water

MDPI

Review

The Current Status, Energy Implications, and Governance of Urban Wastewater Treatment and Reuse: A System Analysis of the Beijing Case

Daohan Huang [1], Lin Jin [1], Jie Liu [2,*], Guoyi Han [3], Wei Liu [4] and Annette Huber-Lee [5]

[1] School of Urban Economics and Management, Beijing University of Civil Engineering and Architecture, Beijing 100041, China
[2] College of Engineering, Peking University, Beijing 100871, China
[3] Stockholm Office, Stockholm Environment Institute, 11523 Stockholm, Sweden
[4] Beijing Drainage Group, Beijing 100044, China
[5] Boston Office, Stockholm Environment Institute, Somerville, MA 02144-1224, USA
* Correspondence: jie.liu@pku.edu.cn

Abstract: Wastewater treatment and reuse are important means of addressing water scarcity and protecting the aquatic environment in urban areas. However, it comes at the cost of energy consumption and greenhouse gas emissions. However, the issues of governance and provincial-scale research have largely been ignored in current urban wastewater treatment and reuse studies. This paper summarizes the current status of 175 wastewater treatment plants (WWTPs) in Beijing, explores energy-intensive processes, energy consumption ratios, and the overall energy intensity of WWTPs, and maps the structure of urban wastewater treatment and reuse governance. The results indicate that most WWTPs in Beijing are medium or small in scale, treating wastewater at less than 200 thousand tons/day. Then, five energy-intensive subprocesses are identified, and their energy consumption ratios vary with treatment technologies and management factors, which calls for individual WWTP analysis and plant-specific strategies. The energy intensity of WWTPs in Beijing varies with treatment capacity and membrane bioreactor treatment technology used. Large-scale WWTPs employing MBR technology have a higher average energy intensity. Furthermore, the current coordination group and the four-layer policy system provide sufficient executive power and promote efficiency in departmental collaborations. Finally, inconsistent data, reductions in energy consumption, and the normalization of the governance structure are discussed, and policy suggestions are proposed.

Keywords: wastewater treatment plant; conceptual framework; energy intensity; energy-intensive processes; wastewater governance policy; wastewater management organization

Citation: Huang, D.; Jin, L.; Liu, J.; Han, G.; Liu, W.; Huber-Lee, A. The Current Status, Energy Implications, and Governance of Urban Wastewater Treatment and Reuse: A System Analysis of the Beijing Case. *Water* **2023**, *15*, 630. https://doi.org/10.3390/w15040630

Academic Editor: Alexandre T. Paulino

Received: 3 January 2023
Revised: 26 January 2023
Accepted: 27 January 2023
Published: 6 February 2023

1. Introduction

Water scarcity and aquatic environment deterioration have been widely recognized as two critical water challenges in urban areas, especially those in developing countries, that impair economic development and human health [1]. Eighty percent of the global population faces water security problems [2]. Ensuring the availability and sustainable management of water and sanitation for all has been proposed as part of the sustainable development goals (SDG 6: clear water and sanitation). Wastewater treatment and reuse are critical means of addressing both water challenges [3], requiring the capacity to treat wastewater in wastewater treatment plants (WWTPs) and the ability of the local government to manage wastewater. Therefore, in this research, the treatment capacity and governance ability related to urban wastewater treatment are studied, and energy consumption in WWTPs in Beijing is explored.

The reclaimed water in Beijing has become a stable source of water, and the scale of its reclaimed water use increased rapidly from 0.21 billion m^3 in 2003 to 1.2 billion m^3 in

2020. The Beijing authorities have issued multiple standards for wastewater treatment and discharge, reclaimed water use, and energy consumption in WWTPs, with stringent standards compared to those at the national level. These stringent effluent standards raise the operational costs of WWTPs and reclaimed water plants [4] and lead to high greenhouse gas emissions [5]. Furthermore, to protect the aquatic environment and conserve the local ecosystem, the Beijing authorities initiated their first three-year action plan (2013–2016) for wastewater governance in 2013, followed by two other three-year action plans for 2016–2019 and 2019–2022. These three three-year action plans not only raised the wastewater treatment rate and expanded the scale of reclaimed water use but also addressed rural water and sanitation issues via infrastructure construction and joint enforcement mechanisms. As a result, the government entities involved in wastewater management are clearly defined, and their working mechanisms are highlighted. Therefore, this study takes Beijing as a case study and summarizes its experiences with wastewater governance.

This study is organized as follows. First, a literature review is conducted and presented in Section 2, highlighting gaps in current review studies in WWTPs. Then, the quantity-intensity-governance framework is developed in the methodology section (Section 3). Our empirical analysis includes describing the current status of 175 WWTPs in Beijing, exploring the energy consumption of WWTPs in Beijing at three scales, and mapping both the entity and policy structure of Beijing's urban wastewater governance. The results and outcomes are presented in Section 4, followed by discussions of inconsistent data, reductions in energy consumption, and the normalization of the governance structure (Section 5) and conclusions (Section 6).

2. Related Work

Wastewater treatment and reuse are energy-intensive and have been widely explored as part of the urban water cycle in consideration of the water-energy nexus. This part of the urban water cycle is composed of wastewater collection, primary treatment, secondary treatment, tertiary treatment, distribution, and sludge treatment processes [6]. The energy intensity of the steps of the urban water cycle has been calculated and compared across different regions and countries, and the minimization of resource consumption and maximization of management efficiency are two core targets in related studies [7,8]. The issue of governance in WWTPs was regarded as the ownership of WWTPs [9], including public–private partnerships and public and private ownership. In practice, a decentralized wastewater system is believed to be more energy-friendly than a centralized wastewater system [10]. The use of constructed wetlands, a nature-based solution, is less energy-intensive than the use of WWTPs. However, there is still a lack of sufficient information on the long-run treatment performance of constructed wetlands [11]. Other studies have focused on individual WWTPs, aiming to investigate the application of renewable energy [12] and to evaluate energy self-sufficiency in WWTPs [13]. However, the issue of governance is not well integrated into this line of research, although it is the key to shifting from theoretical analysis to local practice.

Due to the rapid development of China's wastewater industry, most studies focusing on wastewater treatment capacity have been conducted at the national scale, aiming to review the number, spatial distribution, and treatment technologies of urban WWTPs and to analyze their energy consumption. For example, Yang et al., (2010) [14] analyzed the operational energy consumption and its influential factors of 599 China's WWTPs; Zhang et al., (2016) [15] reported the current state of 3508 WWTPs built in China's 31 provinces and cities; Su et al., (2022) [4] compiled a 10-year inventory of 6032 WWTPs across China to elaborate trade-offs between the elevated standard and the additional burden. The datasets used in recent studies include the public statistical data provided by the Ministry of Housing and Urban–Rural Development (MoHURD) and the Ministry of Ecology and Environment (MoEE), self-reported data from WWTPs in the National Urban Sewage Management Information System provided by the MoHURD, and survey data. This kind of research provides insight into the development of China's WWTPs based on data from different sources and years.

However, the distribution of WWTPs across China is uneven since more wastewater treatment facilities are located in areas with larger population densities and higher economic production in eastern China [16]. Most WWTPs in China are medium-sized or small, with a daily treatment capacity of fewer than 100 thousand m^3, and most of China's WWTPs run below their designed load/capacity [15]. Secondary wastewater treatment and biological processes were the primary processes applied in Chinese WWTPs [17] between 2006 and 2018 [14,18]. With stringent effluent standards and the enforcement of regional reclaimed water reuse policies, advanced treatment processes are expected to be widely adopted to produce high-quality reclaimed water, and energy consumption and greenhouse gas emissions from the wastewater treatment industry are expected to increase in the future [4]. Since the energy consumed in WWTPs is impacted by regional terrain, the volume of wastewater, effluent discharge standards, treatment processes, and load factors [19], these influencing factors should be considered in comparisons of energy consumption. Therefore, conducting a place-specific WWTP review and analysis is necessary to provide comprehensive insight into the development of local wastewater treatment industries, which still requires further research.

The most widely used frameworks in wastewater management include the integrated water resources management paradigm (IWRM; [20]), the management and transition framework (MTF; [21]), and the social-ecological systems sustainability framework (SES; [22]). These frameworks can be applied to wastewater management, which requires the involvement of water-related sectors, stakeholders, and the public, such as polycentric governance [23]. Apart from the various governance entities, laws and policies still need to be integrated into the wastewater management framework [24]. Law and policy systems that include emission and reuse standards, wastewater management plans, WWTP construction and operation guidelines, community initiatives, and adequate funding should be developed at the national, provincial, local, and community levels [23,25]. However, the lack of enforcement related to pollution monitoring and control has become one of the most significant barriers to wastewater management in developing countries such as India [26]. In China, pollution monitoring and control have been enhanced by installing online wastewater monitoring systems at WWTPs: a top-down monitoring system called China's River Chief system [27] and a bottom-up monitoring system, the 12345-complaint hotline [28]. However, current research is still inadequate in terms of mapping the wastewater governance entity and policy network. Still, Beijing has provided fruitful grounds for research through its experiences with wastewater governance as part of its efforts to manage wastewater during the last 20 years.

