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Sustainable Domestic Sewage Reclamation: Insights from Small Villages and Towns in Eastern China

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Abstract: Domestic sewage pollution poses significant risks to human health and the ecological environment but sewage water is gradually recognized as a renewable water resource worldwide. To enhance water resource utilization and facilitate reclamation from domestic sewage, substantial global efforts have focused on developing systematic management strategies and advanced technologies for treatment and resource recovery. This study examines and presents the case of domestic sewage reclamation and water reuse in the rural Hangjiahu region, situated on the southern bank of Taihu Lake in Northern Zhejiang Province, Eastern China. It provides a comprehensive overview of state-of-the-art technologies implemented in the region. In rural areas, sewage treatment is decentralized and involves two primary streams: one where urine is separately disinfected and sterilized, with feces processed into agricultural fertilizer; and another where greywater undergoes bio-composting and wetland treatment to produce recycled water. Additionally, natural rainwater is collected and stored in ponds, enhancing the region's water resources. The results demonstrate that the integration of domestic sewage reclamation and rainwater storage has effectively mitigated the risks of flooding during rainy seasons and water shortages during droughts. Remarkably, no severe floods or droughts have occurred in the region since 1991, contrasting with historical records from 1909 to 1954, when such events were frequent. This study underscores the potential for replicating these approaches in other regions facing similar challenges.

Keywords: domestic sewage; reclamation; reuse; rural areas; rainwater collection; water storage

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1. Introduction

The water crisis has emerged as one of the most significant barriers to sustainable development globally, primarily due to the scarcity of locally available water resources in numerous regions, the impacts of severe droughts, escalating energy prices, the imperative to sustainability of agricultural productions, and the demands of environmental restoration [1,2]. Water reclamation and reuse are increasingly recognized as vital components of global water management and are considered promising strategies for mitigating global water risks [3]. Over the past few decades, substantial developments have been made in water reuse management, particularly regarding new regulatory approaches and risk

management practices. Regional governments and researchers have identified solutions to address water shortages, including the role of water reuse in alleviating the impacts of climate change and the energy-water nexus in water reclamation. Notably, there are numerous successful cases demonstrating the benefits of water reuse in enhancing food production, facilitating urban and industrial development, and ensuring the security of drinking water sources [4].

There are numerous factors contributing to water scarcity, with floods, droughts, and domestic sewage pollution identified as primary contributors to the water crisis, which subsequently poses significant challenges to drinking water safety. Therefore, it is imperative to explore strategies for water conservation and the optimal utilization of limited water resources, emphasizing principles such as sustainability and efficiency in water use. Traditionally, these factors have been addressed in isolation [5]. However, these challenges have been effectively addressed through an integrated approach in Hangjiahu region, which includes the cities of Hangzhou, Jiaxing, Huzhou, and their surrounding areas. Situated to the south of Taihu Lake, in the northern part of Zhejiang Province, this area is referred to as "Five Water Co-Governance" model. This comprehensive strategy not only tackles domestic sewage pollution but also effectively manages floods and droughts to safeguard water resources. The region spans approximately 15,023 km^2 and is home to a population of 10.36 million, with 62% residing in rural areas. Known as the "land of fish and rice" in Zhejiang Province, Hangjiahu is a major grain-producing and economically developed region in China.

Previously, the region discharged approximately 80 million tons of domestic sewage annually during the last century [6–8]. According to the first national pollution survey, non-point source pollution contributed 77% of the total nitrogen and 66% of the total phosphorus to Taihu Lake over the past few decades [9]. Rural sewage is identified as the primary contributor to nitrogen and phosphorus in non-point source pollution, with contribution rates of 30% for total nitrogen and 70% for total phosphorus, respectively [10,11]. Due to inadequate treatment of domestic sewage, rivers and lakes have become severely polluted, adversely impacting drinking water supplies and agricultural irrigation [12]. Although Hangjiahu Plain receives an annual rainfall of approximately 1100 mm, the distribution of rainfall is uneven, with the majority occurring during the spring and summer months. As the largest plain in Zhejiang Province and a key part of Yangtze River Delta, this region is characterized by a subtropical monsoon climate, with precipitation primarily from plum rains in the spring and summer (May to July) and typhoon rains in the summer and autumn (August to October). Historically, the lack of sufficient water infrastructure led to recurrent flooding during the rainy season and water shortages during drought periods. Between 1949 and 1978, Hangjiahu Plain experienced five major floods and eight significant droughts, resulting in considerable economic and social losses. During this period, major natural disasters occurred nearly every other year, while minor disasters were an annual occurrence.

In light of this context, the state places significant emphasis on environmental protection, ecological balance, and sustainable development within the region. To safeguard the water environment of Taihu Lake basin, Hangjiahu region has proactively established rural sewage treatment facilities. By 2018, the coverage rate of administrative villages exceeded 90% [13]. Despite the large number and dispersed locations of these facilities, many have maintained effective operation, maintenance, and supervision over an extended period [14,15]. The implementation of a "Five Water Co-Governance" strategy has effectively addressed water shortages and mitigated natural disasters that previously occurred in the region, thereby benefiting local residents. Notably, there have been no disasters since 1991 in areas where "Five Water Co-Governance" initiative has been in effect. This

represents a commendable and successful example, which is relatively rare globally and merits promotion in other regions. Given that approximately 509 million individuals reside in rural areas of China (according to the seventh national census data from November 2020) and that annual domestic sewage production ranges from 11.037 to 16.565 million tons, the effective treatment and utilization of rural domestic sewage is essential for water environmental protection. These achievements can also serve as a reference for other regions, including those in developing countries.

This study examines the rural domestic sewage treatment facilities and their water reclamation processes, focusing on the latest technologies employed for domestic sewage reclamation and reuse in Hangjiahu region. The objective is to summarize the technologies and measures implemented in sewage treatment within this area, as well as to outline the standardized operating procedures. This information may serve as a reference for related research and provide foundational data and management guidelines for the standardized operation and oversight of sewage treatment facilities in other regions. Currently, the overall level of domestic sewage reclamation and utilization in China remains relatively low, despite the significant potential for wastewater recycling and reuse. This work utilizes the successful case of Hangjiahu region to conduct a comprehensive analysis of the current state of water utilization and to propose recommendations for future water reclamation efforts in other regions that may encounter similar challenges.

2. Recycling and Reusing of Domestic Sewage

The environmental policy of the nation strongly advocates for the reuse of domestic sewage. Sewage reuse refers to the process by which sewage is treated to meet specific water quality standards, allowing it to be utilized as reclaimed water in place of conventional water resources. This reclaimed water can be employed for various purposes, including landscape irrigation, municipal miscellaneous uses, residential needs, ecological water replenishment, groundwater recharge, agricultural irrigation, and industrial production. Additionally, it facilitates the extraction of other resources and energy from sewage. The significance of this practice lies in its potential to optimize the water supply structure, enhance the availability of water resources, mitigate the imbalance between supply and demand, reduce water pollution, and ensure the security of water ecosystems. Currently, the definition and application of sewage recycling in China must adhere to "Guiding Opinions on Promoting Sewage Recycling" (FGHZ [2021] No. 13) [16].

After domestic wastewater treatment, both recyclable water and surplus sludge, which can be reused, are generated [17]. Surplus sludge is rich in phosphorus and other essential plant nutrients, making it a valuable organic fertilizer for agricultural and forestry applications [18]. However, prior to utilizing sludge as a fertilizer, it is essential to ensure the removal of any potential heavy metals present, to comply with agricultural standards [19,20]. Furthermore, recyclable water should not be discharged into natural water bodies; instead, it must be managed appropriately, a process commonly referred to as sewage recycling.

2.1. Reusing of Domestic Sewage

In rural areas, the selection of household treatment systems, village group treatment initiatives, and integration into urban sewage networks has been tailored to regional characteristics and population density. Additionally, modular process technologies that combine engineering principles with ecological considerations have been promoted to enhance the local resource utilization of rural domestic sewage. During the wet season, the discharge limits for sewage treatment plants are established based on scientific and rational assessments, taking into account the necessity of improving the water quality

of the basin's ecological environment. Discharges into the environment, specifically into flowing river systems, are conducted under conditions that ensure stable and compliant effluent quality. In contrast, during the dry season, efforts are prioritized to convert treated effluent into usable water resources, with the aim of replenishing nearby natural water bodies and promoting the recycling and utilization of regional sewage resources. In areas characterized by resource-based water shortages, water supply is determined by both demand and quality, necessitating a strategic arrangement of the layout and construction of sewage treatment plant networks. While promoting for the use of reclaimed water in industrial production and municipal applications, it is necessary to adhere strictly to the water quality standards established by the State. Furthermore, reclaimed water should be utilized as an ecological supplement for rivers and lakes, implemented through a systematic approach of incremental water supplementation [21].

