858X_3, \tag{1}$$

where Y represents the energy consumption, kWh/d; X_1 denotes the influent volume, 10^4 m^3/d; and X_2 and X_3 denote COD and NH_3-N reduction, kg/d.

The R^2 value of the regression linear equation is 0.968, and the linear fitting degree of Y with X_1, X_2, and X_3 is good. The equation shows that influent flow, COD, and NH_3-N reduction impact the total energy consumption of WWTPs. With the increase in influent volume and COD

Table 8 Relationship between effluent NH_3-N concentration and specific energy consumption

Effluent (mg/L)	NH_3-N Specific Energy Consumption (kWh/kg)		
	Average	Minimum	Maximum
< 1	35.78	8.70	150.12
1–3	37.40	8.68	134.85
3–5	21.35	7.79	88.36

reduction, the total energy consumption increases. By contrast, the total energy consumption decreases with the NH_3-N reduction.

3.3 Suggestions for Taihu WWTPs based on stringent discharge standard

3.3.1 Enhanced COD removal

The difficulty in enhancing COD removal is due to the removal of soluble and refractory COD from influent, which are generally derived from industrial wastewater. Therefore, analyzing the source of influent, such as upstream chemicals, pharmaceutical, and dyeing enterprises, is imperative. The treatment capacity of biological system can be enhanced by controlling sludge discharge, increasing sludge and age, and adding suspended carriers (Wang et al., 2019). The effluent soluble and refractory COD can be removed by applying additional advanced treatment processes, including coagulation sedimentation, advanced oxidation, and activated carbon/coke adsorption after secondary sedimentation tank.

3.3.2 Enhanced NH_3-N removal

Improving the removal rate of NH_3-N and ensuring that the effluent NH_3-N reaches the standard steadily are key and difficult points in upgrading WWTPs. Biological nitrification is affected by water temperature, DO, alkalinity, MLVSS/MLSS, and sludge concentration (Zhao et al., 2018a). Effluent NH_3-N is effectively maintained lower than 5 mg/L from WWTPs in summer. However, nitrification capacity is dramatically inhibited by low-temperature conditions. Therefore, the biomass retention, sludge age, and DO concentration in aerobic tank of WWTPs in Taihu Basin should be increased. The addition of suspended carriers is also beneficial to enrich nitrifiers and decrease the effluent NH_3-N in winter.

3.3.3 Enhanced TN removal

The removal efficiency of TN in WWTPs is mainly limited by the BOD_5/TN ratio from influent, and the discharge standard of TN is decreased from 15 mg/L to 10 mg/L. The B/C ratio from influent water in Taihu Basin is relatively low, which enhances the utilization of internal carbon sources. Adding external carbon sources is considered an effective method to facilitate nitrate reduction. Advanced treatment processes, such as denitrification filter or sulfur autotrophic denitrification (Zhu et al., 2019), can be used to enhance the removal of TN when the denitrification capacity of biological system can not meet the demand of denitrification.

3.3.4 Enhanced TP removal

The discharge standard of TP is decreased from 0.5 mg/L to 0.3 mg/L. The average BOD_5/TP of influent in Taihu area is 39.26, which can meet the requirements of biological phosphorus removal in most cases. Therefore, the influent carbon source is conducive to biological phosphorus removal. However, chemical phosphorus removal is supplemented when influent carbon source is insufficient. The possible reason is that the carbon source can be preferentially used for nitrogen removal (Gao et al., 2019). Chemical phosphorus removal can cooperate with the secondary biological treatment system or adopt post-chemical phosphorus removal mode. Furthermore, chemical phosphorus removal can inhibit biological phosphorus removal (Sun et al., 2019). Thus, the addition of chemicals should be applied separately to maintain the bioactivity of activated sludge.

4 Conclusions

Poor biodegradability and insufficient carbon source are discovered from the influent of WWTPs in Taihu Basin, controlling the influent should be prioritized in the new round of upgrading and renovation of urban WWTPs in Taihu Basin. The average energy consumption of WWTPs in Taihu Basin is higher than those in developed countries. With the increase in influent volume and COD reduction, the total energy consumption increases, conversely, the total energy consumption decreases with the NH_3-N reduction. The operation and optimization of WWTPs can facilitate their stable performance. Additional advanced treatment processes should be applied when the contaminant removal can not meet the stringent discharge standards.

Acknowledgements The authors gratefully acknowledge the contribution of Prof. Joo Hwa Tay from University of Calgary, the financial support provided by the Major Science and Technology Program for Water Pollution Control and Treatment (2017ZX07302-001), and the Fundamental Research Funds for the Central Universities (No. JUSRP51512).

