Characteristics of water quality of municipal wastewater treatment plants in China: Implications for resources utilization and management

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Abstract: Influent and effluent quality of municipal wastewater treatment plants play significant roles in selecting the appropriate treatment technologies and influencing the ecology of receiving water bodies. The quality of reclaimed water sources for water reuse can also be determined based on the influent wastewater and treated effluent information. Comprehensive analyses based on statistical data collected from 3340 Chinese municipal wastewater treatment plants were performed so as to better understand the effects of influent and effluent wastewater quality on the treatment performance, environmental concerns and resources utilization. Provincial characteristics of wastewater quality both in quantity and quality were identified, providing valuable information for the proposal of targeted management strategies in pollution control, water reuse and resources recovery. The influents of municipal wastewater treatment plants in north China had high wastewater pollutant loadings, but the effluent was of high quality due to the wide implementation of water reuse strategies in northern water scarcity regions. The potentials for organic and nutrient recovery from the influents were brought forward based on the mass balance. The importance of wastewater as a resource, and the adoption of advanced treatment and resources utilization in the long-term should be highlighted for sustainable water management.

Keywords: Wastewater influent and effluent quality; Wastewater treatment plant; Water reuse; Provincial characteristics; Wastewater resources

Acronyms:

BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
GDP	Gross Domestic Product
NO ₃ -N	Nitrate-nitrogen
NH ₃ -N	Ammoniacal-nitrogen
SS	Suspended solids
TN	Total nitrogen
TP	Total phosphorus
WWTP	Wastewater treatment plant

1 Introduction

Water plays an important role in supporting and maintaining human health and sustainable ecosystem development. Population growth, urbanization, industrialization and consumption pattern changes have generated ever-increasing demands for freshwater resources worldwide (Bagatin et al., 2014; UNESCO, 2015). By 2030, the world is projected to face a 40% global water deficit under the business-as-usual scenario (WRG, 2009). Asia and the Pacific area have lower renewable water resources per capita than the global average, as the population grows, more water will be required for socio-economic activities (UNESCAP, 2013). China, an Asian country with the largest population and the second-largest economy in the world, has been considered as an emerging market country, where the water use situations are far from optimistic (Hsu et al., 2014). Over the past several decades, ever-growing demands and misuse of water resources have caused severe water stress as well as the risks of water contamination in many parts of the country.

1.1 Water resources and consumption

On the one hand, in China, the water availability is approximately 2000 m³ per capita in 2014, a value approaching the defined scarcity threshold of 1700 m³ per capita per year (Jiménez-Cisneros, 2014). On the other hand, the national water consumption in China has been increased by 10.5%, from 550 billion m³ in 2000 to 610 billion m³ in 2014 (NBSC, 2015a). Presently, large water consumers include agricultural, industrial, domestic and ecological environment applications (e.g., artificial wetlands, stream, river and lake flows, recreational impoundments, fountains and waterfalls) with the corresponding proportions of 63.5%, 22.2%, 12.6% and 1.7%, respectively (MWR, 2015). In the next few years, the rapidly ascending industrial and urban demand growth, along with an increasingly complex water-energy nexus, will put mounting pressure on water supply in China (Zhao et al., 2015). According to a report by 2030 Water Resources Group, there will be a gap of about 201 billion m³ between China's current water supply and projected water demand in 2030. Particularly, severe gaps may exist in central and southeast China (WRG, 2009).

Fig. 1 depicts the geographical locations of 31 provinces in China. From the provincial view

point, China's water resources are not equally distributed throughout the year among different regions. About 82.9% of total renewable water resources are concentrated in southern regions of the country, while only 17.1% in northern regions (MWR, 2015). Besides, southern regions have affluent rainfall which may last as long as seven months, while northern regions experience a more arid climate. Consequently, 9 out of 31 Chinese provinces, including Beijing, Tianjin, Hebei, Shanxi, Shanghai, Jiangsu, Shandong, Henan, and Ningxia, suffer from extreme water shortage problems where water availability is less than 500 m³ per capita per year (NBSC, 2013). In terms of economic development, China's coastal provinces, especially Guangdong, Jiangsu, Zhejiang and Shandong, outpace other inland provinces in GDP figures. Notably, 12 coastal provinces had a collective per capita GDP 50% higher than the national average in 2009 (Chovanec, 2011). Thus, water consumption is relatively high in east China, followed by central and west regions. Considering different types of water users, agriculture is still the largest consumer for most of regions while domestic and industrial consumption have been increased largely in east and central China (MWR, 2015).

Fig. 1 Map of geographical locations of 31 provinces in mainland China.

