Maximizing eco-environmental gains

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Maximizing eco-environmental gains: Exploring underground wastewater treatment plants in Beijing for sustainable urban water management

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ABSTRACT

This study assessed the evolution of wastewater systems during the rapid urbanization of Beijing, with special focuses on the carbon footprints and growing underground WWTPs (u-WWTPs). Specifically, the Bishui plant (in situ constructed u-WWTP) was assessed in detail regarding eco-environmental benefits. Our results showed that, the direct emission intensity of 65 WWTPs decreased from 0.47 to 0.24 kg CO_{2eq}/m^3, when the electricity intensity increased from 0.22 to 0.39 kWh/m^3 from 2010 to 2020. Bishui u-WWTP emitted 36.6 kt CO_{2eq}/year (0.09 kg CO_{2eq}/m^3), with electricity intensity of 0.43 kg CO_{2eq}/m^3. Additionally, compare to the hypothetical relocating scenario, it saved 6.67×10^4 m^2 land and 33.0 kt CO_{2eq}/year, and the created urban river carries 6.5×10^{13} J/year heat outside town. The evaluation and balance of choice for conventional or underground WWTP should be made case by case. However, this study demonstrated that u-WWTP is not only a construction manner, but a sustainable management model with positive eco-environment effects, algin with future city expansion, and circular economy visions.

1. Introduction

As early as 3000 BC., the first sewage system emerged in the city of Harappa and Moenjo-Daro, with the original mission of guaranteeing public health and sanitation (James, 1998). Till the turn of 20th century, the development of population and pollution bring the second mission of pollutants removal into modern centralized wastewater management, such as removing organic carbon, nitrogen, and phosphate to protect receiving water bodies (Lofrano and Brown, 2010). Entering 21st century, under the stress of water scarcity and climate change, water reuse and resource recovery have clearly become new trend for urban wastewater management (Takashi et al., 2007; Yadav et al., 2021). The latest estimation in 2021 showed that global wastewater production is around 359.4 billion m^3 yr^-, 63 % is collected and 52 % is treated (James, 1998). Most of the wastewater management infrastructure has been constructed in the late 20th century and early 21st century (Jones et al., 2021). For example, the national statistical data showed that U.S. constructed 2 million kilometers drainage network and 16,000+ WWTPs with a capacity of 83.9 billion m^3/year [6], while China constructed 0.8 million kilometers drainage network and 6000+ WWTPs with a capacity of 76.7 billion m^3/year [7]. The great achievements in wastewater management since 20th century have shown essential value in protecting public health and natural environments from contaminants in wastewater. However, there is still more than 170 billion m^3 yr^{-1} to be collected and treated, most of which is generated in not affluent but highly populated regions. Besides, toady, the wastewater management is facing multiple challenges of aging infrastructures, increasing urbanization, worsening climate change and other uncertainties (Larsen et al., 2016; Dominguez and Gujer, 2006; Smith, 2009). Hence, it is urgently needed to learn lessons from fast developed, heavily populated, and rapid constructed regions to come up with a suitable and sustainable wastewater treatment and management solutions.

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During the whole history of wastewater system evolution, finding locations for WWTPs has always been a critical question from social, technical, and economic perspectives, which related to its social acceptance, system efficiency, and capital investments (Huh et al., 2020). It is a common phenomenon that WWTPs locate at the fringe of urban area due to people's psychological rejection and their repellant odors, noises, health risks and visual impacts. Though a minimum distance to residential zones is required, there is so-called locally unwanted land use concepts (Fu et al., 2022). Unavoidably, the residents near WWTP suffering from obnoxious facilities and value depreciation of their own properties (Gerrard, 1993). Under new challenges, the historical headache met emerging trigger points, questioning how the current wastewater managing system can be the best solution for the changing world as it has been since the beginning of the 20th century (Larsen et al., 2016; Wang and Gong, 2018). The growing population, continuous urbanization, and city expansion raising up the needs of relocating and/or enlarging WWTPs within the limited land onsite (Dominguez and Gujer, 2006; Wang and Gong, 2018). For example, the dramatic city expansion led to 1.5 times increase of urban (built-up) area from 1990 to 2018 (almost 800,000 km^2) (Qu et al., 2019). The urban area is projected to be 1.2 million km^2 by 2030, which will be three times of that in 2000 (Broere, 2016). Meanwhile, the worldwide revolution that transforming WWTPs into resource recovery plant asking for local reuse of water, heat and chemicals rather than collecting wastewater all the way outside the city and sending the resources back to the downtown via pipes or trucks with high capital costs and carbon footprints (Yadav et al., 2021; Wang et al., 2020). Therefore, the location selection becomes crosslink of the historical mission and sustainable vision of wastewater management system.

Potentially, the above-mentioned conflicts and difficulties in WWTP location selection might be solved by constructing underground WWTPs (U-WWTPs) at the optimal locations. The U-WWTP was an established technical system as early as 1940s-1950s in Sweden (Gong et al., 2020). The Henriksdal plant was constructed and operated since 1941 served 700,000 people in 1970s, which has been expanded and serving about 1 million people in the Stockholm region. Another example is the Dokhaven sewage treatment plant in Rotterdam, the Netherlands. Dokhaven was constructed and operated since 1987 served 470,000 people, which is also operational today (Seto et al., 2012). In 1970s, it was very difficult to find a suitable location for southern and western part of Rotterdam, the centralize system with treatment plant located outside the town would become too expensive if including the investment of constructing new sewer networks. In the end, underground plants were constructed at outlets of several sewer districts at Dokhaven, in the middle of developing residential area, on top of which a park and apartment houses were constructed. Though there is debate regarding the high construction and operation cost, the U-WWTP would still be good option since its minimal land occupancy (1/5–1/2 of conventional WWTP) and advantages on sound- and stench-insulation (Wang et al., 2015). There has been a growing trend of U-WWTP construction in China in the last decade, the total capacity has reached 15 million m^3/day.