To address the gaps in the literature, this study aims to summarize the status of and experiences with wastewater treatment and reuse in Beijing and further calls for analyses of WWTPs at the provincial scale rather than macro analyses at the national scale, with useful suggestions for other provincial studies. There are three contributions in this study that complement current wastewater management research, that is, summarizing the current status of WWTPs at the municipal scale, using three datasets to conduct a holistic analysis of the energy consumption of WWTPs in Beijing, and mapping the governance structure of wastewater treatment and reuse in Beijing.

3. Methodology

A level-specific system approach needs to be developed to analyze wastewater treatment and reuse at the local level. Such an approach must focus on local practices and often faces data challenges [29]. To conduct the system analysis of urban wastewater treatment and reuse in Beijing, this study followed the framework of complex system engineering methodology [30], in which four pillars are included: boundary, elements, relations, and external environment. In this study, the boundary equals the Beijing and district administrative boundary; elements are those wastewater treatment plants or reclaimed water plants within the boundary, which are used to conduct quantitative analysis and map spatial distribution; relations focus on the water-energy nexus in specific elements and summarize their energy consumption characteristics; and the external environment includes the social-economic context of each district and the governance requirements of the Beijing municipal government, since both exert impacts on the quantity and intensity of urban wastewater treatment and reuse. The element, relation, and external environment are represented by quantity, intensity, and governance in this study, respectively, and the quantity-intensity-governance framework is presented in Figure 1. Governance exerts impacts on quantity and intensity; for example, stringent local standards (governance) will lead to higher energy intensity (intensity) and larger treatment capacity (quantity). Additionally, both quantity and intensity impact governance via the status of local water scarcity and the aquatic environment; for example, the low capacity (quantity) and efficiency (intensity) of WWTPs in Beijing pollute the local aquatic environment, requiring action plans (governance) to battle against pollution.

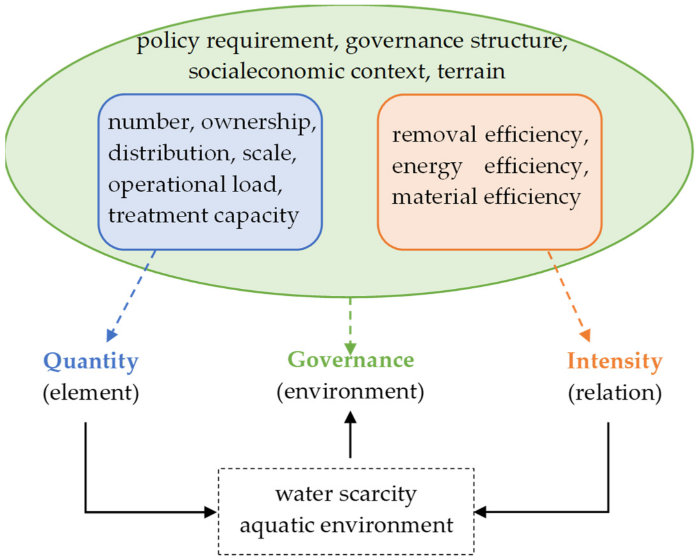


Figure 1. The quantity-intensity-governance framework for analyzing local wastewater treatment and reuse.

Three essential general steps for conducting a system analysis at the local level are identified based on the interactions between quantity, intensity, and governance. In the first step, the current status of local WWTPs is summarized. A local dataset of WWTPs is built to summarize the current status and conduct quantity analysis, including the total number, the treatment technology, and capacity, the location, the ownership, etc. Spatial analysis is used to compare the distribution of WWTPs and the socioeconomic context. In the second step, pollutant removal and the energy and material consumption of local WWTPs are explored. In energy consumption, the water-energy nexus analysis is conducted at three levels: typical WWTPs representing WWTPs and comprehensive analysis. Typical WWTPs are used to identify energy-intensive behaviors; the represented WWTPs aim to explore the energy consumption ratios of those energy-intensive behaviors. A comprehensive analysis, including all WWTPs, is conducted to explore the characteristics of local energy intensity. In the third step, the governance structure of urban wastewater treatment and reuse is mapped, including governance agents, relations, and tools. Agents and relations at the local level can be identified from action plans and sector duty through text analysis and stakeholder meetings. Tools include strategies, policies, and standards issued by the government at the higher level and by the local government.

The basic information on WWTPs is obtained from the national wastewater centralized treatment facility list (2020) issued by the MoEE in November 2020, and data on wastewater treatment technologies for the public and private sectors are collected from the online environmental information open-access platform (http://xxgk.bevoice.com.cn/monitor-pub/index.do). Based on these two data sources, six general and specific characteristics of 175 WWTPs in Beijing are listed in Table S1 in the Supplementary Information (SI). Statistical data sources include the Urban Drainage Statistical Yearbook (2018) and the Beijing District Statistical Yearbook (2020), and official documents can be found online at the municipal and district government websites.

4. Results and Outcomes

4.1. The Current Status of WWTPs in Beijing

Since advanced treatment processes have been widely adopted in Beijing's WWTPs, some WWTPs have been renamed reclaimed water plants, in which wastewater is treated and reclaimed.

4.1.1. The Scale and Ownership of WWTPs and Their Treatment Processes at the Municipal Scale

A total of 175 WWTPs in Beijing are included in this study. The daily wastewater treatment capacity of the 175 WWTPs varies from 500 tons to 1 million tons, and the largest WWTP in Beijing has a daily wastewater treatment capacity of 1 million tons: the Gaobeidian WWTP located in Chaoyang District. Eighty percent of the 175 WWTPs are small-scale WWTPs, and their daily wastewater treatment capacity is less than 50 thousand tons. Only 8 WWTPs are large-scale facilities with a daily capacity of more than 200 thousand tons of wastewater, all located in the central area of Beijing. Other medium-scale WWTPs, which treat 50–200 thousand tons of wastewater per day, are distributed across the ten districts of Beijing.

Regarding the ownership of WWTPs, most WWTPs in Beijing are state-owned. However, public–private-partnerships (PPP) and build-operate-transfer (BOT) projects have been advocated as options for sharing the water market with the private sector since 2001. In total, 150 of the 175 WWTPs are operated by state-owned enterprises, i.e., central government-, municipal-, district- and town-owned WWTPs. In comparison, the other 25 WWTPs are privately owned, mainly through natural person investments or Sino-foreign joint ventures. This is different from Rodríguez-Villanueva and Sauri (2021) [9], in which private companies oversee 66% of WWTPs in Mediterranean Spain. The low market share of the private sector indicates that the private sector is reducing its business activities or retreating from the market because of project risks, such as the uncertainties of wastewater inflow, legal and regulatory barriers, and inefficiency, corruption and a lack of funds [31].

Since sterilization and filtration processes have been widely adopted in Beijing's WWTPs to meet stringent effluent standards, primary treatment, secondary treatment, and advanced treatment are effectively integrated into WWTPs. The anaerobic-anoxic-oxic (AAO) system and related modified processes are the most common treatment technologies, being utilized among 40.24% of the 169 WWTPs for which we have data on treatment technology. This statistic is different from that reported by Yang and Chen (2021) [16], who used the detailed 2018 dataset from MoHURD. According to those authors, biological processes are the most widely adopted in Beijing, followed by the AAO phosphorus removal process. A membrane bioreactor (MBR) can achieve better effluent quality and requires a smaller surface area [32,33], which is suitable for decentralized wastewater treatment in rural areas and the renewal of WWTPs located in urbanized areas [34]. As a result, integrated 'AAO+MBR' treatment technology has been widely adopted among WWTPs of different scales in Beijing [34], occupying 27.2% of the 169 WWTPs. The oxidation ditch system and related modified processes rank second, with a share of 18.9%. Other treatment technologies adopted include sequence batch reactors (SBRs) and biological processes.

4.1.2. The Spatial Distribution, Treatment Capacity, and Operational Load of WWTPs at the District Scale

Based on the intensity of their socioeconomic activities (Figure 2), the 16 districts in Beijing are categorized into three groups in this study: the central area, the area of new urban development (Changping, Shunyi, Tongzhou, Daxing, and Fangshan districts), and the ecological preservation area (Mentougou, Yanqing, Huairou, Miyun, Pinggu districts). More than 50% of the total population is located in the central area, which has the highest level of socioeconomic intensity, followed by the area of new urban development and the ecological preservation area. The spatial distribution of WWTPs corresponds to the distribution of the socioeconomic index. Forty-three WWTPs are located in the central area of Beijing (Figure 2), including all large-scale WWTPs, and state-owned enterprises operate all these WWTPs. A total of 105 out of 175 WWTPs are located in the area of new urban development, and all these WWTPs are medium-sized or small in scale. Twenty-nine and 30 WWTPs have been built in Daxing and Tongzhou districts, respectively, because both districts are located in the plain region downstream of the Beijing catchment and are under severe pressure from upstream effluent.