References

Boltz J P, Morgenroth E, Daigger G T, deBarbadillo C, Murthy S, Sørensen K H, Stinson B (2012). Method to identify potential phosphorus rate-limiting conditions in post-denitrification biofilm reactors within systems designed for simultaneous low-level effluent nitrogen and phosphorus concentrations. Water Research, 46(19): 6228–6238

Bravo L, Ferrer I (2011). Life cycle assessment of an intensive WWTPs in Barcelona (Spain) with focus on energy aspects. Water Science and Technology, 64(2): 440–447

Bru S, Samper-Martín B, Quandt E, Hernández-Ortega S, Martínez-Laínez J M, Garí E, Rafel M, Torres-Torronteras J, Martí R, Ribeiro M P C, Jiménez J, Clotet J (2017). Polyphosphate is a key factor for cell survival after DNA damage in eukaryotic cells. DNA Repair, 57: 171–178

Caniani D, Esposito G, Gori R, Mannina G (2015). Towards a new decision support system for design, management and operation of WWTPs for the reduction of greenhouse gases emission. Water, 7(10): 5599–5616

Cheng L, Li X, Lin X, Hou L, Liu M, Li Y, Liu S, Hu X (2016). Dissimilatory nitrate reduction processes in sediments of urban river networks: Spatiotemporal variations and environmental implications. Environmental Pollution, 219: 545–554

Dąbrowski W, Żyłka R, Malinowski P (2017). Evaluation of energy consumption during aerobic wastewater sludge treatment in dairy WWTPs. Environmental Research, 153: 135–139

Ding A, Qu F S, Liang H, Ma J, Han Z S, Yu H R, Guo S D, Li G B (2013). A novel integrated vertical membrane bioreactor (IVMBR) for removal of nitrogen from synthetic wastewater/domestic sewage. Chemical Engineering Journal, 223(3): 908–914

Ding S Z, Bao P, Bo W, Zhang Q, Peng Y Z (2018). Long-term stable simultaneous partial nitrification, anammox and denitrification (SNAD) process treating real domestic sewage using suspended activated sludge. Chemical Engineering Journal, 339: 180–188

Gao H, Mao Y, Zhao X, Liu W T, Zhang T, Wells G (2019). Genome-centric metagenomics resolves microbial diversity and prevalent truncated denitrification pathways in a denitrifying PAO-enriched bioprocess. Water Research, 155: 275–287

Guner B, Frankford M T, Johnson J T (2009). A study of the Shapiro-Wilk Test for the detection of pulsed sinusoidal radio frequency interference. IEEE Transactions on Geoscience and Remote Sensing, 47(6): 1745–1751

Hae-Young K (2013). Statistical notes for clinical researchers: Assessing normal distribution (2) using skewness and kurtosis. Restorative Dentistry and Endodontics, 38(1): 52–54

Hao X, Li J, van Loosdrecht M C M, Li T (2018). A sustainability-based evaluation of membrane bioreactors over conventional activated sludge processes. Journal of Environmental Chemical Engineering, 6(2): 2597–2605

Joanes D N, Gill C A (1998). Comparing measures of sample skewness and kurtosis. Journal of the Royal Statistical Society, 47(1): 183–189

Liao Z, Hu T, Roker S A (2015). An obstacle to China's WWTPs: The COD and BOD standards for discharge into municipal sewers. Environmental Science and Pollution Research, 22(21): 16434–16440

López-Vázquez C M, Hooijmans C M, Brdjanovic D, Gijzen H J, van Loosdrecht M C M (2008). Factors affecting the microbial populations at full-scale enhanced biological phosphorus removal (EBPR) wastewater treatment plants in The Netherlands. Water Research, 42(10–11): 2349–2360

Lu J Y, Wang X M, Liu H Q, Yu H Q, Li W W (2019). Optimizing operation of municipal wastewater treatment plants in China: The remaining barriers and future implications. Environment International, 129: 273–278

Miyoshi T, Nguyen T P, Tsumuraya T, Tanaka H, Morita T, Itokawa H, Hashimoto T (2018). Energy reduction of a submerged membrane bioreactor using a polytetrafluoroethylene (PTFE) hollow-fiber membrane. Frontiers of Environmental Science & Engineering, 2018, 12(3): 1

Mizuta K, Shimada M (2010). Benchmarking energy consumption in municipal WWTPs in Japan. Water Science and Technology, 62(10): 2256–2262

Müller W E G, Wang S, Neufurth M, Kokkinopoulou M, Feng Q, Schröder H C, Wang X (2017). Polyphosphate as a donor of high-energy phosphate for the synthesis of ADP and ATP. Journal of Cell Science, 130(16): 2747–2756

Olsen R L, Chappell R W, Loftis J C (2012). Water quality sample collection, data treatment and Watershed case study. Water Research, 46(9): 3110–3122

Quan X, Huang K, Li M, Lan M C, Li B A (2018). Nitrogen removal performance of municipal reverse osmosis concentrate with low C/N ratio by membrane-aerated biofilm reactor. Frontiers of Environmental Science & Engineering, 12(6): 5

Samudro G, Mangkoedihardjo S (2010). Review on BOD, COD and BOD/COD ratio: A triangle zone for toxic, biodegradable and stable levels. International Journal of Academic Research, 2(4): 235–239