Beijing, as a highly populated and fast urbanizing megacity, has been experiencing revolutionary development of wastewater management while expanding rapidly since 1990s. This study presented the wastewater management system evolution in Beijing, with a special focus on the trend of underground plants that emerged last decade. The eco-environmental and economic benefits were assessed based on in situ sinking of one WWTP that originally planned for re-locating because of the urbanization, which was generalized for other underground WWTPs in Beijing and elsewhere in China. We demonstrated extendable wastewater management model for sustainable urbanization and argue that relative centralization rather than high centralization or source separation might be the best solution for future wastewater management. Wastewater management system construction requires long planning horizons. This study is meaningful for both the urgent infrastructure renewing in developed countries and new building of infrastructures in developing regions.

2. Materials and methods

2.1. Wastewater management in Beijing

Beijing, the capital of China, is a mega city in the north of China. By 2020, the city covers more than 1000 km^2 with a population of 21.9 million (19.2 million live in urban area) and gross domestic product of 3594.3 billion RMB. The wastewater treatment capacity is 7.1 million m^3/day, which equals to 0.32 m^3/person/day. Most of the wastewater treatment plants and sewage networks were constructed after 1990s. The city expansion data was obtained from Aerospace Information Research Institute, Chinese Academy of Sciences (Isgård, 1975), and the wastewater treatment capacity and facility data was obtained from governmental database, such as National Bureau of Statistics (http://www.stats.gov.cn/).

2.2. Water quality changes and water environment improvements

The historical data on chemical oxygen demand (COD) and total nitrogen (TN) of wastewater treatment plants influents and effluents between 2002 and 2020 were obtained from regular monitoring program in the National Urban Sewage Treatment Management Information System (http://www.mohurd.gov.cn).

2.3. Carbon emission accounting and reduction assessment

Direct greenhouse gas emissions in wastewater management mainly include N_2O and CH_4. The emission factors (EFs) were selected based on IPCC2019 guidelines (Table 6.3, Table 6.8A) (Meijer, 1988). The emission of N_2O and CH_4 were calculated using equations 1 and 2, as given below.

$$N_2O_{\text{ emission}} = N_2O_{\text{ TP}} + N_2O_{\text{ effluent}}$$
$$= EF_{\text{ TP-N2O}} \bullet TN_{\text{ removed}} + EF_{\text{ effluent-N2O}} \bullet TN_{\text{ effluent}} \quad \text{(E1)}$$

$$CH_4{}_{\text{ emission}} = CH_4{}_{\text{ TP}} + CH_4{}_{\text{ effluent}}$$
$$= EF_{\text{ TP-CH4}} \bullet COD_{\text{ removed}} + EF_{\text{ effluent-CH4}} \bullet COD_{\text{ effluent}} \quad \text{(E2)}$$

Specifically, in the treatment plant, $EF_{\text{TP-N2O}} = 0.05$ kg N_2O/kg TN and $EF_{\text{TP-CH4}} = 0.0075$ kg CH_4/kg COD, while in the effluent (receiving waterbody), $EF_{\text{effluent-N2O}} = 0.016$ kg N_2O/kg TN and $EF_{\text{effluent-CH4}} = 0.009$ kg CH_4/kg COD. According to IPCC 2019, it is generally assumed that emission from well-operated centralize treatment plant would be lower than that from polluted receiving waterbody discharged with non- or not properly treated wastewater. All emission factors used in this study are summarized and given in Table S1.

Indirect GHG emissions mainly include electricity and chemicals consumption. Electricity and chemical consumption data of Bishui plant was used for indirect GHG emissions calculation. The indirect GHG emissions were calculated based on Eq. (3):

$$CO_{2-\text{indirect}} = EF_{\text{ grid}} \bullet W + EF_{\text{ chem}} \bullet M \quad \text{(E3)}$$

where EF_{grid} was regional power grid baseline emission factor in China, which was 1 kg CO_2/kWh for Beijing (Feijen, 1981); W is the total electricity consumed, EF chem is different for chemicals, and the factors summarized and used by Li et al. was used in this study (He et al., 2018), M is the total mass of chemical consumption.

2.4. Longitudinal assessment of above and underground WWTP of Bishui

Bishui plant was built in 2002 in Tongzhou District, Beijing, China. It occupies an area of 230,000 m^2, serves 0.7 million people in the region, with a capacity of 100,000 m^3/day. The effluent fulfills I-B standard according to the Chinese regulation GB18918–2002, COD < 60 mg/l, TN < 20 mg/l, TP < 1.0 mg/l, BOD < 20 mg/l [26].The new Bishui plant was re-built on the same site underground (in situ sinking) without interrupting old stream operation. The treatment capacity of new plant was enlarged to 180,000 m^3/d, occupied only 1/3 previous area (73,000 m^2), when the effluent quality improved to Beijing discharge standard of pollutants for municipal wastewater (DB11/890–2012), COD < 30 mg/l, TN < 15 mg/l, TP < 0.3 mg/l, BOD < 6 mg/l. Above the underground WWTP, Bishui park has been constructed. More than 2/3 of the effluent was reclaimed and reused.