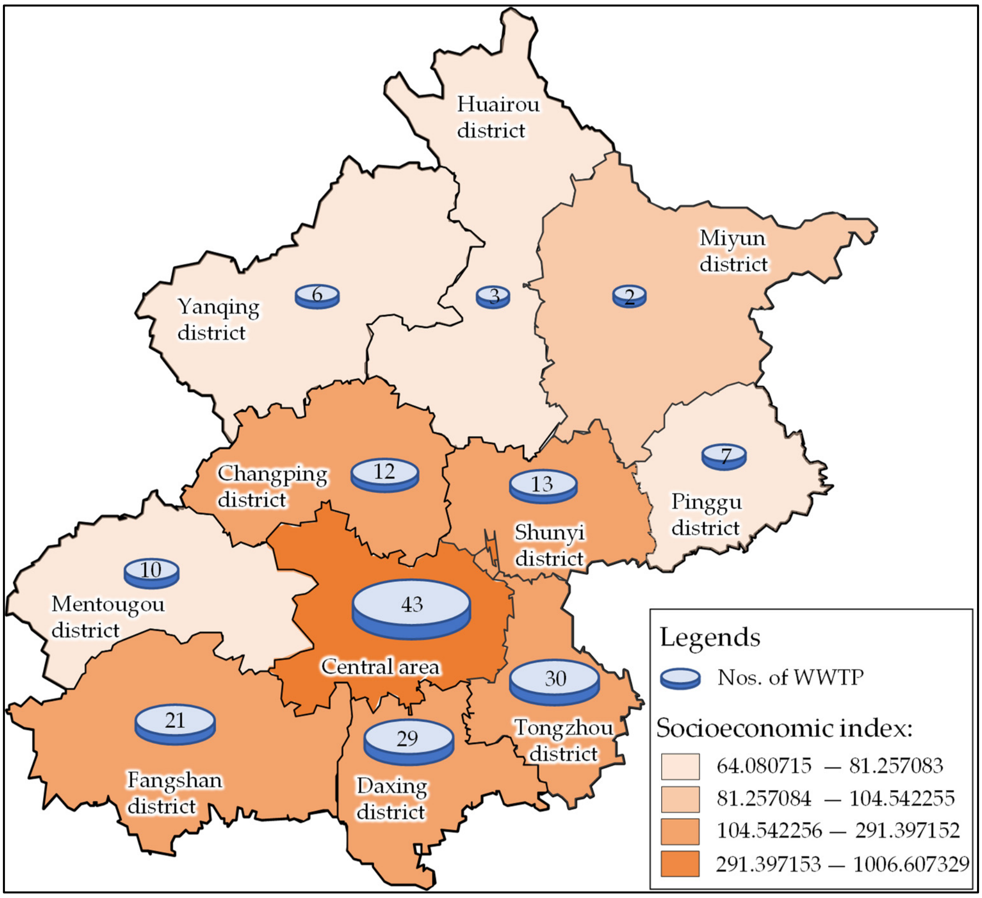


Figure 2. *Cont.*

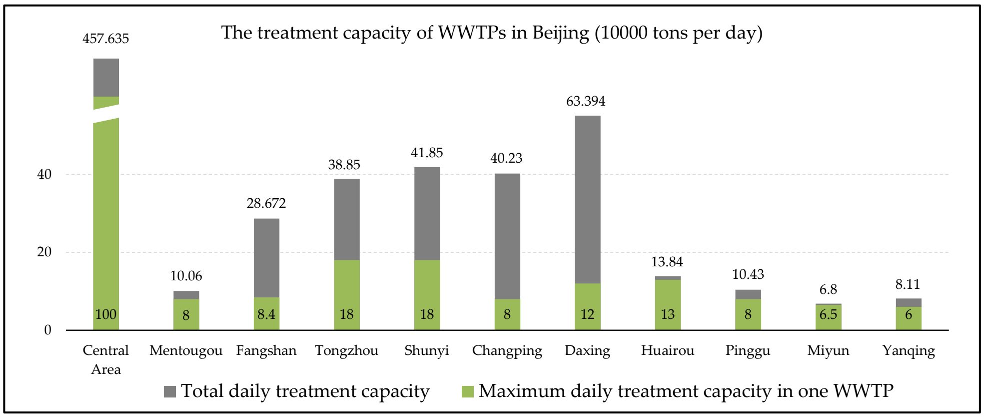


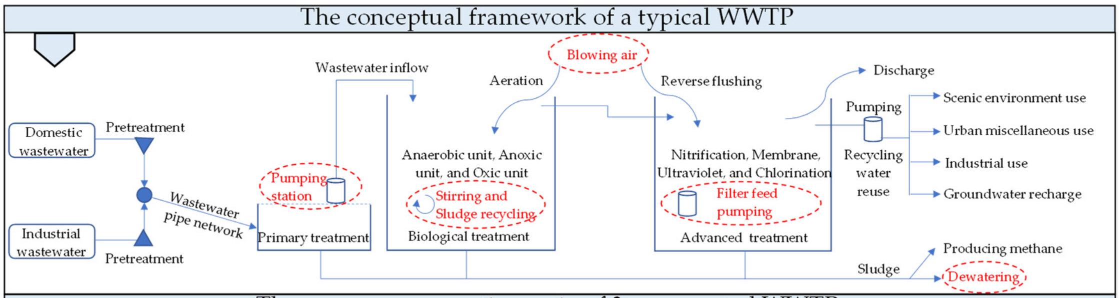
Figure 2. The spatial distribution and treatment capacity of WWTPs in Beijing.

This pattern also holds for treatment capacity. The central area has the largest daily treatment capacity of 4.57634 million tons (Figure 2), and the largest WWTP can treat 1 million tons of wastewater per day. Districts in the new urban development area have a larger treatment capacity than those in the ecological preservation area. Interestingly, the treatment capacity in districts in the ecological preservation area depends largely on their largest WWTP. For example, the largest WWTP accounted for at least 75% of the total treatment capacity in each of those districts (Figure 2). This is because the amount of wastewater discharged in the ecological preservation area is relatively small, and the largest WWTPs are attempting to decrease the consumption of energy by WWTPs [35]. Hence, the governmental subsidy received by those WWTPs in the ecological preservation area is based on their designed treatment capacity rather than the actual amount of treated wastewater. These facts indicate that 99.4% of the discharged wastewater was treated in WWTPs in the central area, which is Beijing's highest wastewater disposal rate (99.7%). The wastewater disposal rates in Daxing and Tongzhou districts are 97.5% and 92.3%, respectively, because of their large number of WWTPs relative to other districts.

The average operational load in Beijing is 61.2%, and the highest WWTP operational loads are in the Fangshan district (88.2%) and the central area (85.6%). Although the Liangxiang WWTP and Jiuxianqiao reclaimed, water plant is overloaded, with operational load rates of 113.3% and 107.5%, respectively, most WWTPs in Beijing were under load in 2019. This is because many reclaimed water plants were newly built or previous WWTPs were upgraded into reclaimed water plants during the last 10 years. For example, building 79 reclaimed water plants and upgrading 37 WWTPs were goals included in the three three-year action plans (2013–2022), increasing treatment capacity and reducing operational loads.

4.2. Energy Consumption of Selected WWTPs in Beijing

The holistic perspective on the energy consumption of WWTPs is conducted at the scale of the energy-intensive subprocess, energy consumption ratio, and energy intensity (Figure 3).