Sid S, Volant A, Lesage G, Heran M (2017). Cost minimization in a full-scale conventional WWTPs: Associated costs of biological energy consumption versus sludge production. Water Science and Technology, 76(9): 2473–2481

Spérandio M, Labelle M A, Ramdani A, Gadbois A, Paul E, Comeau Y, Dold P L (2013). Modelling the degradation of endogenous residue and 'unbiodegradable' influent organic suspended solids to predict sludge production. Water Science and Technology, 67(4): 789–796

Sun G, Zhang C, Li W, Yuan L, He S, Wang L (2019). Effect of chemical dose on phosphorus removal and membrane fouling control in a UCT-MBR. Frontiers of Environmental Science & Engineering, 13(1): 1

Sun J, Yang Q, Wang D, Wang S, Chen F, Zhong Y, Yi K, Yao F, Jiang C, Li S, Li X, Zeng G (2017). Nickel toxicity to the performance and microbial community of enhanced biological phosphorus removal system. Chemical Engineering Journal, 313: 415–423

Sun Y X, Wu G X, Hu H Y, Wu Y H, Guo F, Guo M Y (2013). Statistical analysis of the intake water quality characteristics of the WWTPs in the distribution system and drainage area of Kunming City. Journal of

Environmental Engineering, 7(8): 2885–2891
Tang Y, Guo L L, Hong C Y, Bing Y X, Xu Z C (2017). Seasonal occurrence, removal and risk assessment of 10 pharmaceuticals in two WWTPs of Guangdong, China. Environmental Technology, 40(4): 458–469
Venkatesh G, Brattebø H (2011a). Analysis of chemicals and energy consumption in water and wastewater treatment, as cost components: Case study of Oslo, Norway. Urban Water Journal, 8(3): 189–202
Venkatesh G, Brattebø H (2011b). Environmental impact analysis of chemicals and energy consumption in WWTPs: Case study of Oslo, Norway. Water Science and Technology, 63(5): 1018–1031
Wang J W, Zhang T Z, Chen J N, Hu Z R (2011). Retrofitting conventional primary clarifiers to activated primary clarifiers to enhance nutrient removal and energy conservation in WWTPs in Beijing, China. Water Science and Technology, 63(7): 1446–1452
Wang S, Qian K, Zhu Y, Yi X, Zhang G, Du G, Tay J H, Li J (2019). Reactivation and pilot-scale application of long-term storage denitrification biofilm based on flow cytometry. Water Research, 148: 368–377
Xia J, Wang H P, Stanford R L, Pan G Y, Yu S L (2018). Hydrologic and water quality performance of a laboratory scale bioretention unit. Frontiers of Environmental Science & Engineering, 12(1): 14
Yang S F, Zhou R, Lu S W (2017). A median loss control chart for monitoring quality loss under skewed distributions. Journal of Statistical Computation and Simulation, 87(17): 3241–3260
Yin X Q, Jing B, Chen W J, Zhang J, Liu Q, Chen W (2017). Study on COD removal mechanism and reaction kinetics of oilfield wastewater. Water Science and Technology, 76(9–10): 2655–2663
Zhang F Z, Peng Y Z, Miao L, Wang Z, Wang S Y, Li B K (2017). A novel simultaneous partial nitrification Anammox and denitrification (SNAD) with intermittent aeration for cost-effective nitrogen removal from mature landfill leachate. Chemical Engineering Journal, 313: 619–628
Zhang Q L, Chen Y X, Jilani G, Shamsi I H, Yu Q G (2010). Model AVSWAT apropos of simulating non-point source pollution in Taihu lake basin. Journal of Hazardous Materials, 174(1–3): 824–830
Zhao H, Duan X, Stewart B, You B, Jiang X (2013). Spatial correlations between urbanization and river water pollution in the heavily polluted area of Taihu Basin, China. Journal of Geographical Sciences, 23(4): 735–752
Zhao J, Wang X, Li X, Jia S, Peng Y (2018a). Combining partial nitrification and post endogenous denitrification in an EBPR system for deep-level nutrient removal from low carbon/nitrogen (C/N) domestic wastewater. Chemosphere, 210: 19–28
Zhao W H, Wang M X, Li J W, Huang Y, Li B K, Pan C, Li X Y, Peng Y Z (2018b). Optimization of denitrifying phosphorus removal in a pre-denitrification anaerobic/anoxic/post-aeration + nitrification sequence batch reactor (pre-A2NSBR) system: Nitrate recycling, carbon/nitrogen ratio and carbon source type. Frontiers of Environmental Science & Engineering, 2018, 12(5): 8
Zhu T T, Cheng H Y, Yang L H, Su S G, Wang H C, Wang S S, Wang A J (2019). Coupled sulfur and iron(II) carbonate-driven autotrophic denitrification for significantly enhanced nitrate removal. Environmental Science & Technology, 53(3): 1545–1554