Notes: Each code number (1-31) represents a province in mainland China. Number 1: Beijing; 2: Tianjin; 3:

Hebei ; 4: Shanxi; 5: Neimenggu; 6: Liaoning; 7: Jilin; 8: Heilongjiang; 9: Shanghai; 10: Jiangsu; 11: Zhejiang; 12: Anhui; 13: Fujian; 14: Jiangxi; 15: Shandong; 16: Henan; 17: Hubei; 18: Hunan; 19: Guangdong; 20: Guangxi; 21: Hainan; 22: Chongqing; 23: Sichuan; 24: Guizhou; 25: Yunnan; 26: Tibet; 27: Shannxi; 28: Gansu; 29: Qinghai; 30: Ningxia; 31: Xinjiang. The code number remains consistent in following figures.

1.2 Water pollution

In addition to water shortage, China is also confronted with considerable wastewater discharge and deteriorated water quality of many water bodies. Over the last two decades, the annual GDP growth rate in China was 10.9% in average. Meanwhile, China's urbanization rate has also grown at a fast pace, reaching 54.8% in 2014 (NBSC, 2015b). Given high-speed economic expansions and rising urbanization rates, the quantity of total wastewater discharge in China has been increased over the years, which is up to 69.5 billion m³ in 2013 (Hu et al., 2014; MOEP, 2014). However, China's wastewater treatment development is uneven. Although cities achieved a relatively high treatment rate of over 80%, the national treatment rate is only 69% in 2014 (MOEP, 2014). Besides, the 2014 Environmental Performance Index analysis reported a low wastewater network connection rate of 46.8% in China (Hsu et al., 2014). Discharging excessive poorly treated or untreated wastewater into waterways, together with hazardous wastes and agricultural runoffs of fertilizers and pesticides, has posed serious health and environmental concerns (Cheng et al., 2009). As a result, more than half of the country's lakes, reservoirs and groundwater aquifers are deemed of low water quality, which are unsuitable for human consumption (MWR, 2015).

1.3 Resources utilization

Water reuse can be considered as an effective approach to address water shortage problems and water quality deterioration issues. Moreover, there is a development trend towards ultimate utilization of wastewater as a resource. Fig. 2 shows a novel concept of wastewater refining (Hu et al., 2015). Having recognized these key challenges and opportunities on water use in China, it is essential to conduct systematic wastewater quality analyses for sustainable water management both locally and nationally. As an important part, strategies for further resources utilization such as water reuse and nutrient recovery should be provided.

Fig. 2 The concept of wastewater refining toward the ultimate utilization of wastewater

resources (adapted from Hu et al., 2015).

2 Methods

2.1 Data collection

With an increase in wastewater discharges, municipal wastewater treatment plants (WWTPs) are widely designed and constructed to alleviate water environmental problems. The number of WWTPs is increasing rapidly with a great deal of investment from the Chinese government. However, the development rates are uneven. Major cities normally achieved treatment rates of 70-100%, while some rural villages had little or no wastewater drainage and treatment facilities (Liu and Persson, 2013). Chinese authorities have issued a Five-Year Plan (2010–2015) to address the urban wastewater treatment and reuse. According to the plan, the treatment targets set for metropolises, major cities, small cities and designated towns¹ by 2015 are 100%, 85%, 70% and 30%, respectively. In total, the national daily wastewater treatment capacity will reach to 208 million m³ with a pipeline network of 3.25×10⁵ km by 2015 (CPGPC, 2012).

Overall, statistical data of 3340 Chinese municipal WWTPs in 2012, which receive industrial and urban domestic wastewater discharge, are included in this study. The capacity of the WWTPs ranges from less than 0.01 million m³/day to more than 2 million m³/day. Population size served differs from a few thousand to hundreds of thousands. The raw data were collected by Ministry of Housing and Urban-Rural Construction of the People's Republic of China (MOHURC, 2012) via data report and management systems at all levels of the government. Based on MOHURC (2010), the mostly adopted treatment technologies in municipal WWTPs of China are oxidation ditch (30.5%), anaerobic- anoxic-oxic process (16.2%), conventional activated sludge (10.0%), anaerobic-oxic process (8.2%), and sequencing batch reactor (6.8%). Considering subsequent water reuse potential, advanced membrane biological technologies are being increasingly applied in recent years. Most WWTPs have equipped with online monitoring facilities for analyzing of water flows and routine water quality. Nearly all of these plants take regular samples for compliance purposes (Gao et al., 2015). As China is a large country with substantial regional variations, provincial perspective is of great necessity and significance (Yang and Zehnder, 2001). The data were then grouped according to their administrative provinces and geographical regions. The results were discussed at national, regional and/or provincial levels.

2.2 Data analysis

The concentrations of and ratios between various water quality parameters in wastewater influent can influence the selection and function of treatment processes. Likewise, the concentrations and ratios in wastewater effluent are important for evaluating WWTP performance and subsequent impacts or risks on human health, the environment and design of advanced wastewater treatment and/or reclamation processes. Consequently, it is critical to conduct systematical analyses on water quality parameters of municipal WWTPs across

¹The designated towns are officially registered under the Chinese provincial, autonomous or city government approval. The statuses of designated towns are superior to normal towns.

China, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), ammoniacal-nitrogen (NH₃-N), total nitrogen (TN), and total phosphorus (TP). Therefore, statistical analyses on wastewater influent and effluent quality at municipal WWTPs across the country were performed by Microsoft Excel and the software package OriginPro 8.5 version (developed by OriginLab Corporation, Northampton, USA). The figures were plotted using the OriginPro 8.5 version.

3 Results and discussion

3.1 Quantity of wastewater discharge

The quantity of total wastewater discharge nationwide was 68.5 billion m³ in 2012, in which the amount of industrial and urban domestic wastewater discharge was 22.1 billion m³ and 46.3 billion m³, respectively (MOEP, 2013). Fig. 3 illustrates the amount of wastewater discharge at provincial levels (MOHURC, 2012). Eight provinces, including Guangdong, Jiangsu, Shandong, Zhejiang, Henan, Hebei, Sichuan and Hunan, have larger number of wastewater discharges than other regions. Accordingly, more municipal WWTPs were built and are functioning in these provinces. Besides, 3 provinces, namely Jiangsu, Shandong and Guangdong, are associated with higher amount of industrial wastewater discharges due to more developed industrial clusters, accounting for 10.5%, 8.6% and 8.1% of the national level, respectively. With respect to total domestic wastewater discharges, Guangdong, Jiangsu and Shandong provinces account for 14.3%, 7.7% and 6.5%, respectively because of climate, geographical and economic conditions, cultural and living habits, etc. (MOEP, 2014).

Fig. 3 Quantity of total wastewater discharge, including industrial and urban domestic wastewater discharge, in 31 provinces of China (data adapted from MOHURC, 2012; NBSC, 2012).

3.2 Characteristics of wastewater quality

Fig. 4 presents the concentrations of six crucial water quality parameters that correspond to wastewater influent quality at municipal WWTPs in China (MOHURC, 2012). Notably, the sources of wastewater influent are mainly from municipal sewage and industrial streams, as well as a possible mixture of stormwater and surface water. Hence, in addition to local living and consumption habits, wastewater influent quality can also be affected by the proportion of industrial streams, stormwater interception ratio, etc.

Fig. 4 Wastewater influent quality at municipal WWTPs of China (mg/L)

Notes: The ends of the whiskers represented the 1st and 99th percentile concentrations of each water quality parameter, the bottom and top of the box represented the 25th and 75th percentile also called the lower quartile (LQ) and the upper quartile (UQ), the band near the middle of the box represented the 50th percentile (median), and the hollow square represented the average, the number above the box represented the number of the collected data.

Table 1 shows the concentrations of six crucial water quality parameters that are related to wastewater effluent quality at municipal WWTPs in China (MOHURC, 2012). In addition to mean and median values, the upper quantile (UQ), lower quantile (LQ) and mode of the data were also given so as to better reflect the data distribution and eliminate the impact of noise and outliers. Table 1 also lists the related guideline values that described in Chinese discharge standard of pollutants for municipal WWTPs (GB18918-2002) (MOEP, 2002). The standard specifies four categories of water quality requirements with an emphasis on Class 1A and Class 1B levels. It can be seen that the COD, NH₃-N and TN concentrations of 75% of the data (UQ) satisfy the discharge standard Class 1A level. Wastewater effluent

meeting Class 1A level can be reused or discharged to a recreational or scenic water body that has less diluting capacity. Class 1B should be conducted for effluent directly discharging to level III functional surface waters and level II seawaters. Consequently, most Chinese municipal WWTPs in towns, county-level cities and urban cities, were designed according to requirements of Class 1B level. In 2005, a new governmental statement has indicated that Class 1A level should be carried out for municipal WWTPs at water scarcity regions in northern part of China for effluent reuse purposes (Zhou et al., 2009). An amendment on GB18918-2002 standard has been further made in 2006, stating that Class 1A must be enforced at places identified as national and provincial key watersheds and lakes. At the national scale alone, this designation accounts for 40% of the Chinese land area and 60% of its population. Implementing the new standard level has led to the rapid upgradation and reform of the WWTPs across China (Wang et al., 2015).

Table 1 Wastewater effluent quality at municipal WWTPs of China (mg/L)

Parameter	BOD	COD	SS	NH ₃ -N	TN	TP
UQ	12.2	38.9	14.3	4.9	13.3	0.8
Median	8.3	30.0	10.4	2.8	10.6	0.5
LQ	5.7	23.4	7.4	1.5	7.5	0.3
Mean	10.1	33.8	12.1	4.1	10.9	0.7
Mode	8.0 ^a	25.7 ^a	10.0	3.7	15.0	0.3
<i>n</i>	3148	3260	3194	3234	2794	3115
Standard: Class 1A	10	50	10	5 (8*)	15	0.5 (1**)
Standard: Class 1B	20	60	20	8 (15*)	20	1 (1.5**)
Standard: Class 2	30	100	30	25 (30*)	—	3
Standard: Class 3	60	120	50	—	—	5

Note: UQ, upper quartile, 75th percentile; LQ, lower quartile, 25th percentile; *n*, the number of wastewater treatment; a, as there are multiple modes in the data set, only the minimum value is shown; *indicate the standard limits when temperature is less than 12°C; **indicates the standard limits for municipal WWTPs constructed before Dec 31, 2005.