Presently, the recycling rate in this region is predominantly impacted by rural areas, which encompass various activities such as garden landscaping, municipal miscellaneous uses (road washing), residential greening, ecological water replenishment (pond water replenishment), and agricultural irrigation (planting of flowers and grasses).

When the effluent from a sewage treatment plant is repurposed for urban miscellaneous water applications, the water quality adheres to the stipulations outlined in "Discharge Standard of Pollutants for Urban Sewage Treatment Plants" [22] as well as local regulations. Additionally, it must comply with the criteria specified in "Water Quality of Urban Miscellaneous Water for Reuse of Urban Sewage" [23]. The treated effluent can be utilized for various urban purposes, including irrigation and landscaping, road cleaning, vehicle washing, toilet flushing, and replenishing ecological landscapes. There are many national standards available for wastewater's reuse (see Appendix A Table A1).

There are generally two approaches to reuse: comprehensive reuse and selective reuse. Comprehensive reuse refers to the utilization of an urban sewage pipe network for the collection of sewage, followed by treatment at a sewage treatment plant, and the subsequent distribution of reclaimed water to users. This method aims to achieve the complete reuse of sewage. Furthermore, when employing the comprehensive reuse approach, there is a significant requirement for the demonstration of the design scale of the sewage treatment plant [24,25].

Selective reuse refers to the strategic implementation of reclaimed water reuse pipelines, which are typically installed in proximity to large building complexes or residential areas within urban environments. This approach facilitates the efficient distribution of reclaimed water. For smaller sewage sources located at a considerable distance from urban centers, decentralized sewage treatment systems can be employed. The treated effluent from these systems can be repurposed for applications such as landscaping and irrigation. This method offers greater flexibility and convenience, allowing for a better alignment between demand and system supply, thereby enhancing the development of urban sewage treatment and recycling infrastructures. Table 1 outlines a typical design intended for approximately 400 residents in a rural setting.

Sewage generation primarily originates from two key sources: residential areas and public spaces, which include commercial establishments. In Table 1, public and commercial venues contribute approximately 138.00 m^3/day, while residential consumption of fresh water is about 103.20 m^3/day. This results in a total sewage generation of approximately 252.05 m^3/day. Following appropriate treatment, the recycled water can be utilized for purposes such as road flushing or irrigation, with a requirement of 252.05 m^3/day for these applications. Consequently, the design can eliminate all sewage outlets, thereby minimizing the discharge of sewage into rivers and lakes. Based on local climatic conditions and regulations, a reservoir with a capacity of approximately 3500 m^3 is essential.

Table 1. Typical decentralized design for rural sewage treatment at village scale.

Item	Quantities Day per Person or Area, d·m^2	Quota Day per Person or Area, L/d·m^2	Time h/d	Consumptions m^3/d
Residences	400	258 *	24	103.20
Commercial & public	23,000	6.00	10	138.00
Unexpected		10% of the total		24.12
Total, sewage		95% as produced		252.05
Greening water	70,500	3.00	8	211.50
Municipal miscellaneous	32,100	0.50	8	16.05
Unexpected		10% of the reclaimed		22.76
Total, reclaimed				250.31

(Note: * represents the average water consumption of Zhejiang Province in 2019).

The implementation and construction of water recovery facilities in China are currently exhibiting a steady growth trend. In Zhejiang Province, particularly in Hangjiahu region, rural sewage treatment and reuse practices are relatively advanced compared to other areas in the country. While centralized water reuse systems have traditionally dominated urban settings, decentralized water reuse systems are being adopted in certain individual buildings and rural locales. In 2022, the municipal water supply in Hangjiahu region reached 0.69 billion m^3 (Table 2), with over 70% of this volume derived from sewage. This reclaimed water is utilized for various ecological, environmental, and industrial applications, including cooling water, processing, and boiler water supply. Additionally, it serves agricultural irrigation and urban miscellaneous purposes, such as toilet flushing, gardening, car washing, and fire fighting, as well as irrigation for farmland [26].

In Hangjiahu region, the utilization of reclaimed water for agricultural irrigation is approximately 12.16 million m^3, which constitutes 12.3% of the total water consumption. This consumption also encompasses water used for forestry, animal husbandry, aquaculture, and livestock. Industrial water consumption amounts to 31.87 million m^3, representing 32.2% of the total (Table 3). Additionally, domestic water consumption by residents is recorded at 2.52 million m^3, accounting for 2.5%. The consumption of water for ecological environmental purposes is 52.55 million m^3, which makes up 53.0% of the total water usage.

Table 2. Statistical overview of municipal water treatment across 88 facilities in Hangjiahu regions.

City	Nos. of Facilities	Processing Capacity km^3/d	Actual Treated Water Volume Million·m^3/a	Including Sewage Treated Million·m^3/a	Among Them: Industrial Wastewater Million·m^3/a
Hangzhou	24	763.5	226.87	209.08	24.06
Jiaxing	20	569.0	148.51	53.90	67.47
Huzhou	44	1182.7	313.52	223.89	52.89
	88	2515.2	688.90	486.86	144.43

Table 3. Utilization patterns of reclaimed water in Hangjiahu region.

City	Reclaimed Water, Produced Million·m^3/a	Reclaimed Water, Utilized Million·m^3/a	For Industrial Reuse Million·m^3/a	For Municipal Miscellaneous Million·m^3/a	For Landscape Million·m^3/a
Hangzhou	57.92	48.73	0.65	0.83	47.25
Jiaxing	9.56	6.59	6.59	-	-
Huzhou	31.63	31.62	24.63	1.69	5.30
	99.10	86.94	31.87	2.52	52.55

2.2. Recycling and Treatment Processes of Domestic Sewage

(1) Decentralized rural domestic treatment processes

The treatment and reuse of rural domestic sewage is strongly advocated, with a recommendation to implement a decentralized system [27,28]. The benefits of such an approach are outlined as follows:

(1) Decentralized sewage treatment technology must exhibit strong resistance to impact loads, taking into account the varying qualities of influent and effluent water, as well as the different characteristics of the surrounding biological environment.
(2) The process demonstrates stability, and the treatment effect is optimal. In China, rural sewage treatment technologies typically select methods that exhibit superior sewage removal rates, thereby minimizing the risk of secondary purification or recurrent pollution. This approach ensures that the treatment process maintains a consistent performance, resulting in effluent water quality that complies with local regulations. Consequently, the treated water can be repurposed for use in various other industries.
(3) The investment in construction is minimal, and the operational costs are also low. The development of rural areas in China is characterized by significant disparities, with many regions experiencing relatively slow progress. This situation results in the majority of sewage treatment and recycling initiatives lacking substantial commercial surplus value. Therefore, when selecting decentralized sewage treatment processes, careful consideration has been given to local economic development. The construction and operational costs of these facilities are acceptable to local residents and align with their financial capabilities.

Figure 1 illustrates the most prevalent domestic sewage treatment processes and rural water reclamation methods. The most commonly used practical technologies for rural domestic sewage treatment in the region are integrated processes, including pretreatment combined with ecological filter bed technology, anaerobic processes coupled with A^2/O (Anaerobic-Anoxic-Oxic) technology, and anaerobic systems with subsurface flow constructed or artificial wetland technology.

There are two primary categories of rural wastewater that require recycling: the first is greywater generated from daily water usage, and the second is wastewater produced from toilet drainage, which typically contains significant quantities of essential plant nutrients, such as nitrogen and phosphorus. These nutrients are vital for crop irrigation. Agricultural irrigation does not necessitate the removal of nitrogen and phosphorus, provided that the quality of the effluent is adequately controlled and stabilized [29,30]. Furthermore, Chinese farmers have a long-standing tradition, spanning thousands of years, of utilizing human feces and urine as fertilizers via a feces harmless unit (FHU), often a septic tank.

The treatment processes for toilet drainage primarily involve urinary-fecal separation and urine source separation. Two methods are employed for urinary-fecal separation: the toilet-built-in source separation collection method and the siphon dry method. The toilet-built-in source separation collection method necessitates the direct and separate collection of feces and urine. Both urine and feces can be separately collected, with the supernatant, or "head water", being used for plant irrigation as a fertilizer. The feces, on the other hand, require treatment at a fertilizer manufacturing facility, where they are converted into fertilizers through processes such as fermentation, decomposition, and composting.

