Journal of Cleaner Production 219 (2019) 723–733

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

An evaluation of the environmental benefit and energy footprint of China's stricter wastewater standards: Can benefit be increased?

Kate Smith, Shengjie Guo, Qinhan Zhu [1], Xin Dong**, Shuming Liu*

School of Environment, Tsinghua University, Beijing, 100084, China

ARTICLE INFO

Article history:
Received 7 September 2018
Received in revised form
8 December 2018
Accepted 19 January 2019
Available online 25 January 2019

Keywords:
Wastewater
Electricity
Standards
Discharge
Wastewater reuse

ABSTRACT

In 2015, almost 25% of China's lakes were polluted to the point of being unfit for any purpose. In the same year, China introduced plans to upgrade hundreds of existing and planned wastewater treatment plants to China's highest standard for wastewater discharge. The goal of this paper is two-fold. Firstly, it aims to help policy makers in China understand the impact of China's new wastewater standard on energy use. Secondly, it aims to provide policy makers with suggestions to increase the environmental benefit gained from reducing wastewater contaminant discharge. The most recent data from around 5000 wastewater treatment plants in China are used to estimate the extra electricity required to upgrade a plant from China's commonly used Class 1B municipal wastewater discharge standard to the highest discharge standard, Class 1A. Results show that implementing Class 1A instead of Class 1B tends to use 2%–36% more electricity. This result was used to estimate the overall increase in electricity used over five years by the Chinese wastewater sector due to the introduction of the new policy, an increase that was estimated to be 3–63% of annual electricity used for wastewater treatment. The environmental benefit and electricity cost of three scenarios aimed at reducing wastewater contaminant discharge were compared. Results showed that the benefit-to-cost ratio of implementing stricter standards is greatly improved (by over seven times) when wastewater is not discharged into the environment but instead reused to replace freshwater for purposes that can be met with Class 1A standard. This result has implications for policy makers seeking to increase energy use efficiency, minimise water wastage and reduce environmental pollution within cities.

1. Introduction

Wastewater effluent standards have been progressively tightened around the world over the past hundred years. Until the 1970s, the focus of wastewater treatment was biodegradable oxygen demand (BOD), pathogenic organisms and suspended solids (SS) (Tchobanoglous et al., 2003), with the primary aim being to reduce diseases like diarrhoea. From the 1970s, nitrogen and phosphorus became major targets due to their contribution to eutrophication of waterways (Tchobanoglous et al., 2003). Since then, new contaminants have been added and standards for existing contaminants have become stricter.

As countries attempt to reduce the amount of contaminants released to the environment through wastewater discharge, another environmental problem emerges. Stricter wastewater treatment can increase electricity use. Electricity is one of the main costs for water companies and makes a major contribution to greenhouse gas emissions and air pollution associated with the water industry, particularly in countries where electricity generation is coal dominated (American Water Works Association, 2009; Rothausen and Conway, 2011; Zhang, 2014). The national average electricity use per cubic metre of wastewater treated in China was 0.270 kWh in 2015 (China Urban Water Association, 2018).

The current study investigates the trade-off between decreasing contaminant discharge and increasing electricity use for one of the world's largest producers of wastewater, China. China is in the process of overhauling existing wastewater discharge standards for the first time since 2002 in response to concern over water pollution (Ministry of Ecology and Environment and State Administration for Market Regulation, 2017), which makes the

* Corresponding author.
** Corresponding author.
E-mail addresses: dongxin@tsinghua.edu.cn (X. Dong), shumingliu@tsinghua.edu.cn (S. Liu).
[1] Present address: Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland.

https://doi.org/10.1016/j.jclepro.2019.01.204
0959-6526/

country an ideal case study for this investigation.

The problem of water pollution in China is indeed serious and worsening, and existing wastewater collection and treatment are insufficient. Twenty-six percent of the world's grey water footprint – an indicator of the degree of freshwater pollution – is within China's borders (Hoekstra and Mekonnen, 2012) and the percentage of lakes and reservoirs clean enough to be used for municipal water supply decreased from 50% to 24% between 2006 and 2016 (Ministry of Water Resources, 2016). Meanwhile, the wastewater treated in urban areas of China has more than doubled in the past ten years (China Urban Water Association, 2018), but over 3 billion cubic metres of wastewater remains untreated (Ministry of Housing and Urban-Rural Development, 2016). Around 44% of plants do not treat to the highest municipal wastewater discharge standard (Class 1A, see Table 1) (China Urban Water Association, 2018).

The drafted changes to China's existing municipal wastewater discharge standard will increase the percentage of plants treating to Class 1A, a standard which is comparable to or stricter than discharge standards in developed countries. Currently, Class 1A is adhered to by 56% of plants (see Fig. 1) (China Urban Water Association, 2018). The new standard is based on a major 2015 document that outlines the Chinese government's ten strategies for tackling water pollution (*Action plan for water pollution prevention and control*: *Ten measures on water*) (State Council, 2015) and requires that all newly built plants and all plants in sensitive areas (major lakes, reservoirs and coastal areas) implement Class 1A. Class 1A is stricter than the United States national discharge standard (e.g., China's Class 1A limits for biological oxygen demand (BOD) and suspended solids (SS) are both 10 mg/L compared to the United States limit of 30 mg/L) (United States Environmental Protection Agency, 2010), but not as strict as certain US local standards (e.g., total nitrogen (TN) and total phosphorus (TP) limits for discharge into sensitive areas in the US can be as a low as 3 mg/L and 0.1 mg/L, compared to TN < 15 mg/L and TP < 0.5 mg/L in Class 1A) (Li et al., 2012). Class 1A is stricter than the strictest national standard for domestic wastewater discharge in Germany for four out of five main parameters (see Table 1).

Existing research on the environmental benefit and electricity use associated with Class 1A and Class 1B standards in China focuses largely on case studies. For example, Wang et al. (2015) applied lifecycle assessment methodology to a case study wastewater treatment plant in China prior to 2015 and concluded that upgrading from Class 1B to Class 1A would reduce local eutrophication but not reach an overall environmental benefit, mostly due to an increase in lifecycle electricity and chemical use (the former increased by 28%) (Wang et al., 2015). In an earlier study of 17 plants, Zhu et al. (2013) found that Class 1A plants generally had a lower eutrophication potential than Class 1B plants, but greater global warming potential, mostly due to greenhouse gas emissions associated with electricity use or directly emitted during treatment (Zhu et al., 2013). By contrast, Class 1B plants generally had a lower

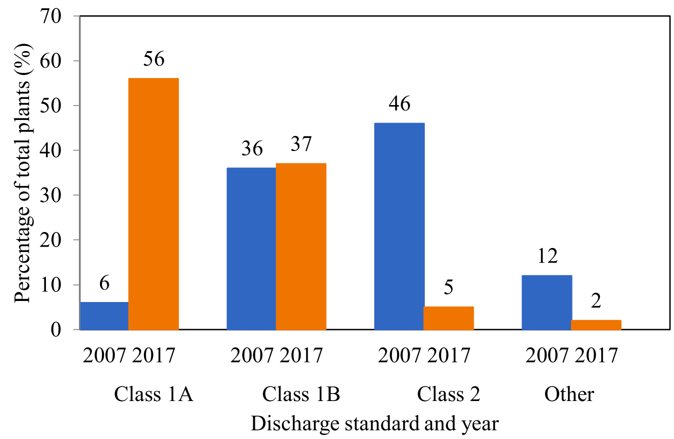

Fig. 1. Change in the portion of wastewater treatment plants meeting the main discharge standards in 2007 and 2017. There were 1154 plants with effluent data in 2007 and 4799 in 2017.

eutrophication potential than Class 2 plants (see Table 1 for standards), but did not differ on average in global warming potential (Zhu et al., 2013). Lu et al. (2017) modified a wastewater treatment plant simulation to represent wastewater treatment scenarios in China and found that stricter discharge standards combined with high penalties would not always be more environmentally friendly.