3.3 Regional characteristics and the analysis of wastewater quality

3.3.1 The concentration and ratio of BOD and COD

The biodegradability assessment of wastewater is of practical significance as it is helpful to optimize the wastewater treatment processes for achieving maximum removal efficiency. BOD and COD are widely used to determine the degradability of wastewater (Xia et al., 2008). At provincial levels, the BOD and COD concentrations of municipal wastewater influents in southern parts of the country were significantly lower than north and northwest China (see Fig. 5). The reasons may include: (1) South and east China have abundant water resources and high-speed economic development, which raise consumption levels and water consumption per capita amount. As a result of increased wastewater discharge, certain contaminant concentrations might be diluted. (2) In water-rich areas, surface water and groundwater may also infiltrate into wastewater discharge and collection systems, causing reduced contaminant levels in wastewater influent.

Moreover, the BOD/COD ratio is generally considered to measure the biodegradability of the wastewater. A high BOD/COD ratio (between 0.4 and 0.6) shows a good biodegradability of wastewater whereas a low BOD/COD ratio (between 0.2 and 0.4) indicates the presence of poorly biodegradable substances in wastewater. Possible consequences of unfavorable BOD/COD ratios include: incomplete denitrification, high COD in the outflow of municipal WWTPs, and deterioration of biological phosphorus removal (Winkler, 2005). Particularly, the BOD/COD ratio (less than 0.1) implies that the wastewater is unsuitable for biological treatment (Sun et al., 2013). It could be seen from Fig. 5 that wastewater influent typically had a BOD/COD ratio of between 0.3 and 0.6. As a BOD/COD ratio of 0.4 to 0.6 indicated a good biodegradability according to literature data (Winkler, 2005), municipal wastewater influent quality in Chinese WWTPs generally exhibited a good biodegradability.

Chen et al. (2009) conducted a survey on biodegradability of municipal wastewaters across China during 2007 and 2008. They found that the BOD/COD ratio of wastewater influent declined from eastern to western regions, and southern to northern regions. However, in this study, BOD/COD ratio in most provinces was about 0.4, which shows no significant difference among various regions. The possible influential factors on the BOD/COD ratio may include: (1) Local industrial types and the proportion of industrial streams in wastewater sources. For instance, the input from food-processing, catering and service industries can contribute to a high BOD/COD ratio of wastewater while the input from heavy industries is associated with a low BOD/COD ratio. Nevertheless, current stringent pre-treatment requirements on industrial wastewater discharge have limited their impacts on the overall wastewater quality to a large extent. (2) Seasonal weather conditions, stormwater runoff and interception ratio. For example, Chen et al. (2009) found that the BOD/COD ratio of wastewater influent in rain seasons was apparently lower than that in dry season, especially in water sufficient areas.

Fig. 5 The median BOD and COD concentration of wastewater influent at municipal WWTPs in 31 provinces of China (data adapted from MOHURC, 2012).

As the BOD/COD ratio in influent wastewater at municipal WWTPs in China showed a good biodegradability (see Fig. 5), the biodegradable organic pollutants in wastewater influent were decomposed and utilized by microorganisms during the biological treatment processes at WWTPs. After wastewater treatment, the effluent concentrations of BOD and COD decreased significantly (see Fig. 6). The BOD/COD ratio of wastewater effluent was also decreased dramatically due to a significant reduction of biodegradable organic matters in treated wastewater. Greater removal efficiencies of BOD and COD were observed in north China, especially in Beijing and Tianjin, as a result of extensive development of water recycling and reuse projects in northern water scarcity regions. However, significant differences were observed in different provinces and regions due to disparities of wastewater influent quality as well as the adoption of different treatment technologies and processes in municipal WWTPs.

Fig. 6 The median BOD and COD concentration of wastewater effluent at municipal WWTPs in 31 provinces of China (data adapted from MOHURC, 2012).

3.3.2 The concentration and ratio of TN and TP

The balanced relationship among carbon, nitrogen and phosphorus in influent wastewater of municipal WWTPs is crucial to the effectiveness of biodegradation processes. These parameters can guide the treatment system process design and configuration so as to achieve maximum nutrient removal efficiency. For efficient wastewater treatment, it is widely stated that the BOD:N:P ratio should be in the range between 100:10:1 and 100:5:1 for aerobic treatment and 250:5:1 for anaerobic treatment (Metcalf and Eddy, 1991; Ammary, 2004). High concentrations of individual substances and unfavorable nutrient ratios can reduce the degradation efficiency of microorganisms (Winkler, 2005).