The siphon dry toilet method facilitates the collection of feces and urine into different storage containers after they have been combined. This separation technique is similar to the classification of kitchen waste, which differentiates between dry and wet waste for uniform recycling. The siphon dry toilet method necessitates the centrifugation of the

liquid and solid components in separate layers, allowing for the individual collection of both the liquid and solid phases.

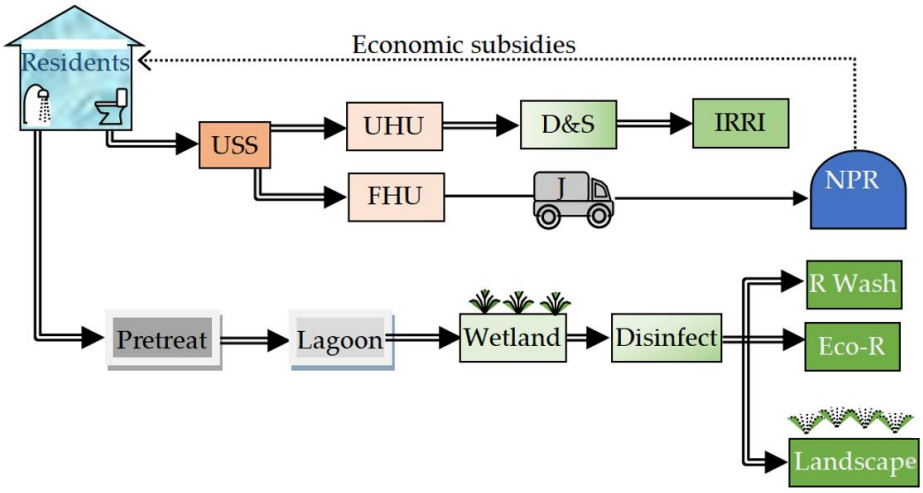


Figure 1. Source separation drainage processes and rural water reclamation systems. Note: Urinary-fecal separation and urine source separation, USS; Urine harmless treatment unit, UHU; Disinfection and sterilization, D&S; Nutrition for agricultural irrigation, IRRI; Harmless treatment of feces, FHU; Plant of fertilizer manufacturing for Nitrogen and Phosphorous recovery, NPR; Grey-water pre-treatment, Pretreat; Treatment via Lagoons and Ponds, Lagoon; Treatment via constructed wetland, Wetland; Disinfection of recycled waters, Disinfect; Road flushing and washing, R Wash; Ecological water replenishment, Eco-R; Urban greening landscape, Landscape.

The urine or supernatant obtained from urine source separation (USS) was processed locally in a urine treatment unit designed to render the urine harmless (UHU), converting it into its inorganic state. Following disinfection and sterilization (D&S), the recycled water is enriched with nitrogen and phosphorus for the recovery (NPR), making it suitable for reuse in agricultural irrigation in the vicinity [31]. The implementation of decentralized rural domestic treatment processes is advantageous due to their reduced costs. Additionally, the collected feces necessitate the establishment of transfer stations or biocomposting facilities within human settlements to facilitate the transportation of the processed resources to a centralized fertilizer manufacturing plant. To promote sustainable practices, local governments may provide financial subsidies to residents through the manufacturer.

In the treatment of grey wastewater, it is essential to eliminate all contaminants. Typically, both aerobic and anaerobic processes, as well as their combinations, are employed to reduce contamination levels. Natural purification methods, such as lagoon digestion and artificial wetland filtration, are prioritized. The recyclability of grey wastewater is limited and is contingent upon the specific applications for which the reclaimed water is utilized. Common uses include landscape irrigation, municipal purposes, road washing (R Wash), residential applications (i.e., residential greening), and ecological water replenishment (Eco-R), including the replenishment of pond water.

The pretreatment of greywater aims to remove larger suspended and floating particles present in sewage. Specifically, the impurities that can be intercepted by screening processes include wood chips, peels, fibers, hair, plastic products, and other materials that may obstruct the water inlet pipes and various pumps of subsequent treatment facilities, thereby increasing the treatment load. During the pretreatment stage, integrated processes, such as anaerobic digestion combined with A^2/O technology, may be employed to mitigate contamination. Following this, techniques such as lagoons or oxidation ponds are typically utilized to further convert organic substances into their inorganic forms. The transformation of nitrogen and phosphorus during the composting of oxidation pond sludge is expected to

be effective. Subsequently, nitrogen and phosphorus removal is achieved through several integrated systems, including Constructed Wetlands (CW) and oxidation ponds. The disinfected effluent from these systems can be safely utilized for applications such as road flushing, ecological water replenishment, and landscape irrigation.

The local government has compiled "Zhejiang Rural Domestic Wastewater Treatment Practical Technology Manual", which establishes technical specifications for the pipe network, technical processes, model selection, construction, and operation and maintenance of rural domestic sewage treatment in Zhejiang Province. This manual has been disseminated throughout the province by Provincial Agricultural Office and the Environmental Protection Department. It serves as a guide and summarizes the "top ten" practical technologies in the domain of rural domestic sewage treatment in Zhejiang Province, including pretreatment combined with ecological filter bed technology, anaerobic processes coupled with A^2/O technology, and anaerobic processes integrated with submerged flow CW technology [14].

According to a survey conducted in 2017, ATT (Anaerobic Treatment Technology) processes and combined anaerobic + ecological treatment processes (e.g., artificial wetlands, ecological ponds, and biological filter bed technologies) constituted 44.23% of the total. In contrast, A/O (Anoxic/Oxic) and A^2/O combined with ecological treatment processes accounted for 35.54%, while micro-power and micro-power combined with ecological treatment processes represented 6.24%. In Hangjiahu region, aerobic and aerobic with ecological treatment processes are predominantly utilized. This differs from other areas, such as Wenzhou, Jinhua, Quzhou, and Lishui, where anaerobic and anaerobic with ecological treatment processes are primarily employed.

The selection of rural domestic sewage treatment technologies is significantly impacted by factors such as topography, geographical location, and economic development. In the northern regions of Zhejiang Province, which are predominantly characterized by plain river network areas, there is a greater emphasis on the complete removal of pollutants and the reduction of contaminant concentrations. Conversely, in the southern regions, where mountainous terrain is prevalent, there is a tendency to favor anaerobic and combined anaerobic with ecological treatment processes. Additionally, alternative technologies, such as soil infiltration, have been explored, as they appear to be more appealing and feasible for implementation in hilly areas compared to artificial wetlands.

(2) Source separation drainage system and resource recovery

Human manure serves as an effective farmyard fertilizer, having played a significant role in agricultural practices for thousands of years [32]. However, the process of water flushing results in the loss of essential nutrients such as nitrogen, phosphorus, and potassium found in feces, which is counterproductive from a sustainable development perspective. Analysis of various types of domestic sewage indicates that the concentrations of nitrogen, phosphorus, and potassium in yellow water and brown water are considerably higher than those in gray water. Human urine and feces are substantial contributors to the nutrient load in central sewage systems, accounting for approximately 80% of nitrogen and 60% of phosphorus in wastewater [33]. Only 1% of the volume of urine contributes to 80% of the nitrogen and 60% of the phosphorus nutrients in municipal wastewater derived from toilet drainage. If all toilet waste were to be repurposed for agricultural use, it is estimated that 75% to 85% of nitrogen, phosphorus, and potassium could be utilized as resources rather than being treated as potential environmental pollutants. The recycling of these nutrients through technological means for agricultural production represents a promising direction for rural sewage treatment. Comprehensive reviews of technologies for nutrient recovery from wastewater have been conducted in previous studies [34,35].

Human urine represents a highly effective resource for the primary macronutrients (e.g., nitrogen, phosphorus, and potassium) essential for fertilizer production. It typically

contains concentrations of 10~12 g/L nitrogen, 0.1~0.5 g/L phosphorus, and 1.0~2.0 g/L potassium. Various technologies are available for the recovery of these nutrients from human urine. However, these processes necessitate source separation and subsequent treatment (Figure 1).

The source separation drainage system not only minimizes the volume of washing water, thereby contributing to water conservation, but also decreases sewage discharge and enhances sewage treatment capacity. Additionally, the organic fertilizer generated from this system can bolster food security. Numerous countries have long implemented engineering applications of source separation drainage systems, and China has also been exploring this approach in recent years.