The authors have identified three knowledge gaps in existing research that this study aims to fill. Firstly, there has not, to the authors' knowledge, been a nationwide assessment of the effect of the draft *Discharge standard* on overall electricity use for wastewater in China. The total plant capacity likely to be affected by the new standard between 2016 and 2020 is almost four times the entire wastewater treatment capacity of India, a country of comparable population size (Government of India Ministry of Environment Forest and Climate Change, 2016; National Development and Reform Commission and Ministry of Housing and Urban-Rural Development, 2016), so such an assessment is necessary. Secondly, this assessment would require an estimate of the difference between Class 1A and Class 1B electricity use at plant level. This estimate would need to be representative of plants across China, but current estimates are only representative of small case studies. Finally, there has not been a comparison of the environmental benefit of the proposed discharge standard to other options for reducing contaminant discharge through wastewater treatment.

In filling these knowledge gaps, the overall goal of this study is two-fold: (1) to help policy makers in China understand the impact of China's new wastewater standard on energy use and (2) to provide policy makers with suggestions (e.g. increasing reuse) that can be incorporated into the standard to increase environmental

Table 1
Comparison of China's most commonly used discharge standards.[a]

Parameter	Class 1A[b] (mg/L)	Class 1B[b] (mg/L)	Class 2[b] (mg/L)	Germany[c] (mg/L)	United States[d] (mg/L)
Chemical oxygen demand (COD)	50	60	80	75	n/a
Biological oxygen demand (BOD_5)	10	20	30	15	30
Suspended solids (SS)	10	20	30	n/a	30
Ammonium-nitrogen (NH_4–N)	5	8	15	10	n/a
Total nitrogen (TN)	15	20	25	13	n/a
Total phosphorus (TP)	0.5	1	1	1	n/a

[a] Main parameters are listed in this table; Class 1A and 1B also differ in limits for animal and plant oils, petroleum products, coliform bacteria and anionic surfactants.
[b] China Ministry of Ecology and Environment and State Administration for Market Regulation (2017).
[c] Federal Ministry for the Environment Nature Conservation and Nuclear Safety of Germany (2004).
[d] United States Environmental Protection Agency (2010); n/a = not applicable, i.e., not included in standard.

benefit gained from reducing wastewater contaminant discharge. The study is separated into three objectives that address the three knowledge gaps. The first objective is to use electricity data for approximately 5000 wastewater treatment plants in China to estimate the average difference in electricity between Class 1B and Class 1A. Electricity data are compared both across plants and through time to reach a reliable conclusion. The second objective is to use these results to estimate the overall effect of the draft *Discharge standard* on electricity use by the wastewater sector in China for the period 2016 to 2020. This period includes both planned changes and changes that have already taken place. The third objective is to assess the environmental benefits of the draft *Discharge standard* and put forward suggestions for how benefit could be increased. This is achieved by calculating the ratio of environmental benefit to electricity use for three scenarios that aim to reduce wastewater contaminant discharge.

2. Methods

An overview of the study method is provided in Fig. 2.

2.1. Estimating the difference in electricity intensity for two discharge standards

The first objective was to use electricity data from around 5000 wastewater treatment plants in China to estimate the average difference in electricity use between Class 1B and Class 1A. Electricity data were compared both across plants and through time to reach a reliable conclusion.

2.1.1. Description of data

The data source used for this purpose was a comprehensive yearbook of wastewater treatment plants in China. The *Urban wastewater treatment yearbooks* (China Urban Water Association, 2018) provide monthly and yearly data on electricity use, treated wastewater volume, sludge production, plant capacity and six influent and effluent water quality parameters (chemical oxygen demand (COD), biological oxygen demand (BOD), suspended solids (SS), NH_4–N, total nitrogen (TN) and total phosphorus (TP)). In 2017, 4980 plants across all provinces, municipalities and autonomous regions in China were represented in *Yearbooks* (China Urban Water Association, 2018). The database is maintained by the China Urban Water Association, making it a reliable source.

This study minimised the effect of data errors on the final result by (1) eliminating plants with missing or inconsistent data and (2) grouping plants in three different ways for analysis, as described in the following sections. These data errors may include missing values (e.g. only five out of six effluent quality parameters are reported), misreported values and outliers (e.g. sudden spikes in effluent concentration).

2.1.2. Identification of discharge standard

The discharge standard met by each plant in a given month or year was identified based on effluent COD, BOD, SS, NH_4–N, TN and TP concentration. Class 1A and 1B have different upper limits for these parameters. If all concentrations were lower than or equal to the value allowed by the Class 1A discharge standard, the plant was assigned Class 1A for that month or year, and likewise for Class 1B.

Class 1A and 1B standards also have different limits for animal and plant oils, petroleum products, coliform bacteria and anionic surfactants, but these four parameters were not included in this analysis because the *Yearbooks* do not contain data on them. This may lead to mischaracterisation in some cases, but the core six water quality parameters provide a strong indication of the standard of treatment.

The standard a plant is meant to meet and the standard it actually meets (i.e. based on effluent quality) may differ and this study uses the latter. The *Yearbooks* do not provide a plant's past standards.

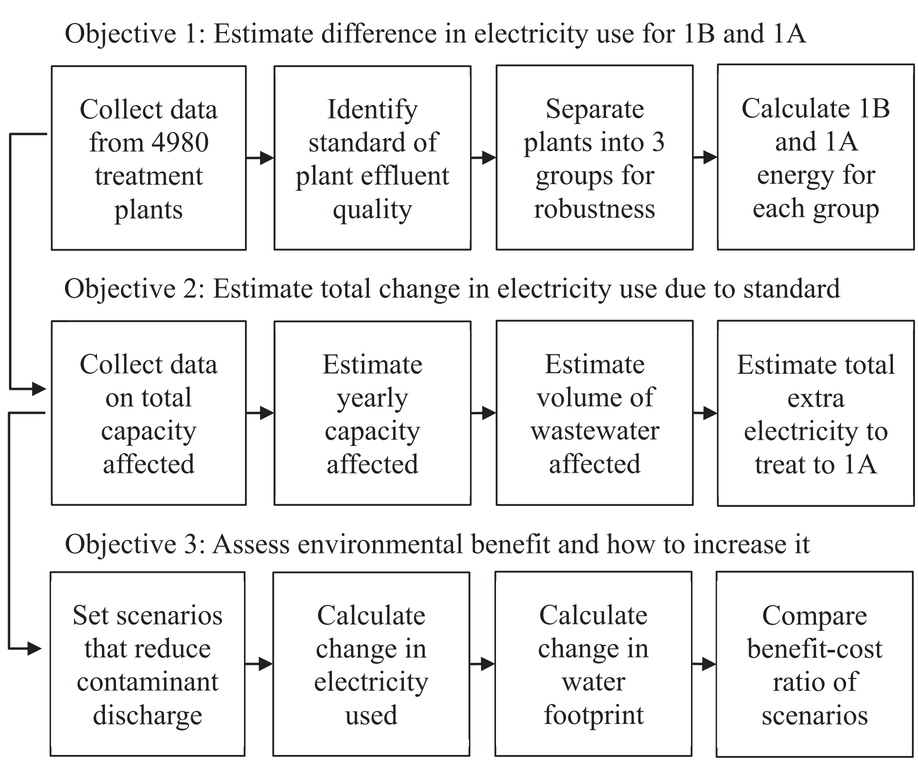

Fig. 2. Overview of study method.