The majority of wastewater influent at municipal WWTPs contained high concentration of nutrients, mainly nitrogen and phosphorus (see Fig. 7). In influent wastewater, TN and TP ranged from 19 to 51 mg/L and 1.8 to 5.9 mg/L, respectively. The influent nutrient concentrations can vary significantly throughout the day and during stormwater events, which can be high in cases of high proportion of industrial sources. Likewise, at provincial levels, TN and TP concentrations of influent wastewater in southern parts were significantly lower than north and northwest China, probably because of dilution effects on wastewater inflows. Fig. 7 demonstrates that wastewater influent at municipal WWTPs in China typically had a TN/TP ratio of between 6.5 and 14.5, which can well satisfy the theoretical nitrogen and phosphorus demands for microbial growth. The TN/TP ratio was relatively consistent in different provinces of south and east China. In comparison, there were significant differences of TN/TP ratio in different provinces of north and northwest China.

Fig. 7 The median TN and TP concentration of wastewater influent at municipal WWTPs in 31 provinces of China (data adapted from MOHURC, 2012).

Due to increasing concerns on eutrophication of surface water bodies, stringent criteria on nutrient removal in Chinese municipal WWTPs were issued. The mostly adopted biological nutrient removal (BNR) processes in China include oxidation ditch, anaerobic-anoxic-oxic process and sequencing batch reactor (Qiu et al., 2010; MOEP, 2011). Fig. 8 shows the median TN and TP concentration of wastewater effluent at municipal WWTPs. As can be seen, similar to BOD and COD removal, greater removal efficiencies of nutrient were observed in north China, especially in Beijing and Tianjin. Compared to criteria on the national discharge standard (GB18918-2002), the average TN values of wastewater effluent at municipal WWTPs in most provinces except Tibet and Xinjiang satisfied Class 1A level. However, it is generally difficult to achieve high TP removal efficiency depending solely on BNR processes as biological phosphorous removal can be affected by other factors and become unstable. Moreover, the TN/TP ratio in wastewater effluent was increased considerably, indicating a better removal efficiency of TP over TN in most WWTPs. This may be related to additional chemical precipitation of phosphorus removal adapted in many Chinese municipal WWTPs (Qiu et al., 2010; Wu et al., 2014).

Fig. 8 The median TN and TP concentration of wastewater effluent at municipal WWTPs in 31 provinces of China (data adapted from MOHURC, 2012).

3.3.3 The concentration and ratio of $\text{NH}_3\text{-N}$ and TN

Nitrogen in wastewater can be found in four major forms, namely $\text{NH}_3\text{-N}$, organically bonded nitrogen (Organic N), nitrite-nitrogen ($\text{NO}_2\text{-N}$) and nitrate-nitrogen ($\text{NO}_3\text{-N}$) (Metcalf and Eddy, 1991). In the influent of WWTPs, nitrogen is normally present in forms of $\text{NH}_3\text{-N}$ and Organic N. Nowadays, the increased concentration of $\text{NH}_3\text{-N}$ in influent wastewater is closely related to expansion of human activities and industrial processes. As $\text{NH}_3\text{-N}$ in wastewater effluent can be a key factor causing eutrophication and producing toxic substances in receiving water bodies, it is imperative to be treated based on Chinese national discharge standard (GB18918-2002).

$\text{NH}_3\text{-N}$ in inflows of Chinese municipal WWTPs ranged from 13 to 40 mg/L (see Fig. 9). From a provincial perspective, while the average $\text{NH}_3\text{-N}/\text{TN}$ ratios in provinces of south and east China showed slight differences (generally between 0.7 and 0.8), large disparities were found in provinces of northwest China. During BNR processes in WWTPs, $\text{NH}_3\text{-N}$ can be converted into oxidized nitrogen (usually nitrite and nitrate) via nitrification. The nitrification efficiency depends on various factors such as wastewater temperature, contact time with microorganisms and dissolved oxygen concentrations (Zheng and Li, 1998). Fig. 10 indicates that the average $\text{NH}_3\text{-N}$ concentrations of wastewater effluents in most provinces except Tibet and Xinjiang satisfied Class 1B level of the national discharge standard (GB18918-2002). Furthermore, most WWTPs in 25 out of 31 provinces were able to maintain the average $\text{NH}_3\text{-N}$ concentration of less than 5 mg/L (Class 1A level). Regarding the $\text{NH}_3\text{-N}/\text{TN}$ ratio, there was no apparent regularity among various regions, which generally varied between 0.17 and 0.58 at provincial scale.

Fig. 9 The median $\text{NH}_3\text{-N}$ and TN concentration of wastewater influent at municipal WWTPs in 31 provinces of China (data adapted from MOHURC, 2012).

Fig. 10 The median $\text{NH}_3\text{-N}$ and TN concentration of wastewater effluent at municipal WWTPs in 31 provinces of China (data adapted from MOHURC, 2012).