Until the conclusion of the 1980s, the predominant agricultural practice in many rural areas of China involved the collection of human urine as a primary fertilizer. Each household maintained its own toilet and cesspit. Following natural fermentation and digestion within the septic tank, the resulting urine and feces were utilized as fertilizer for rice, wheat, fruits, and vegetables cultivated in the fields. However, with the development of urbanization, this traditional method of manure treatment has been progressively supplanted by centralized sewage treatment systems, a trend that is also evident in the rural regions of Hangjiahu region.

The treatment of sewage, primarily due to the discharge of human urine and feces, is often both costly and ineffective. This inefficiency arises from the significant energy expenditure associated with the removal of nitrogen and phosphorus during the water treatment process, which is estimated to constitute approximately 50~70% of the total energy consumption. Notably, nitrogen and phosphorus are valuable resources. Consequently, the removal of these elements not only consumes energy but also leads to the wastage of essential resources. Conversely, if nitrogen, phosphorus, and other resources are recovered prior to treatment, it may be possible to eliminate the need for the nitrogen and phosphorus removal processes altogether.

A demonstration project utilizing a source separation system has been implemented in a rural residential area of Huzhou City. This ecological drainage system for residential areas employs the Struvite process to effectively remove macronutrients from both black water and gray water, subsequently classifying these for treatment, which results in a reduction of sewage treatment costs. The system is capable of recovering 62% of nitrogen, 48% of phosphorus, and 45% of potassium from domestic sewage. Furthermore, a framework for the separate quality discharge, treatment, and recycling of source-separated materials has been established to facilitate the storage, decomposition, and fertilization of the collected struvite, ultimately yielding an organic nitrogen fertilizer that is nutrient-rich and readily decomposable. Additionally, “Eco-Town” project, which integrates “agritainment” with sustainable practices, has been actively implemented, promoting the recycling of resources from the ecological drainage system.

(3) Sludge fertilizer, recovery of phosphorus and potassium in sludge

(1) Method of making organic fertilizer from domestic sludge

The water content of sludge obtained from sewage treatment plants typically ranges from 75% to 80%. This sludge is subsequently dried to approximately 60% moisture content using sludge drying equipment before undergoing composting. The standard operational procedure involves placing raw materials with low water content beneath the fermentation tank, followed by layering mixed organic waste on top. This method optimizes the utilization of liquid organic fertilizer present in the raw materials, thereby enhancing the nutrient availability within the mixture. During fermentation, the moisture content of the material is maintained at approximately 50% to 55%. When the temperature

reaches between 65 °C and 70 °C, the mixture can be turned over to facilitate cooling. It is crucial to monitor the temperature, as excessively high temperatures can result in the destruction of beneficial bacteria within the raw materials. If the concentration of beneficial bacteria in the final product does not meet established standards, the mixture may require an additional fermentation period of 5 days to 7 days during the summer months before being discharged from the tank. In winter, the mixture can be stored in a designated facility for fermentation for 12 days to 15 days, ensuring that the temperature remains at or above 60 °C to 65 °C, with a resultant moisture content of 35% to 40% [36,37].

Figure 2 depicts a standard procedure for the production of organic fertilizer. The cell membranes of the sludge are disrupted to release inorganic substances, including heavy metal ions contained within the intracellular organic matter, through the addition of agents such as acids or chelates. Subsequently, heavy metals are extracted for recovery. Following the adjustment of humidity levels, the sludge undergoes composting under aerated conditions, during which moisture content decreases due to vaporization. The sludge is suitable for use as fertilizer once stabilization has been achieved.

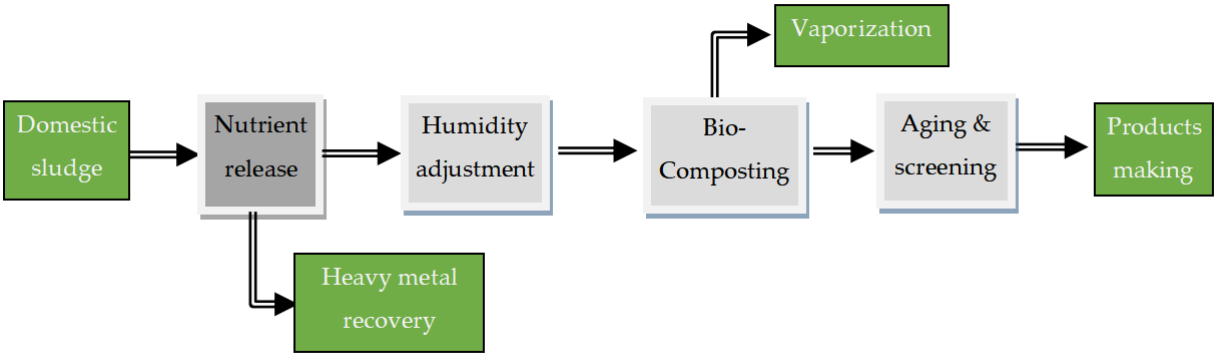


Figure 2. Typical process for organic fertilizer production from domestic sludge in Hangjiahu region. Note: 1. Sludge pretreatment: Crushing sludge flocs and sludge cell membranes to release intracellular organic matter. 2. Adjusting moisture and aeration: Moisture content maintained at 50–60%, and the breathability by inserting tree branches or wooden poles during stacking. 3. Composting fermentation: To regularly flip the mixture to ensure uniform fermentation. The fermentation cycle generally 10–15 days, and may be appropriately extended by 4 days in winter. 4. Aging and crushing screening: To make organic fertilizers more stable, while crushing screening is to remove large substances and obtain uniform powdered organic fertilizers. 5. Packaging and sales: The package of the organic fertilizer to proceed with sales.

The procedures for the production of fertilizer are typically as follows: Firstly, the sludge undergoes preliminary treatment, which includes processes such as screening and compression, aimed at removing impurities and larger particles. This initial step is crucial for facilitating the effective progression of subsequent treatments. Next, the moisture content and air permeability of the sludge are adjusted. Water is added to the treated sludge to achieve an optimal humidity level, generally between 50% and 60%, while ensuring adequate air circulation within the mixture to promote the growth and decomposition of microorganisms. The ideal moisture content is characterized by the material being grasped in the hand, exhibiting watermarks without dripping, and being sufficiently loose to disintegrate upon falling to the ground.

Secondly, the incorporation of auxiliary materials is recommended. Mixing the sludge with other organic materials, such as agricultural waste and food processing byproducts, can enhance the organic matter content and improve the nutrient balance of the resulting fertilizer. Additionally, these auxiliary materials can help regulate the moisture content and air permeability of the mixture.

Thirdly, composting fermentation involves placing the mixture in a well-ventilated composting area and regularly turning it to promote uniform fermentation. Throughout the fermentation process, the microorganisms present in the sludge decompose organic matter, release nutrients, and generate heat, accompanied by the evaporation of water.

Fourthly, After a period of fermentation, the mixture stabilizes through a process known as "aging". Following this, the aged organic fertilizer is crushed and screened to eliminate bulk materials, resulting in a uniform powdered organic fertilizer.

Finally, the prepared organic fertilizer is packaged in accordance with established specifications, labeled with the product name, ingredients, usage instructions, and additional relevant information, before being made available for sale. Through these processes, domestic sludge can be effectively transformed into organic fertilizer, thereby facilitating resource reuse and mitigating environmental pollution.

The amount of sludge generated by rural and urban sewage treatment plants in Hangjiahu region averages approximately 1 ton/day of dry sludge, corresponding to an annual average of 10,000 tons of sewage. This is equivalent to about 5 tons of sludge, assuming a moisture content of 80%. Typically, sludge production is higher during the summer months and slightly lower in winter. The dry sludge output constitutes approximately 5000 to 15,000 of the wastewater treatment capacity. For a treatment facility with a capacity of 100,000 m^3, the daily production of dry sludge ranges from 5 tons to 15 tons. Generally, the sludge is dehydrated to a moisture content of 80%, resulting in a wet sludge cake production of approximately 25 ton/day to 75 ton/day.

Following the fermentation of sludge into organic fertilizer, it can undergo various processes such as crushing, granulation, cooling, and coating to produce the final fertilizer product.