2.1.3. Selection of plants

Plants were separated into three groups so that electricity data could be compared both across plants and through time. Group 1 consists of 36 plants that were chosen based on their location in the Lake Tai region in China. These plants were considered separately because improvement in effluent quality could be directly linked to the implementation of local policy. The Lake Tai region suffered a major eutrophication incident in 2007, which led to a local policy requiring wastewater treatment plants upgrade to Class 1A. Group 2 consists of 316 plants located across China. These plants were chosen because they displayed a clear and sustained change in effluent quality, indicating an upgrade. To be included in Group 2, a plant's monthly effluent quality had to meet Class 1B for at least 12 consecutive months and Class 1A for at least 12 consecutive months, with limited fluctuation between the two standards. Group 3 includes all plants that were treating to either Class 1B or Class 1A in 2017. Some plants fitted criteria for inclusion in more than one group. The advantages and disadvantages of using each group in this analysis are provided in Table 2.

For Groups 1 and 2, electricity, volume and effluent quality data between 2007 and 2017 were used n this study, whereas for Group 3 only one year of data was required. In most cases, data for either five or six effluent concentration parameters were available. In some cases, plants were still included for time periods when more than one effluent concentration parameter was missing.

2.1.4. Calculation of difference in electricity use

For Groups 1 and 2, the electricity intensity for treatment to Class 1B and Class 1A was calculated at plant level as shown in Equations (1) and (2).

$$E_{1B,p} = \frac{\sum_{i=1}^{n} E_{tot,i,p}}{\sum_{i=1}^{n} V_{tot,i,p}} \quad (1)$$

$$E_{1A,p} = \frac{\sum_{j=1}^{m} E_{tot,j,p}}{\sum_{j=1}^{m} V_{tot,j,p}} \quad (2)$$

where $E_{1B,p}$ = electricity intensity for Class 1B treatment by plant p (kWh/m^3); $E_{tot,i,p}$ = electricity for time period i for plant p, where effluent meets Class 1B standard for period i (kWh); $V_{tot,i,p}$ = volume of wastewater treated for time period i for plant p (m^3); n = total number of time periods used to estimate Class 1B electricity intensity for plant p; $E_{1A,p}$ = electricity intensity for Class 1A treatment for plant p (kWh/m^3); $E_{tot,j,p}$ = electricity for time period j, where effluent meets Class 1A standard for period j (kWh); $V_{tot,j,p}$ = volume of wastewater treated for time period j for plant p (m^3); m = total number of time periods used to estimate Class 1A electricity intensity for plant p.

Selection of the total number of time periods (n and m) differed for Groups 1 and 2. For each plant in Group 1, the upgrade year was defined as the first year the plant's effluent met Class 1A. This could be no later than 2015, so that the connection between the original policy in 2008 and the upgrade was still strong. To calculate Class 1B and 1A electricity intensities for Group 1, an equal number of years of electricity and volume data was used on either side of the upgrade year for consistency. Thus, the number of time periods used to calculate average Class 1B electricity intensity (n) and the number used to calculate average Class 1A electricity intensity (m) were the same for Group 1, and varied between 1 and 5 years. For Group 2, n and m (the number of months of data) were much larger (>12) and were not equal.

For Group 3, plants were separated according to plant capacity (large: >100,000 m^3/d, medium: 10,000–100,000 m^3/d, small: <10,000 m^3/d) and influent concentration (low is COD <500 mg/L, SS < 300 mg/L, NH_4–N <35 mg/L, TN < 50 mg/L and TP < 5 mg/L and all other influent is high). This resulted in six categories (e.g. large size and high concentration, small size and low concentration, etc.). This method of categorisation was chosen because plants that treat a large amount of wastewater tend to use less electricity per cubic metre of wastewater than smaller plants (Gu et al., 2017; Wang et al., 2016), and energy consumption is closely connected to influent concentration (Yang et al., 2010) (this was also evident in results for Group 3). Within these six categories, plants were treating to either Class 1A or Class 1B.

The average electricity intensities of Class 1A and Class 1B plants in each category were calculated according to Equations (3) and (4).

$$E_{1B,g} = \frac{1}{N}\sum_{q=1}^{N} \frac{E_{tot,q,g}}{V_{tot,q,g}} \quad (3)$$

$$E_{1A,g} = \frac{1}{M}\sum_{r=1}^{M} \frac{E_{tot,r,g}}{V_{tot,r,g}} \quad (4)$$

where $E_{1B,g}$ = average electricity intensity for Class 1B plants in category g (kWh/m^3); $E_{tot,q,g}$ = electricity use for plant q in 2017, where effluent meets Class 1B standard for plant q (kWh);

Table 2
Details of each group of plants used to judge difference between Class 1A and Class 1B electricity use.

Group	No. of plants	Data years	Plant characteristics	Advantages	Disadvantages
1	36	2007–2017	• Must be located in 'key rehabilitation area' of Lake Tai as defined by (National Development and Reform Commission, 2008). • Annual effluent quality must clearly change from Class 1B to Class 1A between 2007 and 2017, with the first year of Class 1A treatment no later than 2015.	• Class 1A and Class 1B electricity use is compared *through time* for each plant. • Improvement in plant effluent quality between 2007 and 2017 can be directly linked to 2008 policy that required the 36 plants to upgrade to Class 1A (National Development and Reform Commission, 2008).	• Small sample size • Lack of diversity (all plants located in same region).	
2	316	2007–2017	• Can be located anywhere in China. • Monthly effluent must reach Class 1B and Class 1A for at least 12 consecutive months each. • Must show a clear and consistent change from Class 1B to 1A.	• Class 1A and Class 1B electricity use is compared *through time* for each plant. • Larger and more diverse sample than Group 1.	• Changes in electricity use cannot be linked to a clear policy driver.	
3	4161	2017	• Can be located anywhere in China. • Must meet either Class 1B or Class 1A standard in 2017.	• Larger and more diverse sample than both Group 1 and 2. • Data used are the most recent available.	Class 1A and Class 1B electricity use is compared *across plants*, which may differ significantly (e.g. in terms of technology used).	

$V_{tot,q,g}$ = volume of wastewater treated for plant q in 2017, where effluent meets Class 1B standard for plant q (m^3); N = total number of plants in category g that treat to Class 1B; $E_{1A,g}$ = average electricity intensity for Class 1A plants in category g (kWh/m^3); $E_{tot,r,g}$ = electricity use for plant r in 2017, where effluent meets Class 1A standard for plant r (kWh); $V_{tot,r,g}$ = volume of wastewater treated for plant r in 2017, where effluent meets Class 1A standard for plant r (m^3); M = total number of plants in category g that treat to Class 1A.