The energy consumption ratio of 3 represented WWTPs

Basic information			Primary treatment	Biological treatment		Advanced treatment	Sludge treatment
Size (m^3/day)	Treating technologies	Average energy intensity	Pumping station	Air blowers	Stirrer and sludge recycle	Filter feed pumping	Dewatering and thickening
30,000	AAO-Ultrafiltration	0.2463 kWh/m^3	16.54%	29.94%	13.33%	27.64%	2.01%
20,000	SBR-Aquazur sand filters	0.652 kWh/m^3	17.74%	22.73%	27.78%	18%	4.5%
150,000	AAO-MBR	0.53 kWh/m^3	10.84%	36.18%	11.61%	21.52%	15.42%

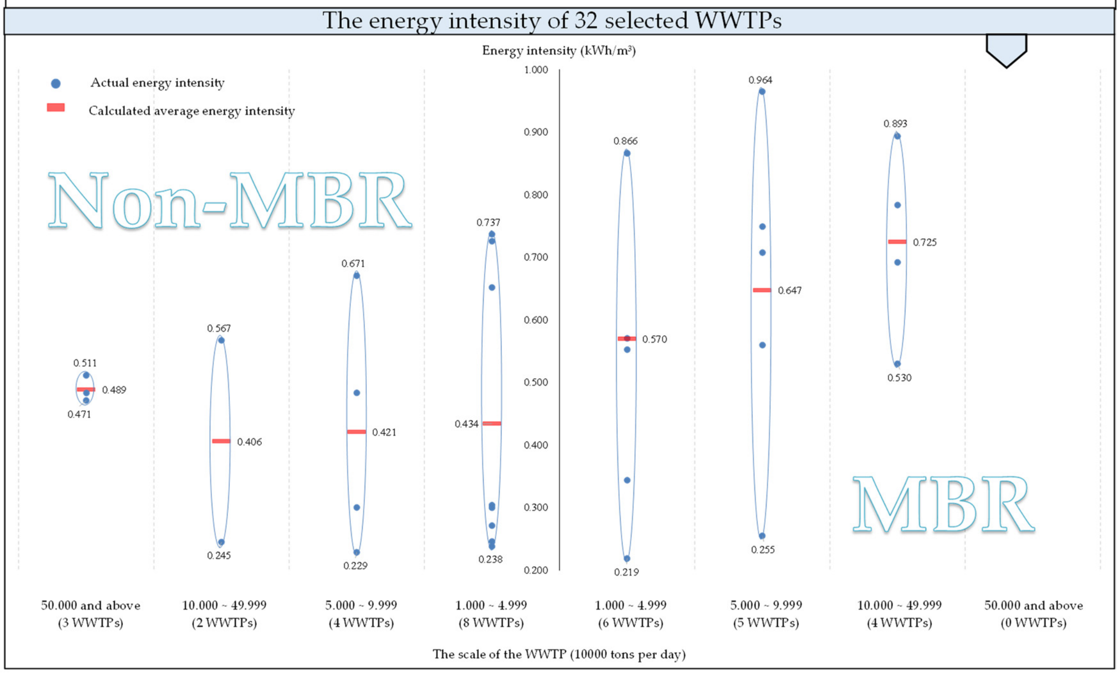


Figure 3. Holistic analysis framework for WWTPs in Beijing. Data sources: *Urban Drainage Statistical Yearbook (2018)*, [36–38].

4.2.1. Five Energy-Intensive Subprocesses in a Typical WWTP

Five treatment processes are included (Figure 3): wastewater collection, primary treatment, biological treatment, advanced treatment, and wastewater reuse [39,40]. In the primary treatment process, the sewage is collected in an underground tank. The average depth of this tank in Beijing is approximately 10 m (Yang et al., (1984) [41] reported depths of 9~12 m), and pumping wastewater into biological treatment processes is energy-intensive. An air blower is used to provide adequate oxygen for biological processes, with the goal of decomposing organic matter in wastewater. This is the most energy-intensive subprocess in WWTPs [3], as it can account for more than one-third of the total energy consumption [42]. To achieve efficient decomposition, biologically processed wastewater requires constant stirring, and sludge or debris must be recycled into the recirculation system to ensure the abundance of microbes in the wastewater [43]. Both stirring and sludge recycling are energy-intensive, just below air blowing in biological processes. The advanced treatment process is more energy-intensive than other processes [39], and filter feed pumping and air blowing consume a larger amount of energy. Filter feed pumping is used to create the pressure needed to push wastewater through the membrane unit, and air blowers in the advanced treatment process are employed to wash the membrane, which dramatically increases energy consumption [40]. Finally, dewatering sludge is also energy-intensive [37], although the sludge can be used for construction materials or methane production. In the dewatering process, energy is consumed in the centrifugal machine and by anhydrous chemicals. Therefore, five energy-intensive subprocesses in a typical WWTP in Beijing have been identified: pumping, blowing air, stirring and sludge recycling, filter feed pumping, and sludge dewatering. Many strategies have been developed to reduce energy consumption in these five energy-intensive subprocesses, such as upgrading the variable frequency feed pump [44] and pulsating aeration [38], but energy and material recovery from wastewater is a promising approach to convert WWTPs into sustainable facilities [45] and to achieve the goal of carbon neutrality.

4.2.2. The Energy Consumption Ratios of the Five Energy-Intensive Subprocesses in Representative WWTPs

The energy consumption ratio focuses on the distribution of the consumed energy within a WWTP. Three medium-scale WWTPs with different treatment technologies are reviewed from the literature. Their average energy intensities and the energy consumption ratio of the energy-intensive WWTP subprocesses are summarized (Figure 3). Although these five subprocesses are the most energy-intensive, their energy consumption ratios vary by treatment technology and management factors. For example, air blowing and filter feed pumping always rank first and second, respectively, in the AAO system, while stirring and sludge recycling consumes the largest amount of energy in an SBR, followed by air blowing. Updating WWTPs with membrane tanks increases energy consumption [40] due to the filter feed pumping used in advanced treatment processes. Although the energy intensity of the ultrafiltration and MBR technologies fluctuates near 0.8 kWh/m^3 in the U.S. [39], the energy consumption ratio for filter feed pumping is different between them. Furthermore, MBR technologies consume more energy during sludge dewatering, which can be attributed to management factors, that is, a lack of systematic optimization in WWTP updating [44]. Finally, primary treatment is less energy-intensive [39]. Still, wastewater pumping stations consume 90% of the energy consumed during primary treatment; therefore, there is great potential for energy savings [42]. As a result, individual WWTP analysis is necessary to develop a plant-specific strategy to reduce energy consumption and increase energy recovery. Furthermore, the government can subsidize those subprocesses with the highest energy consumption ratio.

4.2.3. Energy Intensity by Treatment Capacity and MBR Treatment Technology in Selected WWTPs

Using a dataset from the Urban Drainage Statistical Yearbook (2018), we explore the varying energy intensities of 32 WWTPs by their treatment capacity and use of MBR treatment technology (Figure 3). MBR treatment technology is used to categorize WWTPs for two reasons: MBRs increase energy consumption and greenhouse gas emission intensity in WWTPs [5,33], and MBRs have been widely adopted by WWTPs of different scales in Beijing.

The average energy intensity of WWTPs with an MBR is 0.57~0.725 kWh/m^3, which varies by the treatment capacity of the WWTP. That is, a larger-scale WWTP with an MBR has a higher average energy intensity. For example, the average energy intensity of WWTPs with a daily treatment capacity of 10~49.999 is 0.725 kWh/m^3, which is larger than the 0.57 kWh/m^3 in WWTPs with a daily treatment capacity of 1~4.999. WWTPs without an MBR has a lower average energy intensity of 0.406~0.489 kWh/m^3. This lower intensity is widely documented in the literature, such as by Yang et al., (2021) [40]. Large-scale WWTPs (daily treatment capacity of 50 or above) without MBRs have a slightly higher average energy intensity (0.489 kWh/m^3) than WWTPs of other scales (~0.421 kWh/m^3), contradicting the hypothesis of a decreasing scale effect on the energy consumption of WWTPs [17,35]. We obtain this result mainly because of the decreases in scale efficiency in China's larger-scale WWTPs [16] and the stringent restrictions on energy consumption among WWTPs in Beijing, such as DB11/T 1118—2014. Therefore, these larger-scale WWTPs in Beijing hold significant energy-saving potential [16].

Therefore, the treatment capacity of WWTPs has a positive impact on the density of the energy intensity ratio, indicating that the ratios for larger-scale WWTPs are more similar. For example, the energy intensities of large-scale WWTPs range from 0.471~0.511 kWh/m^3, which is the smallest range in Figure 3. This is also supported by Zhang et al., (2016) [15]. The range of energy intensity ratios for WWTPs with an MBR is larger than that of those without an MBR, and their energy intensities are evenly distributed within their range. However, the energy intensity ratios of WWTPs without an MBR are most dense at either end of the distribution. For example, for WWTPs with a daily treatment capacity of 1–4.999, the energy intensities of those WWTPs without an MBR range from 0.238~0.737 kWh/m^3 and are aggregated at the lower end (0.238~0.304 kWh/m^3) and upper end (0.652~0.737 kWh/m^3). The energy intensities of WWTPs with MBRs vary between 0.219 and 0.866 kWh/m^3.

4.3. Governance Structure for Urban Wastewater Treatment and Reuse in Beijing

In the past 10 years, Beijing has powered its governance structure for wastewater treatment and reuse by focusing on sectoral collaborations, policies, and standards, which are effective for protecting the aquatic environment. For example, the length of rivers inferior to the Grade V national standard decreased from 880.1 km in 2011 to 0 km in 2021 [46].