Sludge organic fertilizer can only be distributed following rigorous quality control measures and compliance with agricultural standards. The applications of sludge organic fertilizer include roadside greening, the cultivation of ornamental plants, mine reclamation, and various agricultural and forestry purposes. As a nutrient-rich soil amendment, sludge can serve multiple functions, such as a soil conditioner, urban lawn enhancement, flower cultivation, landscaping, and the greening of arid regions and barren mountainous areas. Furthermore, it can be utilized as a raw material in agricultural fields to capitalize on the high organic content of the nutrient-rich soil. Additionally, nutrients such as nitrogen, phosphorus, and potassium may be incorporated based on specific soil characteristics to produce organic-inorganic composite fertilizers.

(2) Removal of heavy metals

Sludge serves as a valuable fertilizer, being rich in nitrogen, phosphorus, potassium, and other essential nutrients. However, it may also contain toxic heavy metals that pose safety concerns. The removal of heavy metals from sludge presents an effective solution, and various methods have been developed for this purpose [38,39]. Among these methods, bioleaching has garnered significant attention from researchers globally due to its economic viability, high efficiency, sustainability, and robust engineering applicability. Notably, a critical advantage of bioleaching is that it does not substantially alter the properties of the sludge.

Bioleaching is a biotechnological process wherein specific microorganisms (e.g., *Thiocbacillus acidophilus*) or their metabolites facilitate the dissolution of heavy metals through a series of biochemical reactions, including oxidation-reduction, complexation, adsorption, and dissolution [40]. This microbial leaching technique demonstrates a high efficacy in the removal of various heavy metals, achieving removal rates exceeding 90% for copper, zinc, nickel, manganese, and cadmium [41–43]. Numerous factors affect the efficiency of the bioleaching process:

(a) The form of heavy metals significantly impacts the leaching process; specifically, metals in a stable state exhibit greater resistance to leaching, whereas those in an unstable state are more readily removed;
(b) The dosage and type of substrate impact the metabolic activity of bacteria and determine the prevalence of dominant bacterial species;
(c) The quantity of inoculation can significantly reduce the duration of the cultivation period. An insufficient inoculation amount may result in the failure of the desired strain to establish itself as the dominant strain. In this context, the removal rate increases gradually within the range of 5% to 10%, eventually stabilizing thereafter;
(d) The performance of sludge dewatering is significantly enhanced following biological leaching, although temperature and pH levels will also affect various strains to certain degree.

Additionally, emerging technologies, including anaerobic acidification leaching and the separation extraction of sludge, are being developed to enhance the efficacy of heavy metal removal.

Bio-leachate undergoes appropriate treatment to facilitate resource recovery. The heavy metal sludge produced during the treatment of heavy metal wastewater should be recycled initially to prevent secondary pollution [44]. Hazardous waste must be transferred to qualified facilities for proper treatment. Temporary disposal sites for sludge should adhere to the regulations [45]. The most suitable technique for this process is the electrodeposition method.

The electrochemical method represents a significant cleaning technology with diverse applications [46]. This approach is effective in the removal and recovery of heavy metal ions from wastewater. "Technical Specification for Electrochemical Advanced Treatment of Heavy Metal Wastewater" [47] is a Hunan Provincial Local Standard of China, which offers technical guidance for the treatment of heavy metal-laden wastewater, particularly for electrodeposition technology.

The electrodeposition of heavy metals involves the reduction of metal ions onto the electrode and the chemical deposition of metal hydroxides resulting from the accumulation of alkalinity at the cathode. In Figure 3, as an example, copper ions are predominantly deposited in the cathodic chamber of an electrolytic cell either the metallic element or the precipitation of copper hydroxide due to the formation of hydroxides. The introduction of oxygen at the cathode can be advantageous, as it may either inhibit the formation and evolution of hydrogen gas or facilitate reactions involving iron ions, thereby enhancing overall efficiency. Furthermore, the presence of oxygen can significantly reduce the voltage of the electrolytic cell, which in turn decreases the power input required for the process. In the anodic chamber, the presence of sodium chloride can lead to the formation of chlorine, a highly effective disinfectant. Conversely, in the absence of sodium chloride, the primary reaction at the anode would be the evolution of oxygen, which is not utilizable in this context. Gold, silver, copper, zinc, mercury, lead, and cadmium can be easily deposited onto the cathode in either their metallic element or hydroxide form. Arsenic will dissolves into an alkaline solution that was formed in cathodic chamber and is difficult to form the hydroxide precipitation.

The extraction of heavy metals from sludge facilitates the production of nutritious and safe fertilizers, while also enabling the effective recycling of phosphorus, a critical resource [48]. It is widely acknowledged that a significant portion of the phosphorus utilized by humans ultimately enters wastewater systems. In China, municipal sewage generates over 290,000 tons of phosphorus annually, which accounts for approximately 5.5% of the total phosphate fertilizer consumption. By shifting the paradigm from "phosphorus removal" to "phosphorus recovery", the dual challenges of phosphorus resource scarcity

and environmental pollution more effectively. Phosphorus is a non-renewable resource with unique characteristics, and global reserves of phosphate rock are limited. Various studies provide differing estimates regarding the availability of phosphorus resources on Earth and their longevity, with projections ranging from several decades to several centuries.

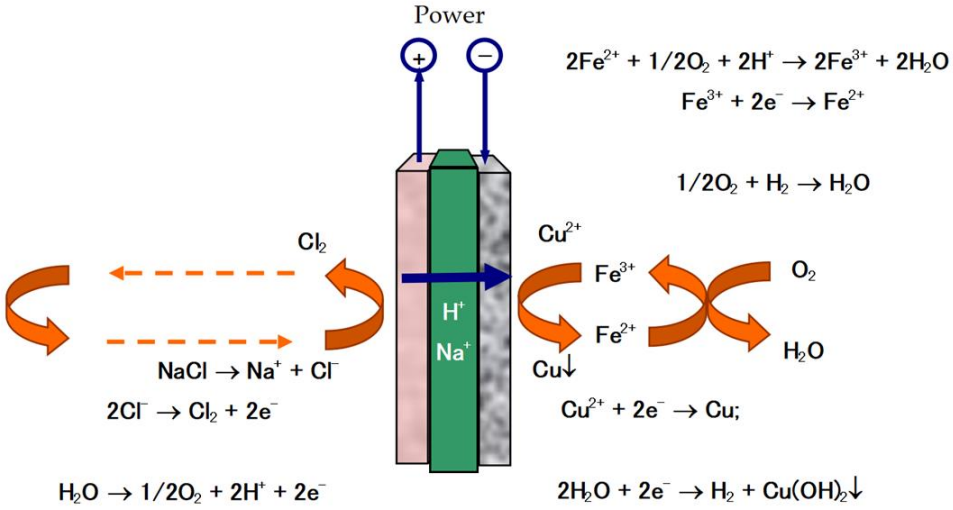


Figure 3. Typical process of metal leaching and electrochemical recovery from domestic sludge. Note: Reactions in cathodic chamber: 1. Cu(II) reduction to Cu, $Cu^{2+} + 2e^- \rightarrow Cu$; 2. Hydroxides formation and $Cu(OH)_2$ deposition in alkaline solution; 3. Mediate reaction: firstly ferric ions reduced to be ferrous ions $Fe^{3+} + 2e^- \rightarrow Fe^{2+}$ and then filled oxygen to oxidize ferrous ions to form ferric ions, $2Fe^{2+} + 1/2O_2 + 2H^+ \rightarrow 2Fe^{3+} + 2H_2O$, secondly ferrous ions formed to reduce copper ions; 4. Suppression of hydrogen: $1/2O_2 + H_2 \rightarrow H_2O$, oxygen oxidize the hydrogen formed in cathode resulting no H_2 release. Reactions in anodic chamber: 1. Sodium chloride was oxidized to be a chlorine gas released, which can be used for disinfection purpose; $NaCl \rightarrow Na^+ + Cl^-$, $2Cl^- \rightarrow Cl_2 + 2e^-$; 2. Side reaction of water oxidization: $H_2O \rightarrow 1/2O_2 + 2H^+ + 2e^-$; 3. Na^+ and H^+ formed moved into the cathodic chamber via a selective membrane between the anode and the cathode.

Another method for the utilization of sludge involves thermal digestion to extract phosphorus. Sludge sourced from Jiaxing Wastewater Treatment Plant in Hangjiahu region has been demonstrated to be effectively reclaimed through thermal treatment [49]. The phosphorus recovery rate can exceed 90%, with struvite purity also surpassing 90%, indicating a highly efficient approach for the utilization of sewage sludge during hydrothermal conversion [50]. Pollution control and resource recovery in the study area constitute a fundamental aspect of the successful implementation of "Five Water Co-Governance" in Zhejiang Province [51,52].