For Groups 1 and 2, the percentage change in electricity intensity between Class 1B and Class 1A was calculated at plant level (Equation (5)) and then averaged across all plants in the group (Equation (6)).

$$E_{\%,p} = \left(\frac{E_{1A,p}}{E_{1B,p}} - 1\right) \times 100 \tag{5}$$

$$E_{\%} = \frac{1}{S}\sum_{p=1}^{S} E_{\%,p} \tag{6}$$

where $E_{\%,p}$ = percentage change in electricity intensity from Class 1B to Class 1A for plant p; $E_{\%}$ = average percentage change in electricity intensity from Class 1B to Class 1A across all plants in the group; S = total number of plants in the group.

For Group 3, the percentage difference between Class 1B and Class 1A for each category g was calculated according to Equation (7).

$$E_{\%,g} = \left(\frac{E_{1A,g}}{E_{1B,g}} - 1\right) \times 100 \tag{7}$$

where $E_{\%,g}$ = percentage difference in electricity intensity between Class 1B and Class 1A plants in category g (there were six categories).

2.2. Estimating total change in electricity use due to change in discharge standard

The second objective of this study was to use the results from Section 2.1 to estimate the overall effect of China's newly drafted wastewater discharge standard (Ministry of Ecology and Environment and State Administration for Market Regulation, 2017) on electricity use by the wastewater sector between 2016 and 2020. This estimation required (1) the capacity upgraded or built each year between 2016 and 2020, (2) the volume of wastewater treated by this capacity, (3) the average electricity used for treatment to Class 1B standard, and (4) the percentage difference between Class 1B and Class 1A electricity use.

Total plant capacity (m^3/day) to be upgraded or constructed between 2016 and 2020 is provided in a government document based on the *Action Plan* called *"Thirteenth Five-Year Plan" national urban wastewater treatment and reclamation infrastructure construction plan* (National Development and Reform Commission and Ministry of Housing and Urban-Rural Development, 2016). See Table S1 in the Supplementary Information for a comparison between the three major government documents used in this study. This document stipulates the capacity of existing plants that should upgrade to Class 1A and the capacity of new plants that should be constructed.

The current study made three assumptions regarding this document. Firstly, existing plants were assumed to be upgrading from Class 1B, because most plants in China met either Class 1A or Class 1B in 2017 (see Fig. 1) (China Urban Water Association, 2018). Secondly, new plants were assumed to treat to Class 1A, as is stipulated in the draft *Discharge standard* (Ministry of Ecology and Environment and State Administration for Market Regulation, 2017). Thirdly, it was assumed that new plants would otherwise have met Class 1B if not for the draft *Discharge standard*.

Plant capacity upgraded or constructed each year was calculated using Equations (8)–(12). The deadline for upgrades was the end of 2017 (Ministry of Ecology and Environment and State Administration for Market Regulation, 2017; State Council, 2015), so half the capacity scheduled for upgrade is assumed to have been completed in 2016 and the other half in 2017. Construction of new plant capacity was assumed to be equally spread across all years 2016–2020.

$$C_{tot,2016} = 0.5C_{upgrade} + 0.2C_{construct} \tag{8}$$

$$C_{tot,2017} = C_{tot,2016} + 0.5C_{upgrade} + 0.2C_{construct} \tag{9}$$

$$C_{tot,2018} = C_{tot,2017} + 0.2C_{construct} \tag{10}$$

$$C_{tot,2019} = C_{tot,2018} + 0.2C_{construct} \tag{11}$$

$$C_{tot,2020} = C_{tot,2019} + 0.2C_{construct} \tag{12}$$

where C_{tot} = total upgraded and new capacity for the given year at provincial level (m^3/day); $C_{upgrade}$ = capacity scheduled for upgrade at provincial level over the period 2016–2020 (m^3/day); $C_{construct}$ = capacity scheduled for construction at provincial level over the period 2016–2020 (m^3/day).

A yearly ratio of treated wastewater (m^3/year) to plant capacity (m^3/day) was calculated for years 2016 and 2017 for each province by dividing total wastewater treated by total capacity, using data obtained from the *Yearbooks* (China Urban Water Association, 2018). Ratios for years 2018, 2019 and 2020 were extrapolated from ratios calculated for years 2007 through to 2017 using the linear trend function of Excel.

The annual volume of treated wastewater affected by the draft *Discharge standard* in each province (e.g. V_{2017}) was estimated by multiplying annual capacity (e.g. $C_{tot,2017}$) by the ratio (e.g. R_{2017}) of treated wastewater to plant capacity for the given year (e.g. $V_{2017} = C_{tot,2017}{}^{*}R_{2017}$). It was assumed that new or upgraded plants only treated wastewater for half of their first year of operation. The total volume of wastewater affected nationally in 2016, 2017, 2018, 2019 and 2020 is the sum of provincial-level volume estimations for that year.

The 2016 average electricity intensity for treatment to Class 1B standard (E_{1B}) was calculated according to Equation (13) for all plants that met Class 1B standard in 2016. All plants with 2016 annual data on electricity use, volume treated and effluent concentration for one or more of COD, BOD, SS, NH_4–N, TN and TP were included in this calculation as long as all available effluent parameters were below Class 1B standard (i.e. plants with missing effluent parameters were also included).

$$E_{1B} = \frac{\sum_{s=1}^{U} E_{tot,u}}{\sum_{s=1}^{U} V_{tot,u}} \tag{13}$$

where E_{1B} = average electricity intensity for treatment across all plants treating to Class 1B in 2016 (kWh/m^3); $E_{tot,s}$ = total electricity use by plant u in 2016, where plant meets Class 1B standard in 2016 (kWh); $V_{tot,s}$ = total volume of wastewater treated by plant u in 2016 (m^3); U = total number of plants that meet Class 1B in 2016.

The total annual volume of wastewater affected by the standards was multiplied by E_{1B} to estimate how much electricity would have been used had this volume been treated to Class 1B. The percentages calculated in Section 2.1 were used to estimate the electricity required to treat the same volume to Class 1A. The difference was summed across all provinces and regions to give the total electricity increase associated with changes proposed by the draft *Discharge standard*.

2.3. Cost and benefit comparison for three scenarios reducing contaminant discharge

The third objective of this study was to assess the environmental benefits of the draft *Discharge standard* and suggest how benefit could be increased. This was achieved by comparing the electricity cost and environmental benefit of three scenarios that aim to reduce wastewater contaminant discharge. Given the difficulty of assessing electricity cost and environmental benefit using comparable indicators, cost and benefit were calculated separately in terms of electricity consumption (kilowatt hours) and water footprint reduction (cubic metres), and then assessed by comparison across scenarios. The scenarios were compared using 2011 data for Beijing.

The three scenarios chosen for this study were based on the *Action plan* (State Council, 2015). They are illustrated in Fig. 3 and described here: (1) A volume *V* of wastewater is originally discharged into a water body without treatment (S1a); in this scenario, the untreated wastewater is treated to Class 1B standard before discharge (S1b). (2) A volume *V* of wastewater is originally discharged into a water body after Class 1B treatment (S2a); in this scenario, this volume is instead treated to Class 1A before discharge (S2b). (3) A volume *V* of wastewater is originally discharged into a water body after Class 1B treatment (S3a); in this scenario, this volume is instead treated to Class 1A standard and reused (S3b). It should be stressed that the status quo in Scenario 1 is the discharge of untreated wastewater into municipal water bodies, which still occurs in Beijing and other Chinese cities (Beijing Water Authority, 2017; Ministry of Housing and Urban-Rural Development, 2016) and that the option for reducing contaminant discharge in this scenario is to collect this wastewater (which would otherwise have been discharged untreated) and treat it to Class 1B. Further details on how the *Action plan* promotes wastewater collection, reuse and treatment are provided in the Supplementary Information.