2.5. Field measurements of CH_4 and N_2O emission

The underground WWTP after 2017 equipped with air collection and treatment system. The central ventilation system collects air from each treatment step/unit separately and sends it to air treatment system. The air samples were taken from each unit before and after air treatment system. The sampling was conducted three days in one week, and three samples (morning, noon, afternoon) were taken each day. The CH_4, N_2O and CO_2 were analyzed by gas chromatography (GC-2010plus, Japan) as previously described by Y. Chen (Bartram et al., 2019). In short, air flow at 40 mL/min, column temperature 60 °C, sample injection port temperature 120 °C, detector temperature 300 °C, the volume was set by 10 μL sample loops.

2.5. Comprehensive emission reduction accounting of Bishui u-WWTP

The in situ sinking of upgraded WWTP achieved emission reduction in the following ways:

1) **Treatment performance.** Better treatment performances because of the higher temperature compared to conventional WWTP, e.g., higher COD removal efficiency. This part of reduction is calculated based on the removal efficiency of contaminants and the different EFs adapted by IPCC2019 for treatment processes and receiving water bodies (Meijer, 1988).
2) **Localized reuse.** Local reuse avoided additional collection of wastewater and distribution of reclaimed water. To simplify the calculation, the wastewater collection and reuse water distribution pipes construction associated emission reduction is excluded from this study. This part reduction only considered the reduction resulted from avoiding re-distribution reclaimed water to point of use, which is calculated by using the average drinking water distribution emission factor in Beijing from previous study in China, $EF_{distribution} = 0.19\ kWh/m^3 = 0.19\ kg\ CO_2/m^3$. (Lizhe et al., 2023)
3) **Secondary source.** The reused water replaces original drinking water production and distribution to the point of use. This part of reduction is calculated by using national average emission factor for sourcing, treatment and distribution of drinking water from previous study in China, $EF_{drinking\ water} = 0.29\ kWh/m^3 = 0.29\ kg\ CO_2/m^3$. (Du et al., 2023)
4) **Air treatment.** Air treatment system remove smell and partially GHGs. This part of reduction is calculated by directly measuring GHGs before and after air treatment facilities.
5) **River restoration.** The discharged water restored a small local river that created a city cooling effect, which benefited from continuous river flow carrying heat outside the region. The carbon reduction benefit was calculated using the reduced air temperature according to the following equation (Administration, S. E. P 2002; Guo et al., 2020; Smith et al., 2017):

$$\Delta Q = \Delta T \bullet \rho_c \quad \text{(E4)}$$

ΔQ stands for the heat reduced per unit volume at unit time (1 h) by the blue space (J m^{-3}); ΔT is the decrease of air temperature (°C) and ρ_c represents the estimated volume heat capacity of the air (1256 J m^{-3} $°C^{-1}$).

In the hot summer days, the inhabitants inevitably use air conditioners to create comfortable indoor-environment consuming energy. The environmental benefits of air temperature reduction can be related and converted to energy savings from cooling effects of green and blue space. The energy saving is calculated by the following equation, considering the transforming efficiency of heat into electrical energy.

$$ES = \alpha \bullet COP \bullet \Delta Q \quad \text{(E5)}$$

ES stands for energy saving, ΔQ is the reduced air heat, α stands for the coefficient of heat transforming into electrical energy (1 $J = 0.278 \times 10^{-6}$ kWh), COP stands for the coefficient of air conditioner performance (mean value 2.9 was used).

Emission reduction associated with avoided infrastructure construction, such as collection sewage and reuse water redistribution pipes, is not counted in this study. The carbon reduction by the green park (15,000 m^2) on top of the underground WWTP was also not counted in this case, because the contribution is too low compared to other categories.

2.6. Trading index between electricity and direct emission

When the wastewater treatment plant is upgraded, especially adapting U-WWTP and tertiary treatments, the total energy consumption and average energy intensity would have significant increase, which will lead to increase of indirect GHG emission. Meanwhile, attributed to the better removal of contaminants (e.g., COD), the direct emission would decrease when the emission from receiving water body is included. Therefore, it is somehow trading of direct emission with energy input.

The decreased direct emission intensity can be calculated by the following equation:

$$\Delta EMI_{direct} = EMI_{original} - EMI_{upgraded}\ (kg\ CO_{2eq}/m^3) \quad \text{(E6)}$$

ΔEMI_{direct} stands for the decreased emission intensity, $EMI_{original}$ stands for the emission intensity before upgrading and/or in situ sinking, and $EMI_{upgraded}$ stands for the emission intensity afterwards.

The increased energy intensity can be calculated by the following equation:

$$\Delta ENI_{electricity} = ENI_{upgraded} - ENI_{original}\ (kWh/m^3) \quad \text{(E7)}$$

$\Delta ENI_{electricity}$ stands for the increased electricity intensity, $ENI_{upgraded}$ stands for the electricity intensity after upgrading and/or in situ sinking, and $ENI_{original}$ stands for the electricity intensity before changes.