4.3.1. The Structure of the Management Organization for Wastewater Recycling and Reuse in Beijing

Multilateral cooperation is necessary to break down political boundaries in water resource governance [47], and a group for coordinating wastewater recycling and reuse at the municipal level and the district level in Beijing was established in 2013 to enhance local wastewater treatment and reuse. At the municipal level, the head of the coordination group is the deputy mayor of Beijing, and the coordination group office is located within the Beijing Water Authority. The members of the coordination group include members of 15 departments, district governments, and state-owned enterprises (Figure 4). These memberships can be widely found in the processes of decision-making, policy implementation, and facility construction and can also be used to define the boundary of wastewater governance. Below the coordination group and its office, the Beijing Discipline Inspection Committee and the Beijing Local Finance Supervision and Administration have been integrated to ensure that wastewater treatment and reuse duties are executed honestly. Thus, integrating the deputy mayor and both accountability offices into the wastewater governance structure has provided sufficient executive power. This integration also ensures a priority to address local wastewater issues by the district government because the achievements in wastewater treatment and reuse are reported to the deputy mayor face-to-face. The coordination group members are divided into three subgroups based on their duties: wastewater facilities, wastewater discharge, and wastewater resources. The structure of the coordination group at the district level is similar to that at the municipal level. Still, district sectors are assigned to the wastewater facilities finance and construction subgroup and the wastewater discharge regulation and governance subgroup (Figure S1 in the SI). This is because district sectors are the largest consumers of reclaimed water and are primarily responsible for the construction of reclaimed water facilities and the pipeline network.

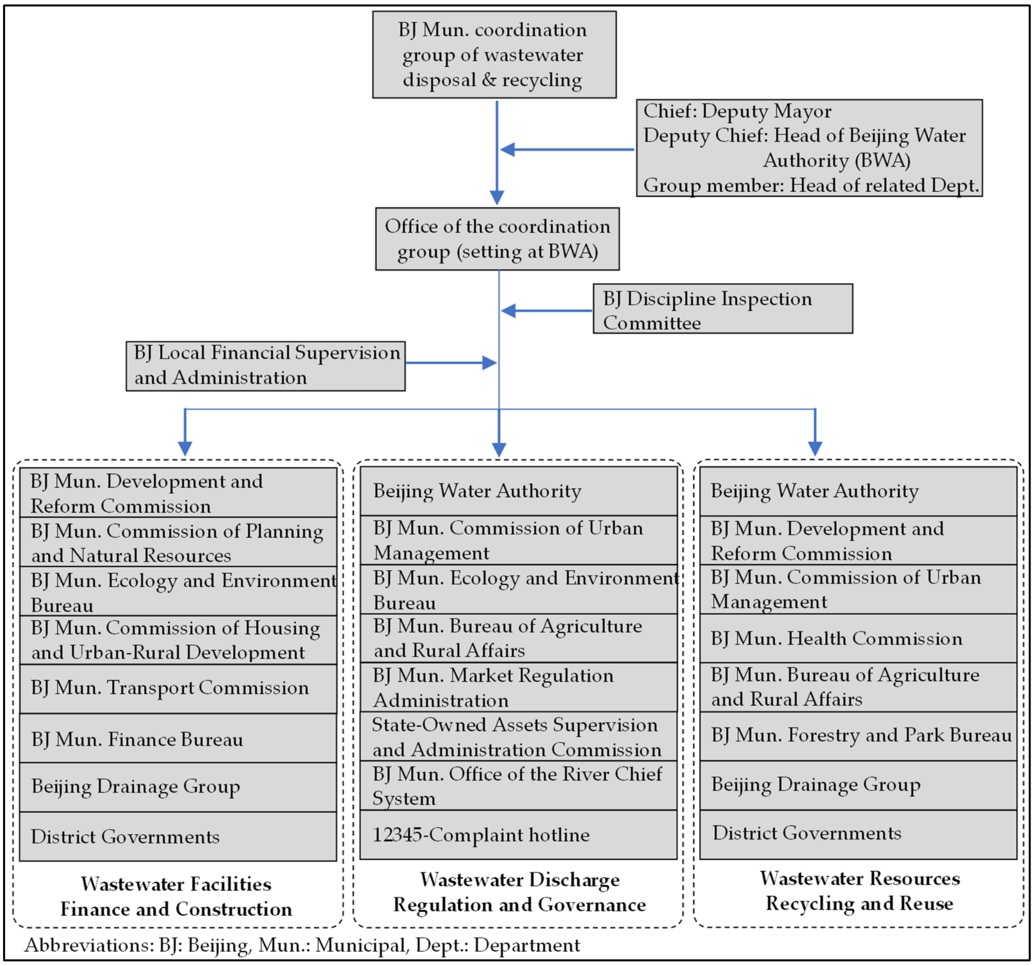


Figure 4. The structure of the coordination group for wastewater treatment and reuse in Beijing.

As shown in Figure 4, the planning, approval, and financing of wastewater-related projects are determined by departments in the wastewater facilities subgroup, with construction and operations conducted by the Beijing Drainage Group in the central area. Enterprises (e.g., Beijing Drainage Group) were introduced through franchises issued by the local government. For example, the Beijing Drainage Group obtained a franchise from the Beijing municipal government in 2015, licensing to collect, treat, dispose, and reuse wastewater in the central area. Reasons for including enterprises are that the government can receive specialized wastewater services by procurement, and its role as a regulator and consumer in wastewater treatment and reuse can be highlighted. Then, in the wastewater discharge group, both water-related sectors and the public are included. Wastewater discharge is regulated via top-down and bottom-up monitoring systems, that is, the River Chief System and the 12345-complaint hotline, respectively. According to the department's duty within the coordination group, both the Beijing Municipal Commission of Urban Management and the Beijing Municipal Market Regulation and Administration are enforcement sectors regulating wastewater-related behaviors by stakeholders such as restaurants. The integration of the Beijing Municipal Bureau of Agriculture and Rural Affairs aims to increase the rural wastewater disposal rate and improve the aquatic environment in rural areas. For example, Beijing's rural wastewater disposal rate was 42% in 2019, and this number is targeted to reach 55% in 2022, as was written in the three-year action plan (2019–2022). Finally, the wastewater resource recycling and reuse subgroup exists only at the municipal level and takes responsibility for supervising reclaimed water prices, monitoring reclaimed water quality, and expanding the scale of reclaimed water use. In Beijing, reclaimed water is purchased for scenic environment use, miscellaneous city use, industrial use, and as a recharge for groundwater (Figure 3), with scenic environment use being the largest use for reclaimed water. For example, the Water Authority in Chaoyang district purchased reclaimed water from the Beijing Drainage Group for scenic environment use at the cost of approximately 9 million dollars in 2022. The department's duties related to wastewater reuse were summarized by Ma et al., (2020) [48], and the price of reclaimed water is supervised by the Beijing Municipal Development and Reform Commission. The current supervised price of reclaimed water has been less than 0.55 dollars/m^3 since 2014, which is cheaper than the price for first-tier tap water, at approximately 0.79 dollars/m^3. This low-price strategy has greatly increased the consumption of reclaimed water in Beijing, and reclaimed water has become Beijing's second most stable water source [49].

4.3.2. The Structure of Governance Policies for Wastewater Treatment and Reuse in Beijing

There are wastewater governance policies at the national and municipal levels (Table S2 in the SI), that is, national strategies and municipal action plans, respectively. Related strategies issued by the central committee of the Community Party of China (CPC) and the State Council at the national level provide working directions and guiding principles for wastewater governance. Promoting urban wastewater treatment was written in the Opinions of the Central Committee of the CPC and the State Council on Comprehensively Enhancing Eco-environmental Protection to Completely Win the Battle Against Pollution, which can enhance the priority of wastewater treatment and reuse within the local massive affairs. Then, the relevant ministries jointly issue policies to implement national strategies, and working tasks, specific targets, and pilot places for wastewater treatment and reuse are highlighted. For example, the Beijing-Tianjin-Hebei area was selected as a pilot place in the Implementation Plan for Conducting Experiments in Regional Reclaimed Water Circular Use. The target wastewater reuse rate is 35% by 2025. Furthermore, both strategies and policies at the national level are written in the municipal plans, and the working directions, targets, and tasks are specified based on the municipal context. For example, Beijing's targeted wastewater reuse rate has also been specified in the Outline of the Fourteenth Five-year Plan for National Economic and Social Development of Beijing Municipality (2021–2025). Finally, the division of work is further clarified in the annual and three-year action plans, in which the work tasks are assigned to the municipal departments and district governments. Therefore, these four vertical layers in the policy system, from the CPC central committee to district governments, ensure the fulfillment of strategies via specified action plans. In this regard, national strategies provide an umbrella directive for wastewater governance [26], indicating focal work in the future and empowering related actions at the municipal level. The municipal action plans integrate the local context into the focal work and specify the responsible agency, which can achieve sufficient collaboration between responsible agencies.