The main water bodies targeted by the *Action plan* (State Council, 2015), draft *Discharge standard* (Ministry of Ecology and Environment and State Administration for Market Regulation, 2017) and *Construction plan* (National Development and Reform Commission and Ministry of Housing and Urban-Rural Development, 2016) are sensitive water bodies and low quality water bodies. Class III from China's *Environmental quality standards for surface water* (Ministry of Environmental Protection and General Administration of Quality Supervision Inspection and Quarantine, 2002) (shown in Table 3) was chosen to represent the water quality of a sensitive water body. Class III water bodies are high quality

Table 3
Comparison of surface water quality standards chosen to represent sensitive and low quality water bodies.

Parameter	Class III [a] (mg/L)	Class V [a] (mg/L)
COD	20	40
BOD_5	4	10
NH_4–N	1	2
TN	1	2
TP	0.2 (0.05[b])	0.4 (0.2[b])

[a] Class III and Class V are two classes of surface water quality in China's *Environmental quality standards for surface water* (Ministry of Environmental Protection and General Administration of Quality Supervision Inspection and Quarantine, 2002). They are not to be confused with Class 1A and Class 1B, which are two classes of municipal wastewater discharge quality in China. China's discharge standard includes suspended solids (SS), but China's surface water quality standard does not.
[b] Lakes and reservoirs.

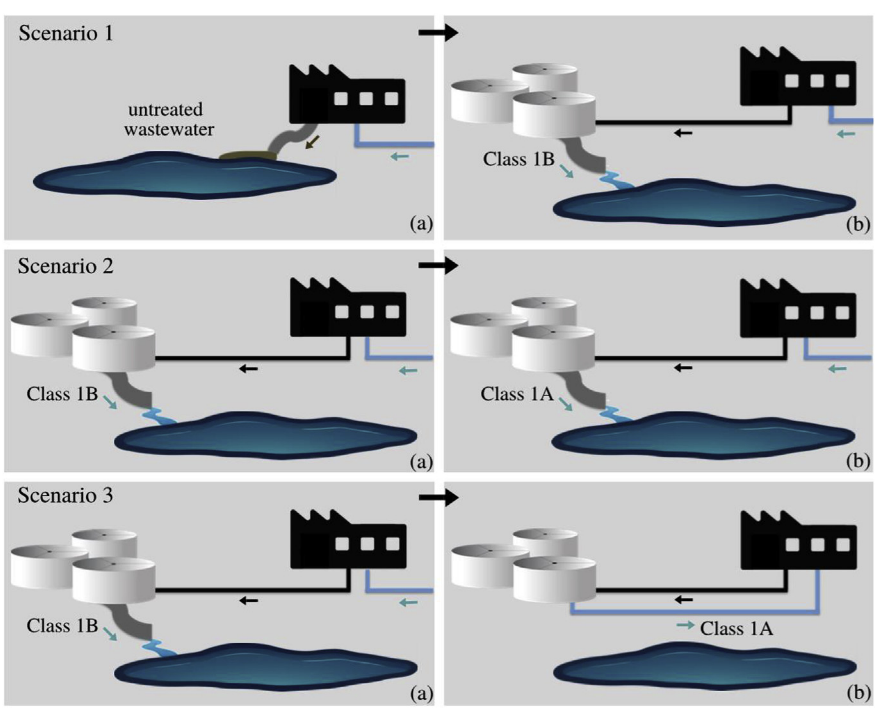

Fig. 3. The status quo (a) and option for reducing contaminant discharge (b) in each scenario. In each scenario, two possible receiving water bodies (i.e. two sub-scenarios) were considered.

(used for residential water supply, swimming and as fish habitats or areas for fish migration or farming) (Ministry of Environmental Protection and General Administration of Quality Supervision Inspection and Quarantine, 2002). These water bodies were also able to receive effluent from wastewater treatment plants in Beijing up until the end of 2011, the year of this case study (Beijing Municipal Environmental Protection Bureau and Beijing Municipal Administration of Quality and Technology Supervision, 2005, 2012). Class V was chosen to represent a low quality water body (which is defined as <Class IV by (State Council, 2015)). Class V water bodies can only be used to provide water for irrigation (Ministry of Environmental Protection and General Administration of Quality Supervision Inspection and Quarantine, 2002).

2.3.1. Cost

In this analysis, change in electricity use (kWh) was used as a measure of cost for each of the three scenarios (with *a* representing the status quo and *b* representing the option for reducing contaminant discharge as shown in Fig. 3). This was calculated using Equation (14).

$$E_{tot,\cos t} = E_{tot,b} - E_{tot,a} = \begin{cases} V_{tot} \times E_{1B,Beijing} \text{ for Scenario 1} \\ V_{tot} \times (E_{1A,Beijing} - E_{1B,Beijing}) \text{ for Scenarios 2 and 3} \end{cases} \quad (14)$$

where $E_{tot,\ cost}$ = total additional electricity required (kWh); V_{tot} = volume of wastewater treated (m^3); $E_{1A,Beijing}$ = electricity intensity for Class 1A in Beijing (kWh/m^3); $E_{1B,Beijing}$ = electricity intensity for Class 1B in Beijing (kWh/m^3).

In 2011, 1.46 billion m^3 of wastewater was discharged in Beijing, of which 1.19 billion m^3 (82%) was treated (Beijing Water Authority, 2017). This left over 270 million m^3 untreated, so V_{tot} is set at a conservative 100 million m^3 for Scenario 1–3. This is well within the target treatment rate of 95% specified in the 2015 *Action Plan* (State Council, 2015).

In Equation (14), the average electricity intensities for Class 1A treatment and Class 1B treatment in Beijing were calculated using 2007–2017 data for all Beijing wastewater treatment plants, taken from the *Yearbooks* (China Urban Water Association, 2018), as shown in the Supplementary Information. Electricity use only includes operational electricity reported by wastewater treatment plants to the *Yearbooks*. If electricity used for collection or discharge of wastewater was not reported by the plant to the *Yearbooks*, then this is not included.

2.3.2. Benefit

Two concepts were used to assess the benefit of each scenario: change in grey water footprint and change in blue water footprint.

Grey water footprint is used to indicate the effect of pollution on water bodies. It is defined as the volume of water needed to dilute pollutants to the water quality standard of the receiving water body (Hoekstra et al., 2011). Thus, a reduction in grey water footprint is the ‘conservation’ of a hypothetical volume of water that would have been required to satisfactorily dilute discharged contaminants.

In this study, the change in grey water footprint in each scenario was calculated according to Equation (15) (Gu et al., 2016; Hoekstra et al., 2011). In the calculation of grey water footprint, it was assumed that the full volume $V_{\rm tot}$ enters the receiving water body, i.e., there is limited loss of effluent during discharge from the wastewater treatment plant to the water body.

$$\Delta WF_{grey} = \min\left\{\frac{c_{i,a} - c_{i,b}}{c_{i,max}} \times V_{tot}\right\} \quad (15)$$

where ΔWF_{grey} = grey water footprint reduction (m^3); $c_{i,a}$ and $c_{i,b}$ = concentration of pollutant *i* in wastewater effluent before and after change (mg/L); $c_{i,max}$ = the maximum allowable concentration of pollutant *i* according to the surface water standard applied to the receiving body (mg/L). In Scenario 1, $c_{i,a}$ is the average concentration of untreated wastewater in Beijing. This was estimated using all annual influent wastewater concentrations corresponding to plants and years used to calculate the $E_{1A,Beijing}$ and $E_{1B,Beijing}$ in Equation (14).