As such, the reduced emission per unit of electricity consumption can be calculated by the following equation:

$$EER_{direct} = \Delta EMI_{direct} / \Delta ENI_{electricity}\ (CO_{2eq}/kWh) \quad \text{(E8)}$$

EER_{direct} stands for electricity contributed emission reduction, which is the CO_{2eq} emission intensity reduction achieved by consuming 1 kWh electricity.

To quantify the trading of direct emission from wastewater with electricity, electricity net emission reduction ($NER_{electricity}$) was defined and calculated as the differences between the CO_{2eq} emission factor of electricity generation and transportation ($EF_{electricity}$, kg CO_{2eq}/kWh) and electricity contributed emission reduction (EER_{direct}, kg CO_{2eq}/kWh).

$$NER_{electricity} = EER_{direct} - EF_{grid}\ (CO_{2eq}/kWh) \quad \text{(E9)}$$

$NER_{electricity}$ stands for the net emission reduction achieved by consuming 1 kWh electricity. Negative NER $_{electricity}$ means additional emission caused by electricity input during wastewater treatment, while positive NER means net reduction achieved. EF $_{grid}$ depends on local energy structure, which will be little if pure renewable energy is used and the energy sector is carbon free.

3. Results and discussion

3.1. City expansion and wastewater management system evolution 1990–2020

By 2020, Beijing has an urban area of 1103.75 km^2, and 65 wastewater treatment plants with a capacity of 7.11 million m^3/day and sewage networks of 17.9 thousands kilometers. The average of 0.32 m^3/person/day is much higher than the national average 0.14 m^3/person/day. Though there is a debate on the choices between conventional and underground plants due to the high construction and operation cost of underground plants, the number of underground plants in Beijing increased rapidly (Wang et al., 2015). After 2010, 10 u-WWTPs were constructed, the capacity of which ranges 60,000 to 600,000 m^3/day, with a total capacity of 1.58 million m^3/day. Overall, the u-WWTPs account for more than 20 % of the total capacity in Beijing in 2020, and around 50 % of the increased capacity since 2010.

Fig. 1 shows the urban area expansion and the construction of WWTPs within central urbanized region of Beijing between 1990 and 2020. From 2000 to 2020, the urban area expanded 40 % from 791.52 km^2 in 2000 to 1103.75 km^2 at a rate of 15.61 km^2/year. For wastewater management, the first primary wastewater treatment plant was constructed in 1960s, with a capacity of 200,000 m^3/day. No secondary wastewater treatment plant was constructed until 1990 (Zhao et al., 2020). Since then, the wastewater infrastructure construction entered a rapid developing period, the wastewater treatment capacity increased by 270,000 m^3/year, while the sewage network inceased by 700 km/year. A good correlation was observed among the expansion of urban area, treatment capacity (Fig. 2a), sewer network (Fig. 2b), which shows the expansion of every 1 km^2 urban area associated with an increase of 16 km sewege pipes and 6400 m^3 wastewater treaetment capacity.

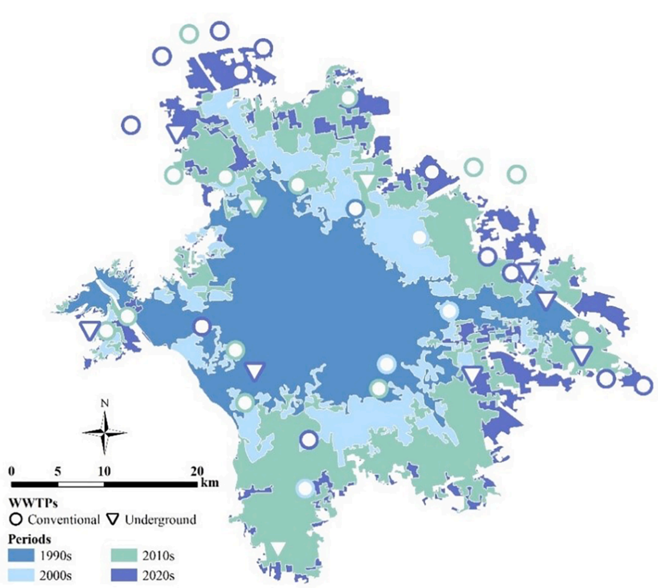

Fig. 1. City expansion and wastewater management system construction in the urban area in Beijing from 1990s to 2020s: city expansion and wastewater treatment plants construction.

3.2. Carbon emission from Beijing WWTPs from 2002 to 2020

With the increase of wastewater treatment capacity in Beijing, 709.8 kt COD and 69.0 kt TN were removed in 2020, while 42.5 kt COD and 13.1 kt TN dischaged into receiving water. In 2010, 450 kt COD and 37 kt TN were removed, 193 kt COD and 32.8 kt TN discharged into receiving water. According to IPCC2019, the carbon emission from wastewater treatment in 2020was slightly lower than that in 2010 (616 kt vs. 635 kt CO_{2eq}), though the volume of wastewater treated in 2020 was almost 2 times of that in 2010. As a result, the carbon emission intensity of 2020 was much lower than that of 2010 (0.24 vs. 0.47 kg CO_{2eq}/m^3). Improved wastewater management from 2010 to 2020 contributed to pollution control and emission reduction, especially after the implementation of "Action Plan for Prevention and Control of Water Poution" in 2015 (Xu et al., 2017). The direct emission intensity in this study is lower than previous study of carbon emission from wastewater in Beijing in 2017, which can be explained by the other work excluded potential emission from receiving water body, and used emission factors in IPCC2006 and IPCC2014 rather than IPCC2019 (Zhang et al., 2014). Another benefit was that the tertraiy treated wastewater is reclaimable. The amount of reclaimed wastewater reached 1.2 billion m^3 in 2020 in Beijing, which accounted for more than 27 % of the total water consumption of the Beijing city (Yang, 1994). Besides water saving, the avoided emission (compare to taking drinking water) by using reclaimed water is 348 kt CO_{2eq}/year.