In addition, two effective policy instruments have also been adopted to enhance the enforcement of pollution monitoring and control [26]. These are the scheduled supervision of central eco-environmental protection at the national level, and the annual assessment of the fulfillment of the responsible objectives in the action plans at the municipal level. To solve the environmental governance "failures" of local governments, the central mechanism for supervising eco-environmental protection was introduced, and central environment inspection teams were established by the central government. National supervision proved to be a highly effective top-down approach to enforcing environmental regulations [50,51]. This is because the central supervisors of eco-environmental protection have sweeping powers granted by the central government, and transaction costs are reduced through the involvement of local residents [52,53]. The latter tool was developed to clarify the bottom-up responsibilities related to wastewater governance, which can be used to monitor and supervise the performance of governmental departments [54,55].

5. Discussions and Policy Implications

Most studies have focused on China's WWTPs at the national scale, and regional differences have been highlighted as a key characteristic of China's wastewater treatment and reuse [1,15]. Thus, detailed analysis at the province level is necessary to provide a knowledge base for local standards that address the actual situation in specific regions. The inconsistency of the data used to summarize the current status of WWTPs, energy consumption in the context of carbon neutrality, and the normalization of the governance structure still deserve further discussion.

5.1. Data Challenges due to Inconsistent Information on WWTPs

The public datasets on WWTPs in Beijing were provided by the Beijing Water Authority, MoEE, and MoHURD, with the total number of WWTPs in 2019 reported as 1117, 175, and 167, respectively. These inconsistent data can be attributed to the adopted statistical standard, with which the WWTPs are divided by treatment capacity and treating processes. The Beijing Water Authority counts all WWTPs in the Beijing administrative boundary, including many decentralized WWTPs. This single-function, decentralized WWTPs are excluded from the MoEE and MoHURD datasets, and only centralized WWTPs with treatment capacities above 500 tons per day are included. Furthermore, the MoEE focuses on these centralized WWTPs with biological or advanced treatment processes, and the MoHURD focuses on those WWTPs in operation. In the context of big data, the Internet of Things (IoT), fifth-generation (5G) wireless systems, and blockchain, all departments with siloed datasets will be integrated into urban platforms such as Alibaba's city brain [56], which can aggregate the massive data generated during the process of urban operations. Therefore, unified datasets at the city level have been formed to reduce the amount of conflicting data and to provide basic data. The bottom-up approach to data collection has been adopted to provide more robust data [57]. For example, the construction of urban operation, administration, and service platforms at the national, provincial, and city levels were key tasks of the MoHURD during the 14th Five-Year Plan period. In addition, 21 cities were selected in 2021 by the MoHURD to build their 3-dimensional digital base, that is, the city information modeling platform, which integrates geographic information systems (GIS), building information modeling (BIM), and a complete and up-to-date urban database [58]. Such platforms can enhance smart urban governance by aggregating and sharing urban data resources. Therefore, a unified statistical standard in WWTPs and qualified statisticians are key bases to address data challenges in the future.

5.2. Blue Water Factory as a Promising Approach to Reducing Energy Consumption

The blue water factory is a promising recovery-based approach, focusing on the recovery of valuable resources and energy during wastewater treatment processes [59], which can convert WWTPs into sustainable facilities [45]. In current WWTPs, energy can be recovered through anaerobic sludge digestion and sewage-source heat pump systems, with the goal of building a net-zero energy WWTP that is 100% self-sufficient in terms of energy [60]. The amount of energy recovered by WWTPs is influenced by environmental, economic, and social factors, and the use of anaerobic sludge digestion with a combined heat and power system in eastern and northeastern China is suggested, as such a system can burn the methane produced in WWTPs to provide heat and power [60,61]. For example, advanced sludge digestion engineering in the Gaobeidian WWTP was approved by the Beijing Municipal Development and Reform Commission in 2021. In this system, the methane produced is consumed to generate electricity. However, most medium- and small-scale WWTPs in Beijing are inefficient sludge producers, and most of their sludge is transported for energy recovery to large-scale WWTPs, such as the Gaobeidian WWTP or landfills, which impacts their ability to recover energy on-site Another energy recovery technology is the sewage-source heat pump system, which can achieve large-scale energy recovery. For example, the Kakolanmäki WWTP in Finland recovered 200,914 MWh in 2020 via its sewage source heat pump system, nearly 10 times more than the 21,042 MWh of energy it consumed [62]. This kind of energy recovery can be widely adopted among Beijing's WWTPs, and two related local standards have been issued: DB11/T 1237-2015 and DB11/T 1651-2019 (Table S3 in the SI). Since the difference between the effluent temperature and the average temperature in Beijing varies by approximately 5 °C, the energy self-sufficiency of WWTPs could greatly increase by 87.1% via a sewage-source heat pump system [37,63].

5.3. Two Strategies for the Normalization of the Current Governance Structure

The current wastewater governance structure in Beijing is effective at preventing the deterioration of the aquatic environment, and the wastewater disposal rate increased from 84.6% in 2013 to 95% in 2020. These achievements are the results of three-year action plans that clarified responsibilities and strengthened performance assessments, activities that are part of a campaign-style of governance [64]. The first strategy for avoiding the return to soft constraints is highlighting the equal importance of the options in the trade-off between environmental protection and economic development. A "redline policy" and sufficient executive power can normalize campaign-style governance by providing enough space for local executors to adapt their policy implementation, which is a more active strategy for implementation [55]. The central government proposed a "redline policy" with bottom-line requirements and has been widely employed in China's ecological conservation, water resource management, cultivated land protection, real estate sector, etc. As a result, effective environmental protection can continue after a governance campaign. The second strategy is to disclose information and enhance public participation. Both are critical components in environmental governance and can increase equality and reduce conflicts in policy implementation [65]. However, limitations to information disclosure and public participation are widespread in China [47]. In Beijing, the self-monitoring of pollutants in WWTPs should be reported through Beijing's online environmental information disclosure platform. Both the 12345-complaint hotline and environmental impact assessments can ensure the involvement of the public in wastewater governance.

5.4. Limitations and Future Research

Based on complex system engineering theory, this study developed a framework including the quantity, intensity, and governance of WWTPs to conduct a systematic review of wastewater treatment and reuse in Beijing, which is different from the wastewater story. Since the data used in this study are mainly collected from multiple public sources, many uncertainties (e.g., inconsistent statistical standards across multiple sources) will affect the results. Because of data shortages, only energy consumption is explored in the intensity analysis.

In the future, the energy intensity of WWTPs with MBR treatment technology requires further research. Our results indicate that larger-scale WWTPs with an MBR have a higher average energy intensity, contradicting the scale efficiency of WWTPs. Additionally, suggestions are given to conduct a complex network analysis of the wastewater governance network, highlighting the key sectors.

6. Conclusions

Wastewater treatment and reuse play a critical role in urban aquatic environment protection, which is dependent on the wastewater treatment capacity of WWTPs and the wastewater management ability of the local government. This paper summarized the current status of 175 WWTPs in Beijing, explored their energy consumption during the treatment process, their energy consumption ratios, and their energy intensity, and mapped Beijing's governance structure for wastewater treatment and reuse. The results show that most WWTPs in Beijing are medium or small in scale, treating less than 200 thousand tons of wastewater per day. The treatment capacity of districts in the ecological preservation area largely depends on their largest WWTP, which constitutes more than 75% of the district treatment capacity. Then, five energy-intensive subprocesses were identified, including pumping station, blowing air, stirring and sludge recycling, filter feed pumping, and sludge dewatering. Their energy consumption ratios vary by treatment technology and management factors, respectively, which calls for individual WWTP analysis and plant-specific strategy. The energy intensity of WWTPs in Beijing varies by the scale and MBR technology use. Larger-scale WWTPs have more highly concentrated energy intensities, and WWTPs employing MBR technology have a higher average energy intensity. Furthermore, the current coordination group for wastewater disposal and recycling at the municipal and district levels was mapped. The policies on wastewater treatment and reuse were divided into four vertical layers: district, municipal, ministry, and CPC central committee. Both the coordination group and the policies can be used to define the wastewater governance boundary. This kind of coordination group provides sufficient executive power and promotes efficiency in departmental collaborations. In the future, the energy intensity of WWTPs with MBR treatment technology still requires further research. How to combat inconsistent data, reduce energy consumption in WWTPs and normalize the campaign-style governance structure are of critical importance to sustaining urban wastewater treatment and reuse in Beijing and other areas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15040630/s1, Figure S1: Governance structure of wastewater treatment and reuse at the district level; Table S1: The characteristics of 175 WWTPs in Beijing; Table S2: Representative policies related to wastewater governance at the national and municipal levels; Table S3: Local standards of wastewater treatment and reuse in Beijing.