Notes: From a statistical view, as the data points of Xinjiang and Tibet resulted in high dispersion of the data set, they were excluded for consideration when analysing the overall patterns of the data set. $\text{NH}_3\text{-N}$ concentration at Xinjiang and Tibet were 16.6 and 15.7 respectively. TN concentration at Xinjiang and Tibet were 17.4 and 22 respectively.

3.3.4 The concentration and ratio of COD and TN

The COD/TN ratio in the influent of municipal WWTPs is crucial to the BNR processes as COD acts as a limiting factor for phosphorus release and denitrification, especially for wastewaters with lower COD/TN ratios (Wang et al., 2009). Henze and Harremoes (2002) reported a typical range of COD/TN ratio of 8 to 12 in wastewater influent, which is essential for satisfactory denitrification or complete denitrification processes (Henze and Harremoes, 2002). If the COD/TN ratio in inflows is low, an external carbon source (e.g., methanol, ethanol, glucose or hydrolysate) should be added to achieve a satisfactory denitrification (Hu et al., 2012). An average COD/TN ratio in wastewater influent of Chinese municipal WWTPs was about 5.4 to 10.9 (see Fig. 11). A number of Chinese municipal WWTPs, especially in south regions, have problems of insufficient carbon source in wastewater influent (Wu et al., 2014). The lower concentrations of COD in wastewater inflows of south regions might be related to incomplete wastewater collection systems (e.g. unaware of uncollected wastewater and interfusion of surface runoff), higher amount of wastewater discharge, possible surface water and groundwater infiltration, etc. (Zhu, 2013). Therefore, in the near future, to increase COD/TN ratio, more effort should be paid on the exploitation of internal carbon source and the development of external carbon source with sound management approach and reasonable cost in municipal WWTPs of China.

Fig. 11 The median COD and TN concentration of wastewater influent at municipal WWTPs in 31 provinces of China (data adapted from MOHURC, 2012).

3.4 Potential for wastewater resources recovery and utilization

Apart from pollutant removal, the potential of wastewater resources recovery and utilization such as water, organics and nutrients from municipal WWTPs is promising for achieving sustainable water cycle in the long-term. Fig. 12 illustrates a schematic flow chart of wastewater treatment toward resources recovery and utilization in China. As can be seen, after sufficient treatment, the effluents from municipal WWTPs can be considered for subsequent water reuse either directly or with the implementation of additional treatment, depending on the water quality and regulatory requirements. Moreover, organics and nutrients can be enriched and concentrated for subsequently reuse. Since the result of a COD test indicates the amount of water-dissolved oxygen consumed by the contaminants, COD is widely used as a basis for indirect measurement of the amount of organic matters in wastewater (Dong et al., 1999). Hence, in Fig.12, organics in wastewater was quantified indirectly by measuring COD concentrations. After treatment, only a small amount of organics remains as dissolved organics in the liquid phase. Most of the organics in influents can be considered for energy and resources recovery (e.g. production of methane, polyhydroxyalkanoates, etc.). Similarly, phosphorus recovery and utilization is possible from sewage sludge and sewage sludge ash.

Fig. 12 Estimation of wastewater resource utilization potentials in China (data adapted from MOHURC, 2012)

The overall quantity of municipal wastewater discharge in 2012 was 46.3 billion m³ (MOHURC, 2012). Since the average COD, NH₃-N and TP concentrations in wastewater influent quality at municipal WWTPs in China are 260.6 mg/L, 25.3 mg/L and 3.6 mg/L respectively (Fig. 4), the amount of organics and nutrients in wastewater were calculated out in Fig. 12. Notably, at present, the proportion of wastewater resources utilization after wastewater treatment in China is still low. The overall water reuse rate in urban areas was about 11.6% (MWR, 2013), while the reuse rates of organics and nutrients were less than 25% (Li, 2014). By changing the present treatment principles of pollutants degradation and

removal, safe and efficient utilization of water, organics, nutrients and inorganic salts can be further exploited by fine separation and directional transformation of valuable materials in wastewater. Advanced treatment, water reuse, energy exploration and resources recovery will likely be the future technological developing direction. Overall, wastewater treatment, as well as resources recovery and utilization rates can be continuously enhanced with great potentials for a sustainable water management.