2.3. Sustainability of Environmental Quality

(1) Further improvements of system planning

Similar to other regions in China, the residential structures in the rural Hangjiahu region are predominantly self-constructed. A significant number of these houses have not undergone professional planning and management concerning construction land. The foundational construction of these buildings lacks standardization, with many structures positioned less than 1 m apart, which presents considerable challenges for pipeline installation. The implementation of the toilet revolution has led to the conversion of many rural households to water-flushing toilets. However, the overall planning of water supply and drainage systems, along with the renovation of rural toilets, has not been adequately addressed. This has resulted in poor infrastructure connectivity and an insufficient sewage collection system, leading to a low rate of sewage collection. Consequently, numerous

domestic wastewater, including kitchen effluent, is allowed to seep directly into the ground or into ditches.

During the 2010s, the development of pipe networks experienced significant delays, leading to suboptimal efficiency in sewage treatment. In certain rural areas, the planning for sewage collection networks has not kept pace, resulting in inadequate separation of rainwater and wastewater, as well as a failure to distinguish between domestic and industrial sewage. This has contributed to the overall inefficiency of sewage treatment systems. Simultaneously, due to challenges in sewage collection, the design capacity of the sewage treatment plant often exceeds the actual wastewater discharge from residents. This mismatch results in insufficient water intake for ongoing operation, leading to the underutilization of the plant and contributing to high operational costs [53].

In response to the aforementioned issues, the local government has implemented robust measures to enhance local conditions and improve top-level design, thereby ensuring that planning is conducted in a scientific and rational manner as follows:

(a) Develop comprehensive planning through stakeholder consultation and coordination: Prior to the planning phase, it is essential to segment the rural sewage treatment project in accordance with the specific conditions of the rural living environment. This segmentation should be based on a thorough consideration of ecological protection, environmental management, resource utilization, rural revitalization, regional development, and an overall assessment of the rural layout, including the construction of water supply and drainage systems as well as the renovation of rural sanitation facilities. Concurrently, it is imperative to engage multiple stakeholders in the formulation of the rural sewage treatment plan. This includes facilitating consultations among government representatives, local residents, and enterprises to ensure that the perspectives and opinions of rural inhabitants and various stakeholders are gathered and integrated into the planning process.

(b) Enhance expert support and guidance to develop unified planning at the county level: By conducting thorough investigations and offering expert guidance, it is essential to assess the current status and challenges associated with rural domestic sewage treatment in local areas. This assessment will facilitate the scientific determination of appropriate collection and treatment methods. Subsequently, a scientifically sound and contextually appropriate planning framework should be developed, utilizing the county as the organizational unit. The objective is to achieve a cohesive strategy encompassing unified planning, construction, and management, thereby addressing the deficiencies in the layout, technology selection, and management integration of rural domestic sewage treatment projects.

(c) Upgrade and remediate existing sewage collection system: This approach is based on the principle of optimizing the utilization of the current pipe network. It evaluates the rationality of the drainage system and the layout of the pipe network, the compatibility of pipe network construction, the standardization of operational and management practices, and the economic feasibility to ascertain the necessity for transformation. In cases of inadequate pipe networks, misconnections, mixed connections, or leakage connections, efforts should be made to improve the construction of the sewage collection system to increase the sewage collection rate. Additionally, for instances where rainwater is inadvertently mixed into the pipe network, leading to persistently low intake concentrations, a rainwater and pollution diversion transformation is recommended. Furthermore, for aging, damaged, or obstructed pipe networks, renovation should be undertaken.

According to the investigation, in 2010, the operational capacity of the sewage treatment plant was less than 66% of its design capacity, with approximately 36% of the system

facing operational difficulties due to a misaligned sewage collection network. This situation has undergone continuous improvement, with enhanced operational management and the assignment of responsibilities to specific individuals. By 2020, the capacity of the sewage treatment plant had increased to over 99%, and nearly 100% of the operational processes were effectively executed, attributed to the successful renovation of the sewage collection network.

(2) Increased sufficient investment in infrastructure construction

The data in Figure 4 indicates that from 2013 to 2019, there has been a consistent year-on-year increase in investment in rural drainage and sewage treatment infrastructure in China. However, the absolute value of this investment remains lower than that allocated to urban areas [54,55]. In 2019, the investments in urban drainage and sewage treatment facilities amounted to 156.24 billion yuan and 80.37 billion yuan, respectively. In contrast, the investments in rural drainage and sewage treatment facilities were 46.144 billion yuan and 27.569 billion yuan, which represent approximately 29.53% and 34.30% of the corresponding urban investments.

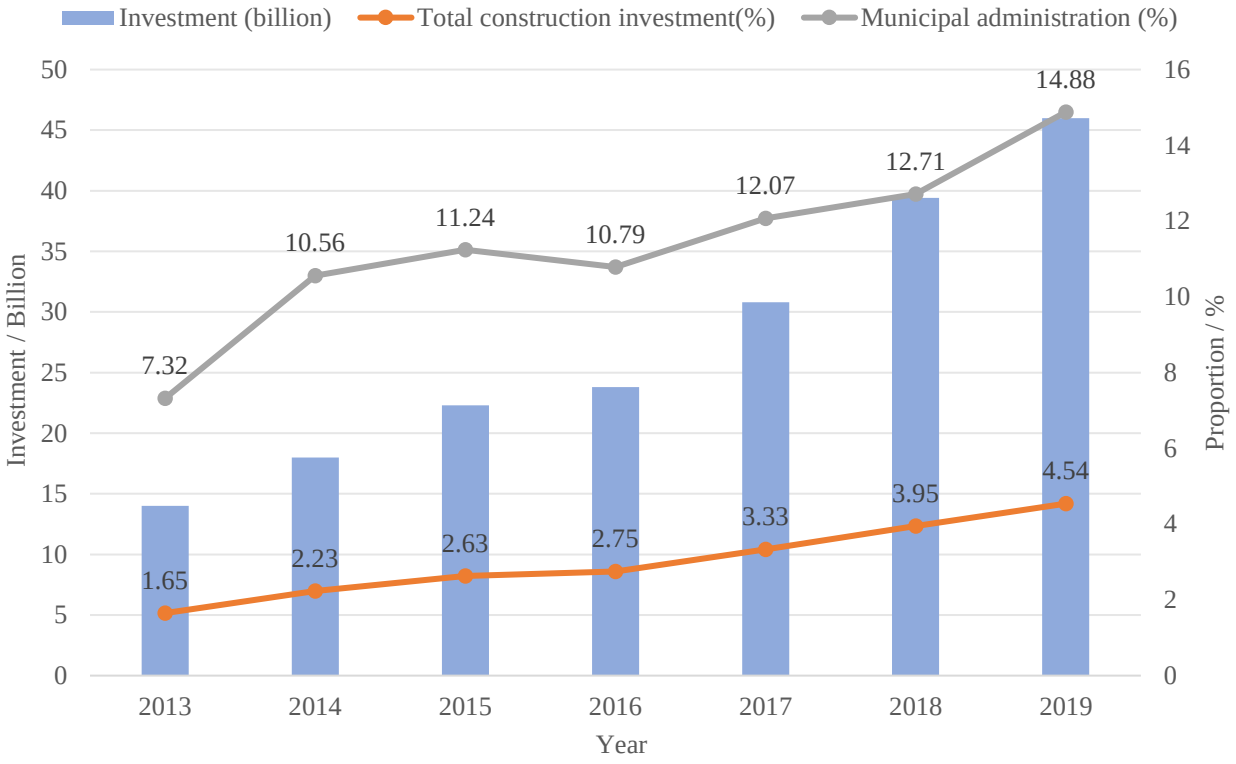


Figure 4. Investment trends and proportions in rural drainage facilities construction (Note: The data is sourced from China Urban Rural Construction Statistical Yearbook published by Ministry of Housing and Urban-Rural Development (https://www.stats.gov.cn/sj/ndsj/2019/indexeh.htm, accessed on 23 December 2024)).

From the perspective of investment allocation, between 2013 and 2019, there was a consistent increase in the proportion of investments directed towards drainage facilities and sewage treatment facilities within the total construction investment, as well as in municipal investment. The regional and national investments in rural drainage and sewage treatment facilities are summarized in Table 4. In 2019, drainage facilities and sewage treatment facilities represented 4.54% and 2.71% of the total investment in rural construction, respectively, with neither exceeding 5%. Conversely, the proportion of municipal investment in rural areas was 14.88% and 8.89%, respectively, both of which did not surpass 15%.