For indirect emission associated with the electricity consumption, it was 1.0 billion kWh in 2020 (0.39 kWh/m^3) and 0.3 billion kWh (0.22 kWh/m^3) in 2010, which can be calculated as 1.0 Mt CO_{2eq} (0.39 kg CO_{2eq}/m^3) and 0.3 Mt CO_{2eq} (0.22 kg CO_{2eq}/m^3), respectively. The higher electricity intensity in 2020 than in 2010 can be attributed to the more intensive treatments applied that required higher energy input. Besides, the obtained electricity intensity in Beijing was in the lower range of the 0 - 1.12 kWh/m^3 in U.S.A and lower than the 0.40 - 0.43 kWh/m^3 in Germany (Wang and Huang, 2004), this might be because the WWTPs in Beijing were constructed more recently with the up-to-date technology and automatic system to optimize the system efficiency.

The combined emissions intensity were 0.63 kg CO_{2eq}/m^3 (2020) and 0.69 kg CO_{2eq}/m^3 (2010), which were comparable with previous studies in Beijing (0.60 kg CO_{2eq}/m^3, 2017) (Zhang et al., 2014). Comparing 2010 and 2020, it is like reducing direct emission in the expense of indirect emission (electricity consumption). According to E6 to E9, the difference of direct emission intensity (ΔEMI $_{direct}$) was 0.23 kg CO_{2eq}/m^3, and the difference of energy intensity (ΔENI $_{electricity}$) was 0.17 kwh/m^3, which lead the electricity investment contributed to direct emission reduction (EER $_{direct}$) becoming 1.35 kg CO_{2eq}/kWh. Taking EF $_{grid}$ of 1.00 kg CO_{2eq}/kWh, the net emission reduction (NER $_{electricity}$) contributed by electricity was 0.35 kg CO_{2eq}/kWh in Beijing. The electricity associated indirect emissions (EF $_{grid}$) depends on the local energy structure. If carbon zero power section can be achieved, e.g. U.S. pledged to establish a 100 % carbon-free eclectric power system by 2035 (China, 2015), the unavoidable direct emissions from human sewage will be traded by consuming green electricity. So far, the achieved trading benefits is 0.35 kg CO_{2eq} reduction per kWh additional electricity used (NER, −0.65 CO_{2eq}/kWh).

3.3. Eco-environmental benefits of Bishui u-WWTP

3.3.1. Water quality improvements and carbon emission reduction

After more than ten years, driven by the population growth and stricter standards, the plant is seeking quantity and quality upgrading possibilities in 2015. The continuous wastewater flow also requires functional operation of old streams during the upgrading work. Meanwhile, there is no available land onsite for enlarging the treatment plant. The original plan was to relocate the plant to a different site 13.4 km away from the current location, moving outside of the town (Fig. 3). In

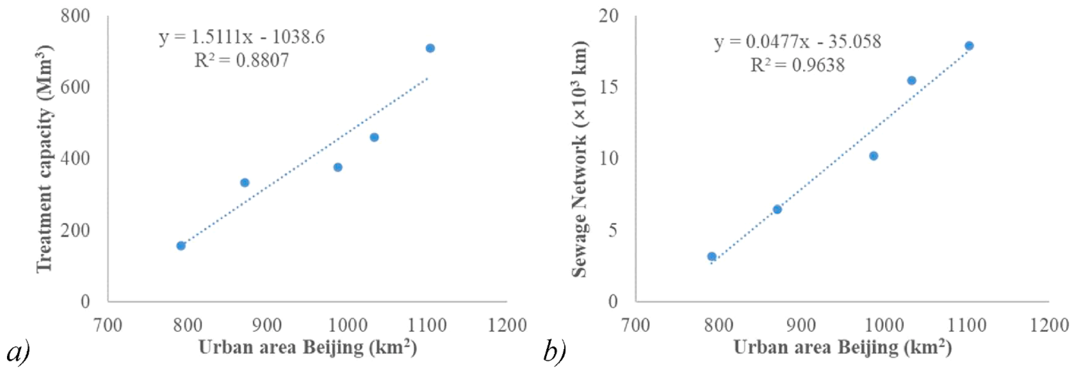

Fig. 2. Wastewater infrastructure contruction. a) the increase of treatment capacity developed with urban expansion; b) the sewage network developed with urban expansion.