Blue water footprint is the consumption of surface water and groundwater resources through evaporation or incorporation into a product (Hoekstra and Mekonnen, 2012). Thus, a reduction in blue water footprint indicates a reduction in the use of freshwater; for example, through replacement of freshwater by reclaimed or desalinated water. Freshwater is defined in this study as groundwater or surface water distributed to the point of use, after any necessary treatment.

Blue water footprint was calculated according to Equation (16) and incorporates (1) the increase in blue water footprint of electricity generation as a result of extra electricity use, and (2) the decrease in blue water footprint of the case city as a result of wastewater reuse. Equation (16) assumes the following in regards to wastewater reuse. Firstly, it assumes that treated wastewater replaces freshwater at the point of use. Starting from point of use, the treated wastewater is consumed (through incorporation or evaporation) in the same way as the freshwater it replaces and undergoes the same downstream processes as the freshwater it replaces (e.g. if used for industrial washing, it would likely be returned to a wastewater treatment plant after use). Secondly, it assumes that part of the volume treated in Scenario 3b ($V_{\rm tot}$) must be lost during distribution to the user. There is often a considerable distance between wastewater treatment plants and users, and leakage during distribution cannot be overlooked.

$$\Delta WF_{blue} = V_{tot,\ reuse} - E_{tot,cost} \times V_{elec} \quad (16)$$

where ΔWF_{blue} = blue water footprint reduction (m^3); $V_{tot,\ reuse}$ = volume of wastewater reused (m^3); V_{elec} = water intensity of electricity generation (m^3/kWh). V_{elec} was calculated using the electricity generation mix for Beijing for 2011 (China Electric Power Press, 2012) and the average water consumption for each type of power (hydro, thermal and wind) for northern China, as shown in Table S2 (Zhu et al., 2015).

The portion of V_{tot} (i.e. treated wastewater) reused for purposes such as industrial cooling and municipal non-potable use (e.g. car washing) was set at $V_{tot,\ reuse} = V_{tot} - 0.07V_{tot}$. In other words, it was assumed that 7% would be lost through leakage during distribution to the user, which is representative of Beijing's physical leakage from water distribution systems in 2011. Reusing just under 100 million m^3 of Class 1A wastewater was considered feasible because Class 1A wastewater meets the reuse standards for industrial cooling, industrial washing, agriculture, forestry and municipal non-potable use (e.g. flushing, car washing, construction, etc.) (Ministry of Water Resources, 2007) and around 2.3 billion m^3 of water was used in Beijing for industry, agriculture, construction and urban greening and sanitation in 2012 (2011 figures are not available and data on specific uses like industrial cooling are not available) (Beijing Water Authority, 2017). Only water lost through physical leakage was subtracted from $V_{tot,\ reuse}$, because water unaccounted for due to other reasons (e.g. meter failure or theft) may have satisfied user requirements and would not affect 'environmental benefit'. Physical leakage from Beijing's water distribution system was 7.34% in 2011, according to unpublished data obtained by the authors.

The overall environmental benefit was the sum of the changes in blue water footprint (m^3) and grey water footprint (m^3) (i.e. the sum of the change in freshwater use and the change in volume of water required to dilute contaminants), as shown in Equation (17).

$$Total\ Benefit = \Delta WF_{blue} + \Delta WF_{grey} \quad (17)$$

A benefit-to-cost ratio was used to compare scenarios. This ratio was equal to the total benefit (as per Equation (17)) divided by the total electricity cost (Equation (14)) of each scenario.

3. Results and discussion

3.1. Difference in electricity use for main discharge standards

This study's first objective was to calculate the difference in electricity required to treat to China's highest (Class 1A) and second highest (Class 1B) discharge standards.

Analysis of data from around 5000 wastewater treatment plants found average differences in electricity intensity for Class 1B and Class 1A of 2–36%. Upgrades from Class 1B to Class 1A led to an average increase in electricity intensity of 14% among plants in Group 1 (see Fig. 4) and 12% among plants in Group 2 (see Fig. 5). The third group of wastewater treatment plants was separated into six categories (see Fig. 6) and the average difference in electricity intensity between Class 1B and Class 1A plants in each category varied between 2% and 36%. A weighted average difference of 19% was calculated by taking the number of Class 1B or Class 1A plants in each category into account (see Fig. 6 for sample numbers). See Tables S3 and S4 for Group 1 and Group 3 data.

Electricity use increased for the majority of plants that upgraded from Class 1B to Class 1A. Electricity used to treat to Class 1A was higher for 26 out of the 36 plants in Group 1 and for 211 of the 316 plants in Group 2. For the remaining plants, Class 1A treatment used less electricity than Class 1B, which may have been due to changes in treatment efficiency (e.g. plants making fuller use of design capacity than before) or influent concentration. It could also have been because upgrades were achieved by increasing chemical dosage alone (the environmental cost of which is outside the scope of this study), rather than by changing technology. The change in effluent standard does not explain all changes in electricity use. Plants were nevertheless very likely to use more electricity after an upgrade (68% for Group 1 and 67% for Group 2).

Electricity intensity for Class 1A was higher than Class 1B for all

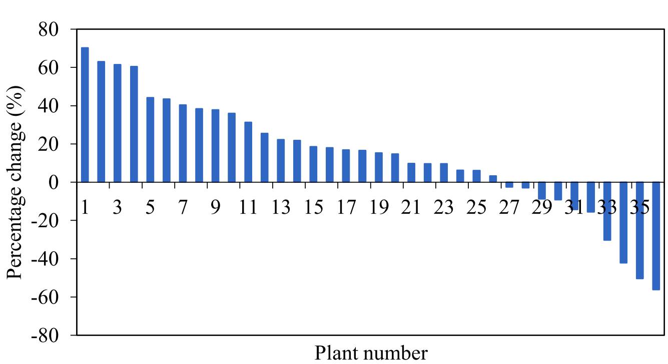

Fig. 4. Percentage change in electricity intensity following upgrade from Class 1B to Class 1A for 36 plants in Lake Tai region (Group 1). Upgrades were associated with an increase in electricity use for most plants (68% of plants, each plant is represented by a line).

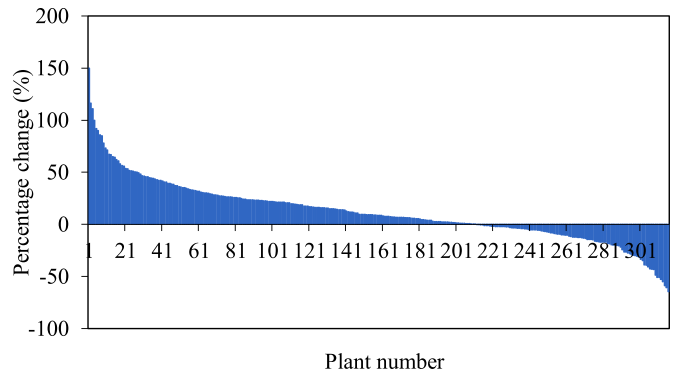

Fig. 5. Percentage change in electricity intensity following upgrade from Class 1B to Class 1A for 316 plants across China (Group 2). Upgrades were associated with an increase in electricity use for most plants (67% of plants, each plant is represented by a line).

categories in Group 3, but variations between categories suggest that certain plants could be upgraded more efficiently than others. Fig. 6 shows that the difference in electricity use between Class 1A and Class 1B is over 18% for small plants, whereas the difference is less than 16% for large plants. This indicates that upgrading larger plants to Class 1A may be more energy efficient than upgrading smaller plants. For the same reason, it may be more efficient to upgrade small and large plants with low rather than high influent concentration. The category for which the difference between 1A and 1B was smallest and for which upgrades might be most efficient is that of medium-sized plants with high influent concentration. It is important to remember that plants represented in Fig. 6 are treating to different standards, rather than upgrading from one standard to another.