Author Contributions: D.H. designed and wrote the draft and participated in the data collection and data analysis; L.J. collected and analyzed the data and mapped some figures; J.L. supervised the research and revised the draft; G.H. developed the research idea and revised the draft; W.L. participated in data collection and energy consumption analysis; A.H.-L. participated in the research idea development. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research and Development Program (No. 2018YFE01960005), the National Natural Science Foundation of China (Grant Nos. 72104018), and the Young Talents Initiative of Beijing University of Civil Engineering and Architecture (JDYC20220822).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: http://www.beijing.gov.cn/ (accessed on 10 February 2022); http://scjgj.beijing.gov.cn/cxfw/, (accessed on 20 February 2022).

Acknowledgments: Thanks are given to the 2022 International Conference on Resource Sustainability (icRS 2022) for their comments on some results of this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tang, W.; Pei, Y.; Zheng, H.; Zhao, Y.; Shu, L.; Zhang, H. Twenty years of China's water pollution control: Experiences and challenges. *Chemosphere* **2022**, *295*, 133875. [CrossRef]
2. Vörösmarty, C.J.; McIntyre, P.B.; Gessner, M.O.; Dudgeon, D.; Prusevich, A.; Green, P.; Glidden, S.; Bunn, S.E.; Sullivan, C.A.; Liermann, C.R.; et al. Global threats to human water security and river biodiversity. *Nature* **2010**, *467*, 555–561. [CrossRef]
3. Water in the West. Water and Energy Nexus: A Literature Review. A joint program of Stanford Woods Institute for the Environment and Bill Lane Center for the American West. 2013. Available online: https://waterinthewest.stanford.edu/sites/default/files/Water-Energy_Lit_Review.pdf (accessed on 15 February 2022).
4. Su, H.; Yi, H.; Gu, W.; Wang, Q.; Liu, B.; Zhang, B. Cost of raising discharge standards A plant by plant assessment from wastewater sector in China. *J. Environ. Manag.* **2022**, *308*, 114642. [CrossRef] [PubMed]
5. Zhou, X.; Yang, F.; Yang, F.; Feng, D.; Pan, T.; Liao, H. Analyzing greenhouse gas emissions from municipal wastewater treatment plants using pollutants parameter normalizing method: A case study of Beijing. *J. Clean. Prod.* **2022**, *376*, 134093. [CrossRef]
6. Ahmad, S.; Jia, H.; Chen, Z.; Li, Q.; Xu, C. Water-energy nexus and energy efficiency: A systematic analysis of urban water systems. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110381. [CrossRef]

7. Lee, M.; Keller, A.A.; Chiang, P.-C.; Den, W.; Wang, H.; Hou, C.-H.; Wu, J.; Yan, J. Water-energy nexus for urban water systems: A comparative review on energy intensity and environmental impacts in relation to global water risks. *Appl. Energy* **2017**, *205*, 589–601. [CrossRef]
8. Vakilifard, N.; Anda, M.; Bahri, P.A.; Ho, G. The role of water-energy nexus in optimising water supply systems—Review of techniques and approaches. *Renew. Sustain. Energy Rev.* **2018**, *82*, 1424–1432. [CrossRef]
9. Rodríguez-Villanueva, P.; Sauri, D. Wastewater Treatment Plants in Mediterranean Spain: An Exploration of Relations between Water Treatments, Water Reuse, and Governance. *Water* **2021**, *13*, 1710. [CrossRef]
10. Shehabi, A.; Stokes, J.R.; Horvath, A. Energy and air emission implications of a decentralized wastewater system. *Environ. Res. Lett.* **2012**, *7*, 024007. [CrossRef]
11. Vymazal, J.; Zhao, Y.; Mander, Ü. Recent research challenges in constructed wetlands for wastewater treatment: A review. *Ecol. Eng.* **2021**, *169*, 106318. [CrossRef]
12. Kollmann, R.; Neugebauer, G.; Kretschmer, F.; Truger, B.; Kindermann, H.; Stoeglehner, G.; Ertl, T.; Narodoslawsky, M. Renewable energy from wastewater—Practical aspects of integrating a wastewater treatment plant into local energy supply concepts. *J. Clean. Prod.* **2017**, *155*, 119–129. [CrossRef]
13. Nguyen, H.T.; Safder, U.; Nguyen, X.Q.N.; Yoo, C.K. Multi-objective decision-making and optimal sizing of a hybrid renewable energy system to meet the dynamic energy demands of a wastewater treatment plant. *Energy* **2020**, *191*, 116570. [CrossRef]
14. Yang, L.; Zeng, S.; Chen, J.; He, M.; Yang, W. Operational energy performance assessment system of municipal wastewater treatment plants. *Water Sci. Technol.* **2010**, *62*, 1361–1370. [CrossRef]
15. Zhang, Q.H.; Yang, W.N.; Ngo, H.H.; Guo, W.S.; Jin, P.K.; Dzakpasu, M.; Yang, S.J.; Wang, Q.; Wang, X.C.; Ao, D. Current status of urban wastewater treatment plants in China. *Environ. Int.* **2016**, *92–93*, 11–22. [CrossRef] [PubMed]
16. Yang, J.; Chen, B. Energy efficiency evaluation of wastewater treatment plants (WWTPs) based on data envelopment analysis. *Appl. Energy* **2021**, *289*, 116680. [CrossRef]
17. Niu, K.; Wu, J.; Qi, L.; Niu, Q. Energy intensity of wastewater treatment plants and influencing factors in China. *Sci. Total Environ.* **2019**, *670*, 961–970. [CrossRef] [PubMed]
18. Zhang, J.; Shao, Y.; Wang, H.; Liu, G.; Qi, L.; Xu, X.; Liu, S. Current operation state of wastewater treatment plants in urban China. *Environ. Res.* **2021**, *195*, 110843. [CrossRef]
19. He, Y.; Zhu, Y.; Chen, J.; Huang, M.; Wang, P.; Wang, G.; Zou, W.; Zhou, G. Assessment of energy consumption of municipal wastewater treatment plants in China. *J. Clean. Prod.* **2019**, *228*, 399–404. [CrossRef]
20. Rahaman, M.M.; Varis, O. Integrated water resources management: Evolution, prospects and future challenges. *Sustain. Sci. Pract. Policy* **2005**, *1*, 15–21. [CrossRef]
21. Rotmans, J.; Kemp, R.; Van Asselt, M. More evolution than revolution: Transition management in public policy. *Foresight* **2001**, *3*, 15–31. [CrossRef]
22. Ostrom, E. A diagnostic approach for going beyond panaceas. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 15181–15187. [CrossRef]
23. Cong, W.; Li, X.; Qian, Y.; Shi, L. Polycentric approach of wastewater governance in textile industrial parks: Case study of local governance innovation in China. *J. Environ. Manag.* **2021**, *280*, 111730. [CrossRef] [PubMed]
24. Malisa, R.; Schwella, E.; Kidd, M. From 'government' to 'governance': A quantitative transition analysis of urban wastewater management principles in Stellenbosch Municipality. *Sci. Total Environ.* **2019**, *674*, 494–511. [CrossRef]
25. Lasut, M.T.; Jensen, K.R.; Shivakoti, G. Analysis of constraints and potentials for wastewater management in the coastal city of Manado, North Sulawesi, Indonesia. *J. Environ. Manag.* **2008**, *88*, 1141–1150. [CrossRef] [PubMed]
26. Breitenmoser, L.; Quesada, G.C.; Anshuman, N.; Bassi, N. Perceived drivers and barriers in the governance of wastewater treatment and reuse in India: Insights from a two-round Delphi study. *Resour. Conserv. Recycl.* **2022**, *182*, 106285. [CrossRef]
27. Zhang, Z.; Li, Y.; Wang, X.; Xu, Y.; Liao, Y.; Wan, Z.; Tang, N. Investigating the spatiotemporal dynamic evolution and driving factors of wastewater treatment efficiency in the context of China's River Chief system. *Ecol. Indic.* **2021**, *129*, 107991. [CrossRef]
28. Peng, X.; Li, Y.; Si, Y.; Xu, L.; Liu, X.; Li, D.; Liu, Y. A social sensing approach for everyday urban problem-handling with the 12345-complaint hotline data. *Comput. Environ. Urban Syst.* **2022**, *94*, 101790. [CrossRef]
29. Terrapon-Pfaff, J.; Ortiz, W.; Dienst, C.; Gröne, M.-C. Energising the WEF nexus to enhance sustainable development at local level. *J. Environ. Manag.* **2018**, *223*, 409–416. [CrossRef]
30. Qian, X.; Yu, J.; Dai, R. A New Discipline of Science The Study of Open Complex Giant System and Its Methodology. *Chin. J. Syst. Eng. Electron.* **1993**, *4*, 2–12.
31. Keremane, G.B.; McKay, J. Critical Success Factors (CSFs) for private sector involvement in wastewater management: The Willunga Pipeline case study. *Desalination* **2009**, *244*, 248–260. [CrossRef]
32. He, Z.; Chen, S.; Li, Y. Research progress of MBR in rural domestic wastewater treatment. *J. Environ. Eng. Technol.* **2022**, *12*, 137–144.
33. Van Bentem, A.G.N.; Petri, C.P.; Schyns, P.F.T.; van der Roest, H.F. *Membrane Bioreactors-Operation and Results of an MBR Wastewater Treatment Plant*; IWA Publishing: London, UK, 2007.
34. Feng, S.; Li, Z.; Feng, K. Summarization and discussion of reclaimed water treatment process in Beijing central area. *Water Wastewater Eng.* **2020**, *46*, 20–24.
35. Friedler, E.; Pisanty, E. Effects of design flow and treatment level on construction and operation costs of municipal wastewater treatment plants and their implications on policy making. *Water Res.* **2006**, *40*, 3751–3758. [CrossRef] [PubMed]