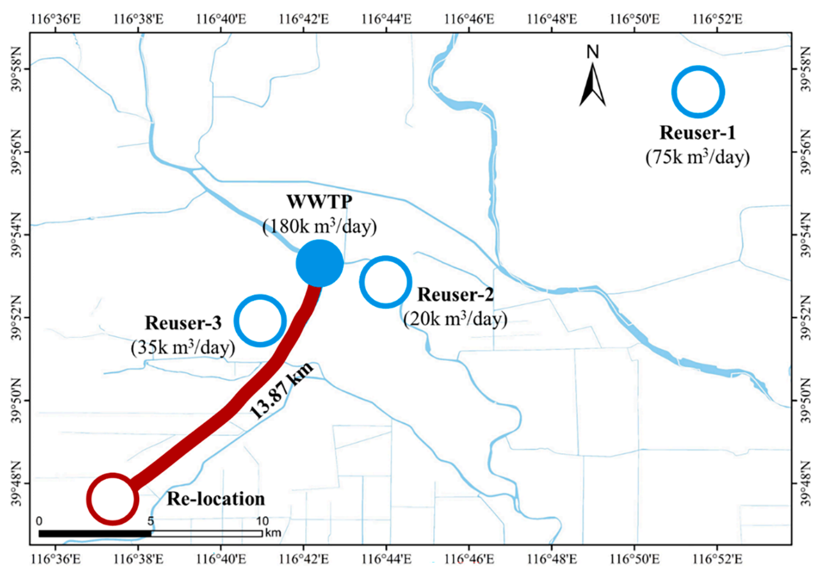

Fig. 3. The illustration of two options for Bishui Plant: a) re-location and rebuilding on another site 13.87 km away from the current location (red) vs. in situ sinking at the same site which closer to the water re-users and replenishing local reiver (blue).

the end, after quite some discussion and evaluation, the new Bishui plant was re-built on the same site underground (in situ sinking) without interrupting old stream operation.

For conventional plant period, COD removal rates flocculated between 68 and 95 % (Fig. 4a), among which all Januarys and Februarys showed the lowest efficiencies because of the cold winters in the Northern China (Zhou et al., 2022). After launching the underground plant, the COD removal efficiencies (92–95 %) were not only high, but also stable regardless of the seasons. This could because the upgraded tertiary treatments is embedded underground, which is better protected with heat preservation and favorable for bio-chemical processes (Xu et al., 2021). According to IPCC2019, the u-WWTP emitted 12.9 kt CO_{2eq}

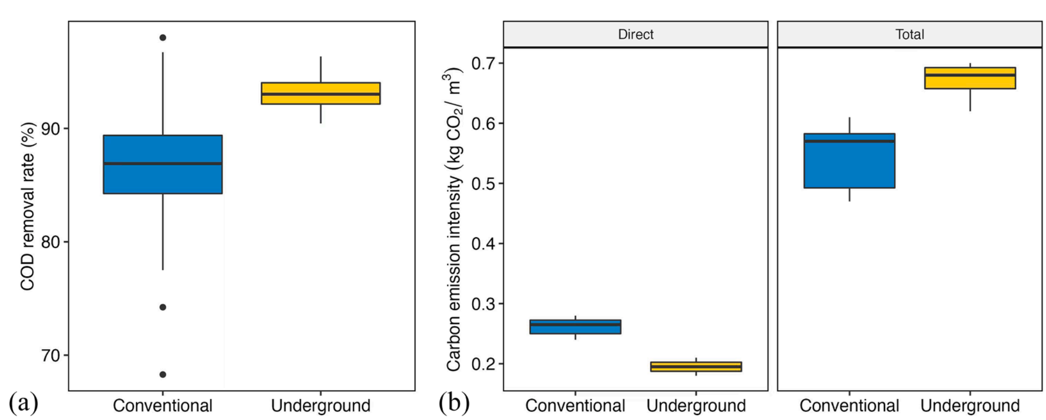

Fig. 4. Eco-benefits achieved by in situ sinking compared to WWTP relocation: a) better removal efficiency of COD in underground plant than the conventional plant, removal rate by year and month in Figure S1; b) direct and indirect carbon emission.

while treating 65.7 million tons of wastewater in 2020. Its direct carbon emission intensity (0.19 kg CO_{2eq}/m^3) was 29.6 % lower than conventional WWTP (0.27 kg CO_{2eq}/m^3), and 20.8 % lower than average intensity of 65 WWTPs in Beijing (0.25 kg CO_{2eq}/m^3) (Fig. 4b). This can be explained by the better removal of contaminants (e.g. COD) and lower CH_4 emission coefficient in WWTP than in receiving water body according to IPCC2019 (Meijer, 1988). When include electricity consumption, the emission intensity of u-WWTP was higher than conventional plant (0.62 vs. 0.57 kg CO_{2eq}/m^3). The additional electricity consumption contributed to 0.61 kg CO_{2eq}/kWh direct emission reduction (EER $_{direct}$). Considering the EF $_{grid}$ is 1.0 kg CO_{2eq}/kWh, the NER is - 0.39 kg CO_{2eq}/kWh.

Differently, according to field measurements, Bishui plant emitted 130 t CH_4 (treatment 35 t; network, 95 t) and 12 t N_2O (treatment), while removing 15 kt COD and 2.6 kt TN in 2020. This resulted in EF_{CH4} = 0.0023 t CH_4/t COD and EF_{N2O} = 0.0044 t N_2O/t TN during wastewater treatment, which were lower than IPCC2019 suggested values (CH_4, 0.0075; N_2O, 0.016) (Meijer, 1988). Besides, CO_2 emission coefficient was 0.789 kg/t COD, which is two orders of magnitudes higher than that of CH_4. CO_2 emission during wastewater treatment was not counted according to IPCC2019. However, considerable reduction would be achieved if such CO2 emission could be avoided.