4 Conclusions

Water may become the most strategic resource in many parts of the world within the next decades. The identifications of critical control water quality parameters and their concentrations provide great opportunities for improving water sustainability in the future. In this study, the water quality parameters indicated that wastewater influents at municipal WWTPs in China were within suitable ranges for subsequent biological treatment processes. Due to geographical, climate and living habit variations, wastewater pollutant loadings in inflows of municipal WWTPs were much lower in south and east China, compared to north and northwest China. Besides, a number of Chinese municipal WWTPs in south regions have problems of insufficient carbon source in wastewater influent. After wastewater treatment, the wastewater effluent quality at municipal WWTPs in China generally satisfied the Class 1A level of the Chinese discharge standard of pollutants for municipal WWTPs (GB18918-2002). However, better removal efficiencies are found in north regions, such as Beijing and Tianjin, because of extensive implementation of water reuse practices in northern water scarcity regions. Furthermore, the potential of wastewater resources recovery and utilization such as water, organics and nutrients from municipal WWTPs was identified. The amount of water reuse, organics and nutrient recovery in China is likely to be improved significantly. With accumulated knowledge on multiple aspects of wastewater quality, China's experience on water reuse and wastewater resources management can not only benefit local water industries but also provide valuable information for other water scarcity regions.

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References

- Ammary, B.Y., 2004. Nutrients requirements in biological industrial wastewater treatment. *Afr. J. Biotechnol.* 3, 236–238.
- Bagatin, R., Klemeš, J., Reverberi, A.P., Huisin, D., 2014. Conservation and improvements in water resource management: a global challenge. *J. Clean. Prod.* 77, 1–9.

Chen, Z.Y., Liu, A.P., Liu, Y., Xu, Z.C., 2009. Investigation and analysis on biodegradability of municipal sewage in China. *Water Supply Drain.* 35, 248–251 (in Chinese).

Cheng, H., Hu, Y., Zhao, J., 2009. Meeting China's water shortage crisis: current practices and challenges. *Environ. Sci. Technol.* 43, 240–244.

Chovanec, P., 2011. Closing the gap between China's coast and interior. Available from: <http://www.businessinsider.com/closing-the-gap-between-chinas-coast-and-interior-2011-1> (accessed 09.04.2016, in Chinese).

Central People's Government of the People's Republic of China (CPGPRC), 2012. Five-Year Plan of national urban wastewater treatment and reuse. The State Council. Available from: http://www.gov.cn/zwgg/2012-05/04/content_2129670.htm (accessed 27.09.2015, in Chinese).

Dong, D.M., Nelson, Y.M., Lion, L.W., Shuler, M.L., Chiorse, W.C., 1999. Adsorption of Pb and Cd onto metal oxides and organic material in natural surface coatings as determined by selective extractions: new evidence for the importance of Mn and Fe oxides. *Water Res.* 34, 427–436.

Gao, J.F., Brien, J. O., Lai, F. Y., Nuijs, A., He, J., Mueller, J. F., Xu, J., Thai, P. K., 2015. Could wastewater analysis be a useful tool for China? — A review. *J. Environ. Sci.* 27, 70–79.

Henze, M., Harremoes, P., 2002. *Wastewater Treatment: Biological and Chemical Processes*, third ed. Springer, Heidelberg, Germany.

Hu, M.D., Zhou, X.F., Zhang, Y.L., Jiang, M., Tan, Y.Z., 2012. Simulation and optimization of domestic wastewater nutrients removal process: VFA as external carbon source. *Adv. Mater. Res.* 383–390, 6554–6560.

Hu, F., Tan, D., Lazareva, I., 2014. 8 Facts on China's wastewater. *China Water Risk*. March. Available from: <http://chinawaterrisk.org/resources/analysis-reviews/8-facts-on-china-wastewater/> (accessed 27.09.2015).

Hu, H.Y., Wu, G.X., Wu, Q.Y., Guan, Y.T., Li, H., Tao, Y., 2015. Wastewater refining technologies and modes toward ultimate utilization of wastewater resource. *J. Environ. Eng. Technol.* 5, 1–6 (in Chinese).

Hsu, A., Emerson, J., Johnson, Malik, O., Schwartz, J.D., Alison, A., Coplin, K., Guy, S., Lujan, B., Hawkins, N., Lipstein, R., Miao, W., Mala, O., 2014. Environmental Performance Index. Yale Center for Environmental Law & Policy. Available from: www.epi.yale.edu (accessed 27.09.2015).

Jiménez-Cisneros, B., 2014. 3.15 Water Reuse and Recycling. Comprehensive Water Quality and Purification, Volume 3, Elsevier, UK.

Li, Y., 2014. Resource utilization of surplus activated sludge based on sludge disruption-recycling carbon source, phosphorus and nitrogen and biomass Energy. PhD Dissertation, South China University of Technology, Guangzhou, China (in Chinese).

Liu, S., Persson, K. M., 2013. Situations of water reuse in China. Water Policy, 15, 705–727.

Metcalf and Eddy, 1991. Wastewater Engineering, Treatment, Disposal, and Reuse, third ed. McGraw-Hill, Inc., New York.

Ministry of Environmental Protection of the People's Republic of China (MOEP), 2002. Discharge standard of pollutants for municipal wastewater treatment plant. GB18918-2002. Beijing, China (in Chinese).

MOEP, 2011. Technical specifications for oxidation ditch activated sludge process, HJ578-2010; Technical specifications for sequencing batch reactor activated sludge process, HJ577-2010. Beijing, China (in Chinese).