Table 4. Investment analysis for rural drainage and sewage treatment infrastructure in 2019.

Region	Drainage Facilities			Sewage Treatment Facilities		
	Investment/100 Million RMB	Investment Intensity per Administrative Village/10,000 RMB	Per Capita Investment Intensity/Yuan	Total Investment/100 Million RMB	Investment Intensity per Administrative Village/10,000 RMB	Per Capita Investment Intensity/Yuan
nationwide	460.65	9.03	63.20	275.50	5.40	37.80
eastern	277.05	14.25	112.25	187.61	9.65	76.02
middle part	92.62	5.74	37.67	43.73	2.71	17.78
west	88.71	5.82	37.68	43.93	2.88	18.66
Hangjiahu region	239.14	16.58	121.3	/	10.86	80.71

(Note: The data is sourced from China Urban Rural Construction Statistical Yearbook published by Ministry of Housing and Urban-Rural Development (https://www.stats.gov.cn/sj/ndsj/2019/indexeh.htm, accessed on 23 December 2024)).

From the perspective of investment intensity, the investment in drainage facilities and sewage treatment facilities in administrative villages across the nation in 2019 amounted to 90,300 yuan and 54,000 yuan, respectively. In comparison, the investment intensity for these facilities in Hangjiahu region was significantly higher, at 165,800 yuan and 108,600 yuan, respectively. In 2019, the per capita investment intensity for national drainage facilities and sewage treatment facilities was recorded at 63.20 yuan and 37.80 yuan, respectively. In contrast, the investment intensity in Hangjiahu region was significantly higher, at 121.30 yuan and 80.71 yuan, respectively.

For the increasing costs associated with building materials and labor, the current low level of investment intensity is insufficient to address the pressing issues faced in rural areas. Consequently, relevant departments within local government are compelled to resort to compromising the quality of projects to fulfill work tasks and meet performance indicators. Notably, Hangjiahu region exhibits investment levels that are more than double the national average in China, indicating that there remains significant potential for enhancement. Therefore, it is imperative to strengthen investment and incentive mechanisms to ensure the effective sourcing and management of funds [55,56].

This study aims to enhance the mechanisms governing government funding. This will be achieved through a comprehensive evaluation of diverse capital investments, thereby improving the matching funds at this level. Specific awards and subsidies will be formulated to expedite the allocation of funds. For instance, it can effectively integrate project funds related to agriculture, rural development, human settlements, and rural beautification. This includes establishing a dedicated fund for rural domestic sewage treatment, enhancing the government funding mechanism through a model of "central subsidies, local financing, and cost recovery", and creating a robust fund guarantee system.

The enhancement of social capital can be achieved through various channels. Given the limited capacity of enterprises to contribute to social capital and the inadequate effectiveness of rural sewage treatment initiatives, it is necessary to strengthen the incentive mechanisms for social capital investment. By implementing demonstration projects for rural sewage treatment, relevant enterprises can receive both financial and policy support. Additionally, regional projects can be bundled together, allowing for the integration of multiple initiatives such as road construction, toilet reform, and ongoing management in rural development. This approach aims to create profitable complex projects that will attract enterprise participation. Furthermore, contributions from environmental protection organizations, investments from public welfare funds, and the active engagement of successful entrepreneurs returning to their hometowns can significantly mobilize social resources for funding. Concurrently, it is important to guide qualified regions in effectively integrating the development of rural sewage treatment infrastructure with distinctive industries, leisure agriculture, and rural tourism. This strategy seeks to achieve the integrated

development of rural industries while simultaneously enhancing the quality of human settlements [57].

The refinement of capital allocation and management is essential. In accordance with the developmental needs of various regions, it is imperative to delineate the objectives and requirements specific to different areas and types of rural domestic sewage treatment. A scientific assessment of the financial resources necessary for the execution of various stages of rural sewage treatment must be conducted to ensure that capital investments yield the anticipated results. During the construction and renovation of rural sewage facilities, it is advisable to actively explore the implementation of an agent construction system. This approach would facilitate the optimal utilization of market funds, enhance the allocation and management of financial resources, and transition the management and maintenance aspects to the market in the later stages. Such measures aim to establish a robust industrial chain encompassing enterprise products, operations, and the enhancement of research and development efficiency.

(3) Quality of late operation management

The funding for the construction of rural drainage and sewage treatment infrastructure in China primarily derives from national and local financial support, while the funds for operation and maintenance are predominantly sourced from local finances. In numerous regions, although government-funded infrastructure is constructed, rural areas often struggle to bear the ongoing operation and maintenance costs. This has led to a challenging situation where projects are "affordable to build but unsustainable to operate", resulting in the gradual discontinuation of sewage treatment facilities. Factors contributing to this issue include the economic development level in rural areas, the absence of specialized operation and management teams, an overall low standard of management, and the lack of scientifically sound and reasonable management and protection mechanisms. Therefore, rural sewage facilities are unable to fulfill their intended functions effectively.

Currently, the administrative agencies responsible for rural sewage treatment are fragmented, leading to significant overlap in functions. This fragmentation results in ambiguous regulatory responsibilities and exacerbates the challenges associated with supervision. For instance, Hangzhou's "One Hundred Villages Demonstration, One Thousand Villages Renovation" project is overseen by Rural Agricultural Department, "1250" project is managed by Ecological Environment Bureau, and "One Million Household Sewage Purification Biogas" project is handled by Energy Office.

The local government is currently implementing various management models. The selection of an appropriate management approach should be contingent upon local conditions and a comprehensive evaluation of multiple factors, with economic considerations being paramount. In regions characterized by favorable economic conditions, a market-oriented operational model that incorporates government oversight and social participation may be adopted. This model allows for the engagement of third-party companies to ensure the professional management of facilities. Conversely, in areas with less favorable economic conditions, a phased management approach that combines independent management by villagers with government assistance, or a financial contribution model for village management, may be more suitable. Furthermore, to optimize resource utilization and enhance the effectiveness of management operations and maintenance, it is necessary to leverage advancements in Internet technology to establish an unattended sewage treatment operation system and an intelligent supervision platform.

There is a need to establish and enhance relevant mechanisms. This includes improving the diversified, full-process supervision system for rural domestic sewage treatment, strengthening oversight throughout all phases (i.e., from planning and construction to acceptance and long-term operation and maintenance). A comprehensive supervision

framework should be developed, with government law enforcement as the primary authority, while actively involving rural residents and society. This system should enable online evaluation, supervision, reporting, problem consultation, and immediate feedback for national rural domestic sewage treatment projects. Furthermore, a long-term infrastructure management and protection mechanism should be created, with the government enhancing systems and management practices across operation, administration, oversight, and technical inspection. This could include establishing management awards, appropriate payment mechanisms for villagers, and assigning technical personnel for routine inspections and maintenance. Additionally, a multi-departmental cooperation framework should be established, with clear roles and responsibilities, ensuring effective policy coordination, defining departmental tasks, and fostering communication by adjusting supporting policies on environmental protection, finance, and ecology, while formulating detailed responsibility lists.

Sustainable efforts are ongoing and have never ceased. The local government has consistently increased support and funding for environmental protection in rural wastewater treatment. As a result, the processing rate and efficiency have more than doubled the national average. Sewage treatment and water supply protection remain key challenges in implementing "Five Water Co-Governance" strategy within river network areas. Continuous water treatment, ecological restoration, and monitoring will be essential to ensuring long-term sustainability in Hangjiahu region.

2.4. Domestic Sewage Treatment and Ongoing Environmental Policy

(1) Improvement of surrounding water quality after domestic sewage treatment

One of the key components of "Five Water Co-Governance" initiative is sewage treatment. This plan, introduced in 2014 by Zhejiang Province, encompasses sewage treatment, flood prevention, waterlogging drainage, water supply protection, and water conservation, all aimed at enhancing environmental quality and improving people's livelihoods [58,59]. Below are examples of the improvements in domestic sewage quality in the region following treatment:

Jiashan County is one of the cities in Hangjiahu region, situated within the water network area of Hangjiahu Plain, characterized by an complex system of rivers and numerous lakes. Historically, the inhabitants of this region have relied on water for their livelihoods, and the pristine waters of Jiashan envelop the city [60]. It is a shared aspiration among the residents of Jiashan to restore and preserve the picturesque landscape of clear waters and verdant shores.