The measured direct carbon emission intensity (0.09 kg CO_2/m^3) was lower than IPCC2019 calculation. The electricity intensity was 0.43 kWh/m^3 for u-WWTP and 0.30 kWh/m^3 for conventional Bishui WWTP, based on which the EER was 1.38 kg CO_{2eq}/kWh, and the NER became 0.38 kg CO_{2eq}/kWh. This means the trading of direct emissions with electricity can be highly eco-beneficial, which would be further enhanced under the vision of carbon free power sector, e.g., U.S. in 2035. (China, 2015; Wang et al., 2016)

3.3.2. Extra carbon benefits from in situ sinking u-WWTP

Remarkably, the tertiary treatment (for reuse) and the waste air collection-treatment (for odor control) also have significant carbon reduction benefits. As shown in Fig. 5, the water reuse achieved 19.1 kt CO_{2e}/year reduction. The waste air treatment achieved a direct emission reduction of 1.4 kt CO2ep/year. However, how is CH_4 removed during air treatment is not clear yet, future study should be carried out uncover the mechanism and optimization of GHGs removal. Moreover, the in situ u-WWTP solution rather than relocating-reconstructing saved sewage collection network and pipes re-distributing water back to the town for reuses (2 × 13.87 km). It saved energy for distributing the reclaimed water, gained another reduction of 12.5 kt CO_{2eq} /year. In total, the Bishui u-WWTP achieved 33 kt CO_{2eq} reduction, when generated 36.6 kt CO_{2eq} per year.

Besides, the well-treated effluent discharged directly as surface water and created a shallow urban river (width 10 m, length 5.0 km). According to E4 and E5, taking the ΔT = 1.2 °C (Administration, S. E. P 2002), cooling degree days = 90 days (Guo et al., 2020), the urban river cooling effect carries 6.5 × 10^{13} J/year heat outside town, which equals to 52.5 k CO_{2qe}/year reduction. Additionally, there is a great potential for thermal energy recovery and reuse since the underground plant is in the middle of residential area with short distances to the potential consumers (<100 m). This promising reduction potential could be up to 12.8 kt CO_{2eq} (calculated by E4 and E5). The realization of ~1/4 potential will make the Bishui underground plant carbon neutral.

3.3.3. Economic and other benefits

Considering the u-WWTP alone, its investment cost is much higher than that of conventional above ground plants (Table 1, 0.53 billion RMB more expensive). However, when including costs on constructing new sewage collection and reuse water re-distribution networks under relocating scenario (moving out town, Fig. 3), the construction investment of relocating option becoming similar or even higher than u-WWTP. Additionally, the saved land (6.67×10^4 m^2) could be used for green space or commercial purposes, which will offer extra environmental or economic benefits. For the operational cost (e.g., electricity consumption), the u-WWTP is higher than that of conventional plants, contributing to higher indirect emission. However, as mentioned above, it should be noted that such increases in indirect emission is compensated by decreases in direct carbon emission because of the better removal of COD and TN from wastewater.

Besides, the in situ sinking of Bishui plant created considerable residence-friendly urban blue-green spaces (BGS), such as the blue space of above-mentioned artificial river, and the green space of park constructed on the saved land. The BGS is popular spot for exercises, student excursion, pilot research, and entertainments, which is good for local climate, education, scientific activity, and physical and mental health of the residents (Li et al., 2012).

Table 1
Cost analysis for Bishui case, comparing relocating conventional plant and in situ sinking upgrading plant.

	Land (m^2)	Investment (billion RMB)			
		Land	Plant	Network	Total
Relocating	14×10^4	2.84	0.54	0.62	4.00
In Situ Sinking	7.33×10^4	1.49	1.07	0	2.86
	−6.67×10^4	−1.35	0.53	−0.62	−1.14

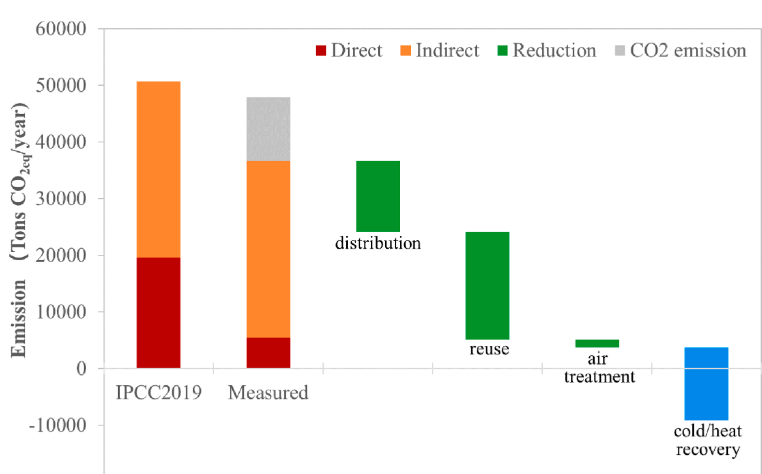

Fig. 5. Calculated and measured GHG emission and corresponded emission reduction attributed to in situ sinking, such as avoided re-distribution, implemented local reuse, air treatment, and (potential) thermal energy recovery.