MOEP, 2013-2014. Environmental Statistics Bulletin – Various Years. Ministry of Environmental Protection of the People's Republic of China, Beijing, China. Available from: <http://www.mep.gov.cn/zwgk/hjtj/> (accessed 27.09.2015, in Chinese).

Ministry of Housing and Urban-Rural Construction of the People's Republic of China (MOHURC), 2010. Statistical data on WWTPs of China, Beijing, China (unpublished, in Chinese).

MOHURC, 2012. Management information system on wastewater treatment in 2012, Beijing, China (unpublished, in Chinese).

Ministry of Water Resources (MWR), 2013. 2013 Annual report of water resources management. Department of Water Resources Management, Beijing, China. Available from: <http://szy.mwr.gov.cn/xxfb/nbao/> (accessed 22.11.2015, in Chinese).

MWR, 2015. 2014 Chinese Water Resources Bulletin, Beijing, China (in Chinese).

National Bureau of Statistics of China (NBSC), 2012, 2013, 2015a. China Statistical Yearbook – Various Years. China Statistics Press, Beijing, China. Available from: <http://www.stats.gov.cn/tjsj/ndsj/2012/indexch.htm> (accessed 05.04.2016, in Chinese).

NBSC, 2015b. 2014 National economic and social development statistic bulletin. China

Statistics Press, Beijing, China. Available from: http://www.stats.gov.cn/tjsj/zxfb/201502/t20150226_685799.html (accessed 22.11.2015, in Chinese).

Qiu, Y., Shi, H.C., He, M. 2010. Nitrogen and phosphorous removal in municipal wastewater treatment plants in China: A Review. *Int. J. Chem. Eng.* 2010, 1–10.

Sun, Y.X., Wu, G.X., Hu, H.Y., Wu, Y.H., Guo, F., Guo, Y.M., 2013. A statistical study of influent quality of wastewater treatment plant with separate sewer system in Kunming City. *Chinese J. Environ. Eng.* 7, 2885–2891 (in Chinese).

UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific), 2013. Statistical Yearbook for Asia and the Pacific. Available from: <http://www.unescap.org/stat/data/syb2013/ESCAP-syb2013.pdf> (accessed 27.09.2015, in Chinese).

UNESCO (United Nations Educational, Scientific and Cultural Organization), 2015. Water for a sustainable world. The United Nations World Water Development Report 2015. Available from: <http://unesdoc.unesco.org/images/0023/002318/231823E.pdf> (accessed 27.09.2015, in Chinese).

Wang, Y.Y, Peng, Y.Z., Stephenson, T., 2009. Effect of influent nutrient ratios and hydraulic retention time (HRT) on simultaneous phosphorus and nitrogen removal in two-sludge sequencing batch reactor. *Bioresour. Technol.* 100, 3506–3512.

Wang, X.H., Wang, X., Huppes, G., Heijungs, R., Ren, N.Q., 2015. Environmental implications of increasingly stringent sewage discharge standards in municipal wastewater treatment plants: case study of a cool area of China. *J. Clean. Prod.* 94, 278–283.

Winkler, M., 2005. Optimal nutrient ratios for wastewater treatment. Practical report. Hach Lange Publisher. Available from: ro.hach.com/asset-get.download.jsa?id=25593611376 (accessed 11.11.2015).

WRG (Water Resources Group), 2009. Charting our water future: Economic frameworks to inform decision-making. Water Resources Group, Washington DC.

Wu, Y.Y., Wang, H.C., Sun, J., Zhang, W.J., 2014. Current status and suggestions of nitrogen and phosphorus removal in Chinese urban wastewater treatment facilities. *Water Supply Drain.* 40, 118–122 (in Chinese).

Xia, W.X, Li, J.C., Zheng, X.L., 2008. Biodegradability Assessment of Industrial Wastewater by Warburg Respirometer. In: The 2nd International Conference on Bioinformatics and Biomedical Engineering. 16-18 May, 2008, Shanghai, China.

Yang, H., Zehnder, A., 2001. China's regional water scarcity and implications for grain supply and trade, *Environ. Plann. A.* 33, 79–95.

Zheng, X.C., Li, Y.X., 1998. Nitrogen and phosphorus removal technologies in wastewater. China Architecture and Building Press, Beijing, China (in Chinese).

Zhao, Z.Y., Zuo, J., Zillante, G. Transformation of water resource management: a case study of the South-to-North Water Diversion project. *J. Clean. Prod.* in press.

Zhou, J.Q., Dong, X.L., Jiang, B.Z., 2009. New technologies and case studies regarding WWTP upgrade for meeting Class 1A discharge standard. *Water Ind. Mark.* 1–2, 84–88 (in Chinese).

Zhu, L., 2013. Reasons and strategies of low concentrations in wastewater influents in south regions of China. *City Constr. Theory Study*, 27, 1–3 (in Chinese).