The main implication of the results presented in this section is that upgrading a plant from Class 1B to Class 1A is likely to cause electricity use to increase. This does not occur in every instance, but it is true on average.

3.2. Total change in electricity use due to change in discharge standard

The results from Section 3.1 were used to estimate the overall effect China's newly drafted wastewater discharge standard (Ministry of Ecology and Environment and State Administration for Market Regulation, 2017) could have on electricity use by the wastewater sector between 2016 and 2020.

The total volume of wastewater affected by the stricter standards nationally was estimated to be 97.9 billion m^3 for the period 2016 to 2020 (see Table S5 for provincial level values). This is two times the volume of wastewater treated in Chinese cities in 2015 (which was 46.7 billion m^3) (China Urban Water Association, 2018). In other words, the change in standards was estimated to affect the equivalent of two years' worth of treated wastewater.

The change in standards was estimated to have caused an increase in electricity use for wastewater in China of between 0.5 billion kWh and 8.7 billion kWh over the five years between 2016 and 2020. This is equivalent to 3–63% of the 13.9 billion kWh of electricity (China Urban Water Association, 2018) used to treat wastewater in China in 2015. If a 12% increase is assumed (i.e. the estimate for Group 2), this is equivalent to 2.9 billion kWh, or 21% of electricity for wastewater in China in 2015. Table 4 shows the estimated increase in electricity use for Class 1A compared to Class 1B for percentages calculated in Section 3.1. Treating wastewater to Class 1B standard required an average of 0.251 kWh/m^3 in 2016;

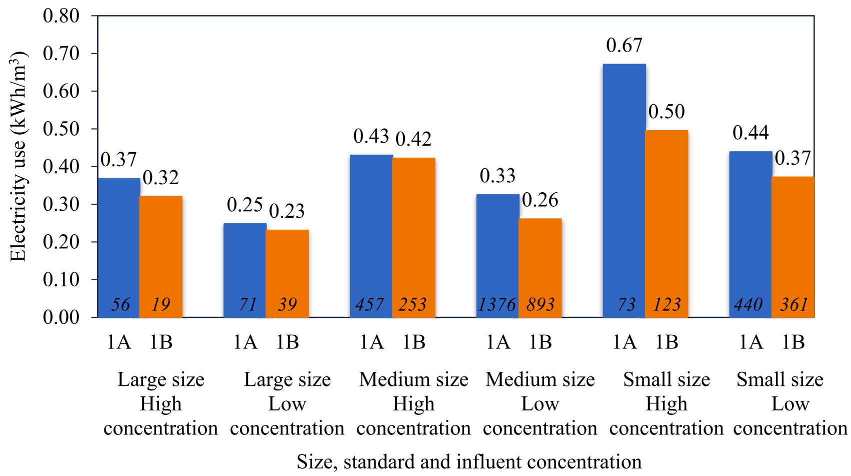

Fig. 6. Average electricity intensity for 4161 plants of different size and concentration in 2017. The number of plants in each category is shown in italics.

Table 4
Estimated difference in electricity use for wastewater treatment to Class 1A compared to Class 1B, 2016–2020.

Group	Percentage increase between Class 1B and 1A (%)	Electricity cost for Class 1A (billion kWh)	Electricity increase compared to Class 1B (billion kWh)
1	14.1	28.0	3.5
2	11.7	27.4	2.9
3 Lower range	1.9	25.0	0.5
Upper range	35.6	33.3	8.7
Weighted value	19.3	29.3	4.7

thus, treating 97.9 billion m^3 of wastewater to Class 1B standard would require around 24.6 billion kWh.

The main implication of these results is that the introduction of China's draft *Discharge standard* is likely to increase electricity use for wastewater in China. The total increase over a five-year period constitutes a significant percentage of annual electricity use for wastewater treatment.

3.3. *Comparing cost and benefit of three scenarios that reduce contaminant discharge*

The third objective of this study was to compare cost (measured by electricity use) and benefit (measured by water footprint) of three scenarios that aim to reduce wastewater contaminant discharge, in order to assess the environmental benefit of the draft *Discharge standard* and suggest how benefit can be increased.

The benefit-to-cost ratio was greatest for Sub-scenarios 1.1 (ratio 32) and 3.1 (ratio 30), as shown in Table 5, which highlights the importance of increasing wastewater reuse and wastewater collection. Both of these sub-scenarios involved Class III water bodies (the higher quality of the two water bodies used in this scenario analysis). The latter scenario had lower benefit for the same volume of wastewater treated, but also required much less electricity; hence the benefit-to-cost ratios were similar. See Table S6 for a detailed grey water footprint for each scenario and Beijing's average influent concentration.

The environmental benefit associated with treating Class 1B wastewater to Class 1A before discharge (Scenario 2) was significant, with the decrease in grey water footprint outweighing a small increase in blue water footprint. The grey water footprint decreased by 25–50 million m^3 for each 100 million m^3 of wastewater treated. There was a 28% increase in electricity required to treat wastewater to Class 1A when compared with Class 1B. The blue water footprint associated with generating this extra electricity was small compared to the reduction in grey water footprint achieved, as was the case for all scenarios.

The benefit associated with Scenario 2 was greatest when wastewater was discharged into water bodies of better water quality (i.e. Class III). This was the case in all scenarios. The implication of this result is that efforts to reduce the release of wastewater contaminants should focus on discharge into water bodies of excellent water quality for maximum environmental benefit.

The benefit associated with upgrading wastewater treatment plants to Class 1A can be drastically increased if effluent is reused, not discharged, as shown by Scenario 3 in Table 5. There are two reasons for this increase. Firstly, no wastewater is discharged to the environment in Scenario 3, which eliminates the effect of wastewater on the health of water bodies (as measured by grey water footprint). Secondly, reuse of wastewater reduces freshwater use (as measured by blue water footprint). Scenario 3 is the only scenario where overall blue water footprint was reduced. The implication of this result is that Class 1A wastewater should be reused (as in Scenario 3) rather than directly discharged (as in Scenario 2) whenever there is demand for water for suitable purposes, such as industrial cooling or washing, agriculture, forestry, flushing, car washing and construction, and whenever distribution is feasible. Class 1A wastewater that would otherwise have been discharged into Class III water bodies should be given first priority because this sub-scenario rates among the two highest in terms of benefit-to-cost ratio (see Table 5).

Regarding reuse, it is important to note that reuse of Class 1B wastewater is also a way to reduce the discharge of wastewater contaminants and does not increase electricity use for treatment. According to the indicators of cost and benefit used in this study, reusing Class 1B would lead to the same grey water footprint reduction as Scenario 3, without the electricity cost.