3.4. General eco-benefits of u-WWTPs in Beijing and practical implications

Taking the carbon emission reduction benefits of Bishui for all 10 u-WWTPs in Beijing. The benefits could be enlarged by 90 times (1.58 Mt/day vs. 0.018Mt/day), which will roughly be a reduction of 2.97 Mt $CO_{2\text{-}eq}$ and saving of 6 × 10^6 m^2 land. Lately, the world population reached 8.0 billion in November 2022. As estimated by UN, the urbanization rate is 56.2 %, and there are 4.38 billion people lives in the city (Collins et al., 1978). By 2050, the total population will increase to 9.76 billion, the urbanization rate will increase to 68.4 % and 6.68 billion people will live in the city, which means considerable increase in both urbanization and city population (net flux of 2.3 billion people, 52.5 %). Worldwide, cities today are not equipped to address dramatic urban growth and strain on existing infrastructure in a sustainable way (Commission, E.-E. 2019). Especially, the rapidly expanding cities will need to tackle the increased demands for sustainable wastewater management, for which considerable land and innovative systems would be needed. Most of the population growth will take place in developing countries, for example, the Africa population is projected to increase from 1.3 billion to 2.5 billion in 2050, but it has only 20 % wastewater collection and treatment rate now (Jones et al., 2021; Collins et al., 1978).

China's experience over the last three decades, such as the wastewater system evolution in Beijing, may offer a feasible and sustainable solution to other countries. For the land occupancy, taking the average land occupancy of 1.51 m^2/m^3•day for wastewater treatment (Wang et al., 2015), the 210 Mm^3/day by more than 6000 treatment plants in China would have occupied more than 317 km^2 land. As achieved by Bishui plant in situ u-WWTP, more than 1/2 land (200+ km^2) could be saved, which would be the area of Amsterdam, Washington D.C., and two times of Paris. By 2021, there are 161 U-WWTPs in China, with capacity of 15.5 million m^3/day, the number of which is keep growing rapidly. The fast expanding of U-WWTPs not only solves the land crisis in the cities, but also meets the emerging need of local resource recovery and reuse for sustainability. Though expensive in construction and operation, it has clear eco-economic advantages from system perspective, with a special strength of providing stable service without conflicts with city expansion. Moreover, the feature of "not limited by location" makes it possible to optimize wastewater management system according to system efficiency. For example, it is possible to realize optimal degree of centralization of wastewater infrastructures (Gong et al., 2018), which may lead to revolutionary development on the existing wastewater management system after being the best solution for the world since the beginning of the 20th century (Larsen et al., 2016; McDougall et al., 2021). This would be especially meaningful for the less developed countries to develop their suitable and sustainable wastewater solutions, such as "Belt and Road initiative" countries (Economic and Division, 2018).

It should be mentioned that the additional benefits from in-situ sinking (underground) plant were based on the comparison of current plant with another plan, which did not happen in reality. This can be seen as assumed eco-economic benefits, but it did not really happen. Besides, it is undoubtable that construction of underground plant itself is expensive compared to conventional wastewater treatment plant. We do argue the U-WWTP offers great potential regarding its positive ecological effects, algin with future city expansion, and long-term economic return. However, it should be clear that the evaluation and balance of choice should be made case by case.

4. Conclusion

This study assessed the carbon emission from WWTPs in Beijing, with special focuses on the eco-economic benefits of the growing underground WWTPs from 2010 to 2020. The following conclusions can be drawn:

- For the 65 WWTPs, the direct emission intensity decreased by 49 %, while the electricity intensity increased by 77 % from 2010 to 2020.
- According to IPCC 2019, the direct carbon emission intensity of Bishui u-WWTP was 29.6 % lower than conventional WWTP (0.19 kg vs. 0.27 kg CO_{2eq}/m^3), and 20.8 % lower than average intensity of 65 WWTPs (0.25 kg CO_{2eq}/m^3).
- According to the measured data, the direct emission intensity was 0.09 kg CO_2/m^3. The measured EF_{CH4} (0.0090 t CH_4/t COD) and EF_{N2O} (0.0044 t N_2O/t TN) were much lower than IPCC2019 suggested values (CH_4, 0.075; N_2O, 0.016).
- For Bishui plant, the electricity intensity was 0.43 kWh/m^3 for u-WWTP (since 2018) and 0.30 kWh/m^3 for conventional WWTP (till 2018). The EER was 1.38 kg CO_{2eq}/kWh, and the NER became 0.38 kg CO_{2eq}/kWh, indicating the trading of direct emissions with electricity can be highly eco-beneficial.
- Compare to the hypothetical relocating scenario, the in situ construction of underground plants saved 6.67 × 10^4 m^2 land, reduced 33.0 kt CO_{2eq}/year, and the created urban river carries 6.5 × 10^{13} J/year heat outside town. Considering all 10 u-WWTPs constructed after 2010, would have saved 6 × 10^6 m^2 land and 297 kt $CO_{2\text{-}eq}$/year emission.

CRediT authorship contribution statement

Lujing Zhang: Writing – review & editing, Writing – original draft, Resources, Investigation, Formal analysis, Data curation, Conceptualization. **Yuchen Hu:** Writing – review & editing, Formal analysis. **Peng Li:** Writing – review & editing, Investigation. **Renke Wei:** Writing – review & editing, Methodology. **Hongtao Pang:** Writing – review & editing, Investigation. **Merle de Kreuk:** Writing – review & editing, Supervision. **Shen Qu:** Writing – review & editing, Supervision, Conceptualization. **Ka Leung Lam:** Writing – review & editing, Formal analysis. **Walter van der Meer:** Writing – review & editing, Supervision. **Gang Liu:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107698.

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