36. Li, Y.; Jiang, J.; Li, Y. Energy saving and consumption reducing for the modified A2/O- ultrafiltration membrane combined process in a reclaimed water plant. *Ind. Water Treat.* **2018**, *38*, 106–109.
37. Song, X.; Liu, J.; Lin, J.; Li, J.; Li, C.; Jiang, H.; Wang, H.; Yin, F. The development direction and practice of energy self-sufficiency sewage treatment plants in China under Carbon Neutral Era. *Acta Sci. Circumstantiae* **2022**, *42*, 1–11.
38. Yang, M.; Li, Y.; Wei, Y.; Lü, J.; Yu, D.W.; Liu, J.B.; Fan, Y.B. Energy Consumption Comparison and Energy Saving Approaches for Different Wastewater Treatment Processes in a Large-scale Reclaimed Water Plant. *Environ. Sci.* **2015**, *36*, 2203–2210.
39. Wakeel, M.; Chen, B.; Hayat, T.; Alsaedi, A.; Ahmad, B. Energy consumption for water use cycles in different countries: A review. *Appl. Energy* **2016**, *178*, 868–885. [CrossRef]
40. Yang, Z.; Ma, S.; Du, S.; Chen, Y.; Li, X.; Wang, R.; Luo, J.; Pan, Z.; Tan, Z. Assessment of upgrading WWTP in southwest China: Towards a cleaner production. *J. Clean. Prod.* **2021**, *326*, 129381. [CrossRef]
41. Yang, S. Energy consumption in urban wastewater treatment plant. *Water Wastewater Eng.* **1984**, *6*, 15–19. [CrossRef]
42. Yang, A. Energy Conservation Method and Technology of Aeration in Municipal Wastewater Treatment Plant. Ph.D. Thesis, Beijing University of Technology, Beijing, China, 2012.
43. Ma, Y.; Peng, Y.; Wang, X. Improving nutrient removal of the AAO process by an influent bypass flow by denitrifying phosphorus removal. *Desalination* **2009**, *246*, 534–544. [CrossRef]
44. Sun, H.; Wang, J.; Lv, Z.; Lv, Z.; Jiang, B.; Chen, C.; Liu, X.; Yu, L. Analysis of Approaches and Effects of Energy Saving and Consumption Reduction in a Large Scale Wastewater Treatment Plant in Beijing. *China Water Wastewater* **2019**, *35*, 31–34.
45. Guven, H.; Ersahin, M.E.; Ozgun, H.; Ozturk, I.; Koyuncu, I. Energy and material refineries of future: Wastewater treatment plants. *J. Environ. Manag.* **2023**, *329*, 117130. [CrossRef] [PubMed]
46. Beijing Municipal Ecology and Environment Bureau (BMEEB). 2021 Report on the State of the Ecology and Environment in Beijing. Beijing; 2022. Available online: http://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/sthjlyzwg/1718880/1718881/1718882/index.html (accessed on 8 February 2022).
47. Wang, Y.; Zhang, R.; Worden, S.; Cao, H.; Li, C. Public participation in environmental governance initiatives of chemical industrial parks. *J. Clean. Prod.* **2021**, *305*, 127092. [CrossRef]
48. Ma, D.; Tang, Y.; Yu, Z. The countermeasures for the development of reclaimed water utilization in Beijing. *J. Northwest Univ. Nat. Sci. Ed.* **2020**, *50*, 779–786. [CrossRef]
49. Beijing Water Authority (BWA). Beijing Water Resources Bulletin. Beijing; 2020. Available online: http://swj.beijing.gov.cn/zwgk/szygb/ (accessed on 8 February 2022).
50. Liu, L.; Zhao, Z.; Zhu, R.; Qin, X. Can national environmental protection supervision and control have a lasting impact on corporate production efficiency?—An empirical study based on the multi-phase difference-in-difference model. *Environ. Sci. Pollut. Res.* **2022**, *24*, 56136–56153. [CrossRef] [PubMed]
51. Lu, J. Can the central environmental protection inspection reduce transboundary pollution? Evidence from river water quality data in China. *J. Clean. Prod.* **2022**, *332*, 130030. [CrossRef]
52. Li, R.; Zhou, Y.; Bi, J.; Liu, M.; Li, S. Does the central environmental inspection actually work? *J. Environ. Manag.* **2020**, *253*, 109602. [CrossRef]
53. Xiang, C.; van Gevelt, T. Central inspection teams and the enforcement of environmental regulations in China. *Environ. Sci. Policy* **2020**, *112*, 431–439. [CrossRef]
54. Burns, J.P.; Wang, X. Civil Service Reform in China: Impacts on Civil Servants' Behaviour. *China Q.* **2010**, *201*, 58–78. [CrossRef]
55. Caprotti, F.; Liu, D. Platform urbanism and the Chinese smart city: The co-production and territorialisation of Hangzhou City Brain. *GeoJournal* **2020**, *87*, 1559–1573. [CrossRef]
56. Cui, J. The Adaptive Implementation of Policy in Local Governance: Case Studies on Y District and H Town. *J. Public Manag.* **2022**, *19*, 52–64.
57. Scanlon, B.R.; Ruddell, B.L.; Reed, P.M.; Hook, R.I.; Zheng, C.; Tidwell, V.C.; Siebert, S. The food-energy-water nexus: Transforming science for society. *Water Resour. Res.* **2017**, *53*, 3550–3556. [CrossRef]
58. Souza, L.; Bueno, C. City Information Modelling as a support decision tool for planning and management of cities: A systematic literature review and bibliometric analysis. *Build. Environ.* **2022**, *207*, 108403. [CrossRef]
59. Hao, X.; Li, J.; Wu, Y.; Li, S.; Li, F.; Wang, Z.; Cai, R.; van Loosdrecht, M. Blue Water Factories (BWFs): Framework and Technologies. *China Water Wastewater* **2022**. Available online: https://kns.cnki.net/kcms/detail/12.1073.TU.20220823.1342.002.html (accessed on 15 September 2022).
60. Xiong, Y.-T.; Zhang, J.; Chen, Y.-P.; Guo, J.-S.; Fang, F.; Yan, P. Geographic distribution of net zero energy wastewater treatment in China. *Renew. Sustain. Energ. Rev.* **2021**, *150*, 111462. [CrossRef]
61. Sanscartier, D.; MacLean, H.L.; Saville, B. Electricity production from anaerobic digestion of household organic waste in Ontario: Techno-economic and GHG emission analyses. *Environ. Sci. Technol.* **2012**, *46*, 1233–1242. [CrossRef] [PubMed]
62. International Water Association (IWA). 200–1000% Energy Recovery: Tapping Power of Wastewater. IWA Cluster for Resource Recovery in Water. 2021. Available online: https://www.sohu.com/a/453613330_120053850 (accessed on 10 February 2022).
63. Hao, X.; Huang, X.; Liu, G.; Hu, Y. Energy deficits and their potential replenishments of wastewater treatment operation towards carbon neutral. *China Water Wastewater* **2014**, *30*, 1–6.

64. Zhao, Y.; Zhang, X.; Wang, Y. Evaluating the effects of campaign-style environmental governance: Evidence from Environmental Protection Interview in China. *Environ. Sci. Pollut. Res.* **2020**, *27*, 28333–28347. [CrossRef] [PubMed]
65. Klyza, C.; Sousa, D. *American Environmental Policy: Beyond Gridlock*; MIT Press: Cambridge, MA, USA, 2013.