The potential for Class 1B wastewater to reduce a city's blue water footprint may be lower than for Class 1A wastewater because

Table 5
Electricity cost and environmental benefit of three scenarios and seven sub-scenarios proposed for the case of Beijing.

Scenario	Sub-scenario	Receiving water body		Additional electricity use (kWh)	Grey water footprint reduction (m^3)	Blue water footprint reduction (m^3)[a]	Total footprint reduction (m^3)	Benefit vs cost (m^3/kWh)
		a	b					
1	1.1	Class III	Class III	46 million	1479 million	- 173,500	1479 million	32
	1.2	Class V	Class V		739.6 million		739.5 million	16
	1.3	Class V	Class III		345.6 million		345.4 million	7
2	2.1	Class III	Class III	13 million	50 million	- 48,740	49.95 million	4
	2.2	Class V	Class V		25 million		24.95 million	2
3	3.1	Class III	No discharge	13 million	300 million	+92.95 million	393.0 million	30
	3.2	Class V	No discharge		150 million		243.0 million	19

[a] Calculation of water for electricity generation in Beijing is provided in Table S2.

the scope of reuse for Class 1A wastewater is greater than Class 1B. Class 1B wastewater meets the standard for reuse for industrial washing, agriculture, forestry and urban greening (Ministry of Water Resources, 2007). Class 1A wastewater can be used for the same purposes as Class 1B and can also be used for industrial cooling, toilet flushing, dust control, car washing and construction. The implication of this is that reuse of Class 1A is more feasible and more important than reuse of Class 1B, particularly in cases where treatment to Class 1A is unavoidable due to government regulation.

Treating raw wastewater to Class 1B standard rather than discharging it directly without treatment (Scenario 1) offers the greatest benefit in terms of grey water footprint reduction, regardless of the water quality standard of the receiving body. This is due to the large difference between the concentration of untreated and Class 1B effluent, compared to the difference between Class 1B and Class 1A effluent. Scenario 1 reduces COD discharge by almost 300 mg/L, compared to only 10 mg/L for Scenarios 2 and 3. Electricity cost is also higher; the increase for treating untreated wastewater to Class 1B in Scenario 1 was 0.46 kWh/m^3, compared to an increase of 0.13 kWh/m^3 for Scenarios 2 and 3. The implication of this result is that increasing wastewater collection in urban areas should be a priority alongside increasing reuse even when effluent is discharged into low quality water bodies. These scenarios lead to the greatest benefit-to-cost ratio.

The benefit-to-cost ratio of each scenario and sub-scenario can be significantly affected by a 10% variation in electricity intensity but the general conclusions stated above still hold. This is based on a sensitivity analysis in which input parameters were varied by 10% and the effect on the final output (i.e. benefit-to-cost ratio) was noted. If Class 1A electricity use were to decrease by 10%, the benefit-to-cost ratio for Scenario 3.1 would increase from 30 to 56, making this scenario much more beneficial than Scenario 1.1. By contrast, if the electricity use of Class 1A were to increase by 10%, the benefit-to-cost ratio of Scenario 3.1 would decrease from 30 to 21, two thirds of the ratio for Scenario 1.1. A 10% change in Class 1B electricity use would have an impact of similar magnitude on the benefit-to-cost ratio. If Class 1A electricity use were to decrease by 10% and Class 1B electricity use were to increase by 10% at the same time, Scenario 3 would become by far the best scenario in terms of benefit to cost. In each case, however, Scenario 1.1 and 3.1 remain the top scenarios, or remain among the top three. A 10% change in the COD and NH_4–N concentration of untreated, Class 1B and Class 1A wastewater can impact results by changing the grey water footprint reduction, but the change is small compared to that caused by changes in electricity intensity (see Figs. S1 and S2).

The implications of this sensitivity analysis is that accurate calculation of Class 1B and Class 1A electricity intensities is particularly important, as it can significantly impact the benefit-to-cost ratio. That said, the ranking of scenarios tends to remain similar even when benefit-to-cost ratios change significantly. Nevertheless, this study uses multiple years of data from many plants across Beijing to produce a reliable estimation.

There are a number of limitations associated with this scenario analysis. On the cost side, the sole measure of cost is the operational electricity use associated with wastewater treatment. The energy embedded in extra infrastructure associated with each scenario (e.g. to construct extra wastewater treatment plants or treatment units, or install piping required for distribution of reclaimed wastewater) and the electricity used to pump Class 1A wastewater to the user (i.e. in Scenario 3) is not included. Other costs incurred during treatment (e.g. chemicals) or construction (e.g. concrete) are also excluded. The difference in the cost of sludge treatment by Class 1A and 1B plants is not included, although a comparison of sludge produced per cubic of meter of wastewater before and after upgrade by plants in Group 2 did not reveal a significant increase in volume. On the benefit side of this scenario analysis, water footprint is just one method of calculating the environmental benefit of a change. It was deemed the most appropriate for this study, but it is not without limitations. For example, grey water footprint reduction only considers the influent and effluent concentrations and the water quality standard of the receiving water body. It does not consider the function of the water body. Therefore, in the case that one receiving body is a municipal drinking water source and the other is not, reducing contaminant discharge to the former could have extra benefits for human health, even if all other factors are the same (i.e. influent, effluent, surface water quality). This would not be reflected in the grey water footprint.

4. Conclusion

This study estimated the energy footprint and environmental benefits associated with China's plans to implement stricter wastewater discharge standards using the country's largest database for wastewater treatment plants. These plans, recently outlined in a major policy document (*Action plan for water pollution prevention and control*) and currently drafted into the first overhaul of national discharge standards since 2002, would require numerous existing and future plants to meet China's highest discharge standard, Class 1A, rather than lower standards, of which Class 1B is the most commonly used. The study finds:

- Plants treating to Class 1A tend to use between 2% and 36% more electricity than plants treating to Class 1B. These upper and lower values were calculated by comparing Class 1A and Class 1B plants for 2017. An increase of 12% was estimated by comparing electricity use for 316 plants from across China before and after a clear and sustained change in effluent quality.
- Extra electricity use China's wastewater sector over the period of 2016–2020 as a result of the new *Discharge standard* would be equivalent to between 3 and 63% of China's total electricity for wastewater for the year 2015.
- Analysis of three scenarios for reducing wastewater contaminant discharge showed that the benefit-to-cost ratio of treating wastewater to Class 1A rather than Class 1B and reusing it was more than seven times the benefit-to-cost ratio of treating to Class 1A and then discharging. Thus, while there is benefit associated with improving the quality of wastewater effluent, plant upgrades and construction of new plants should also incorporate plans for how effluent can be reused rather than discharged. This would make the added environmental impact of extra electricity use more justifiable.

The results of the study may help policy makers in China understand the impact on energy use of China's new wastewater standard and provide policy makers with suggestions for increasing the environmental benefit of reduced wastewater contaminant discharge. These suggestions could be incorporated into the *Discharge standard* or related policy.

Future research could focus on incorporating energy embedded in new infrastructure and electricity for pumping of reclaimed wastewater into the benefit-to-cost ratio. Additionally, the environmental benefit of each scenario could be assessed using alternative methods and the result could be compared to the water footprint method used in this study.

Declarations of interest

None.

Acknowledgements

This work was supported by the National Key Research and Development Program of China for International Science & Innovation Cooperation Major Project between Governments [2016YFE0118800] and the Major Science and Technology Program for Water Pollution Control and Treatment [2017ZX07108002].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.01.204.

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