Cities, including Jiashan, have responded to the provincial government's initiative to implement "Five Water Co-Governance" campaign. This initiative has facilitated developments in sewage treatment while simultaneously promoting the objectives of "Five Water Co-Governance" framework. Since 2021, various regions within the county have exerted considerable effort to establish zones with zero direct sewage discharge, as well as to develop and enhance a long-term operation and maintenance mechanism. These efforts aim to further improve public satisfaction and well-being regarding the water ecological environment. Following the successful establishment of zero direct discharge sewage areas in 2021, the county has achieved municipal acceptance for the establishment of a provincial benchmark park in Yaozhuang Economic Development Zone. Additionally, the construction of benchmark towns within the zero direct discharge sewage areas in Tianning Town and Dayun Town has been completed and has also received municipal acceptance.

Jiashan County, with a population of approximately 664,000, has 24.8% of its residents living in rural areas. In pursuit of enhancing the quality and expanding the zero-direct sewage discharge zone, the county has prioritized the establishment of a long-term su-

pervision, operation, and maintenance mechanism for this initiative. The water quality standard compliance rate in Jiashan County is 100% across various categories: the overall area, the drinking water source area, the exit section, and the city-to-town section. Since 2022, the county has fully embraced the concept of "lucid waters and lush mountains are invaluable assets", actively advancing the comprehensive prevention and control of water pollution as well as ecological restoration efforts. These initiatives have led to a significant improvement in the quality of the water ecological environment. The achievement of these four "100%" compliance rates reflects the county's effective water management strategies, particularly in relation to sewage treatment and its positive effect on the surrounding water quality in rural areas.

In the rural areas, a monthly inspection competition is conducted across each town, village, and street to ensure zero direct sewage discharge from industrial sources. This initiative encompasses comprehensive inspections, high-standard rectifications, industry supervision, and graded assessments. Over the past year, a total of 397 industrial enterprises, residential areas, and various other sectors were subjected to on-site inspections, resulting in the identification of 477 issues, all of which have been addressed and rectified. The provincial environmental technology company has been commissioned to evaluate the effectiveness of the zero direct sewage discharge initiative in nine towns and streets within the county, utilizing expert assistance. Simultaneously, the county has also pioneered an innovative "Construction, Management, and Maintenance integration" mechanism for ensuring zero direct sewage discharge in urban residential areas. Since the beginning of this year, transparent operation and maintenance practices have been implemented in 115 residential areas, with the establishment of operation and maintenance bulletin boards. Among these, 67 areas have been entrusted to Water Group for professional operation and maintenance, thereby reinforcing long-term operational responsibilities. For instance, Tianning Town has consolidated the management of 26 residential areas and has engaged the county water service group for professional operation and maintenance, ensuring that each facility is constructed, accepted, and maintained effectively. Currently, 24 residential areas have passed the water storage test, achieving a qualification rate of 92.3%.

(2) Ecological environment improvement project

An additional example of increased investment can be observed in the domain of rural sewage treatment. "Xiangfudang Ecological Environment Improvement" project represents one of the 20 landmark initiatives and allocated to "Xiangfudang Water" project amounts to 189 million yuan in the Jiashan area, coinciding with the third anniversary of the establishment of the demonstration area. This project employs a comprehensive approach that includes simultaneous treatment of water and shorelines, ecosystem restoration, and the conceptualization of water as a vital element. The experiences and practices derived from the demonstration area are integrated and showcased, focusing on the protection of water ecology, enhancement of water quality, and effective management of water resources.

Specifically, in the Jiashan area, lakes, ponds, and small streams have been rearranged to connect the rivers with water channels, expanding the smooth flow of the river network, establishing ecological ponds, and providing habitats for migratory birds. Through the diversion, expansion, and excavation of water ponds, lagoons, streams, and creeks, the water surface area of large rivers has been widened, in somewhere ponds, lagoons and creeks are reallocated and rivers are enlarged. Also, the sewage entering ponds or lagoons undergoes strict quality control to ensure that the water quality meets environmental requirements. Thus, it effectively provides habitats for wild animals and establishes ecological diversity. The results indicate that presently, the regional ecology is thriving, characterized by vibrant biodiversity. A comprehensive survey and assessment of the region's biodiversity revealed the presence of five species of nationally protected second-

class birds, six species of nationally protected second-class wild animals, eight species of fish endemic to China, 97 species of other birds, and 52 species of fish in Jiashan. The enhancement of water quality and environmental conditions has facilitated the emergence of fireflies in rural areas such as Xitang, Yaozhuang, and Weitang. In 2022, Shengjiawan was designated as a key site for the province's biodiversity experience initiative. High-standard water ecological restoration projects in areas such as Jiangjiagang, Yaozhuang Town, Shili Water Town, and Dayun Town have effectively realized the concept of "transforming beauty into prosperity" in rural regions.

This initiative represents a microcosm of Jiashan's endeavors to establish a pilot county for water ecological restoration within the province. Emphasizing top-level design, the county allocated 7.5 million yuan to develop a comprehensive water ecological protection and restoration plan, as well as an implementation strategy, from a high starting point. The plan aims to establish "Jiashan Model for Waterfront Residential Development in Yangtze River Delta", focusing on four key areas: water ecological restoration, comprehensive water environment treatment, protection and utilization of water resources, and the intelligent supervision of water ecology, all within a framework of systematic planning [61].

(3) Ecological water restoration and scenery

Jiaxing is situated in the lower reaches of Taihu Lake and Canal Basin within Hangjiahu Plain, an area characterized predominantly by inbound water flows. The region has historically faced significant challenges related to water quality. In recent years, a novel approach has been advanced to water pollution management that emphasizes a balanced focus on pollution prevention, ecological restoration, and the reconstruction of water systems. These efforts aim to enhance the quality of the water environment, transitioning from mere category improvements to achieving ecological health.

To maintain the water quality and environment, in Lanxi Pond located at the junction of Tongxiang City and Wujiang District of Suzhou, Jiangsu province, an Unmanned Aerial Vehicle (UAV) is used to in situ monitor unusual situation, ascends slowly over the river, swiftly covering a wide area. Real-time images of the entire river are observed by inspectors from both Tongxiang and Wujiang. These stakeholders communicate and collaborate via the screen to monitor water quality and the ecological development along both riverbanks. With UAV's high-altitude capabilities, thermal imaging (e.g., to monitor cyanobacteria outbreak), and other advanced features, the water environment and floating objects for instance on the surface can be clearly observed.

To collaboratively protect the Border Rivers, staff from both sides conducted a joint inspection of Lanxi Pond, located at the confluence of the two provinces. Compared with the traditional river patrol mode, the joint river patrol can, on the one hand, better find the problems in the river through UAV, on the other hand, the 'river leaders' of the two places can directly communicate face-to-face, discuss countermeasures, solve problems immediately in the exchange, and make the river patrol more comprehensive and efficient.

Rivers and ponds are not only hydrophobic and water storage areas, but also scenery. Transforming a river into a green space not only improves the urban living environment but also enhances the well-being and happiness of its residents. In recent years, Jiaxing has effectively leveraged the assessment to strengthen water governance, and allocates a budget and invests in the daily maintenance of landscape water every year. By refining the evaluation process and advancing upgrades, the city has reinforced water control responsibilities at all levels, addressing obstacles and encouraging underperforming areas to overcome challenges and strive for excellence.

Also, the local government has actively integrated into the "Five Water Co-Governance" platform, promoting multi-dimensional coordination and digital management of the water ecological environment, including supervision, protection, and restoration. This approach

has significantly enhanced the city's overall capacity for intelligent water governance. A smart sewage management system is also developed, featuring a "digital twin" application for the sewage pipe network, and establishing a smart network for the city's sewage infrastructure.

As a result of these measures, the two banks of rivers and ponds are adorned with verdant trees, while the river flows in a long, blue course. As one traverses the land of Jiahe, one can observe the prevalence of clear waters and lush banks [62]. Jiaxing, situated to the eastern of Hangjiahu region, is characterized by its picturesque waterways. This scenic beauty has consistently represented the aspirations of the residents of Jiaxing. With the ongoing enhancement of water management initiatives, the aquatic environment has experienced significant improvement.

Currently, the proportion of Class I to III water quality in the state-controlled, provincial-controlled, and municipal-controlled sections of the city is 100%. Furthermore, the compliance rate for the functional areas at junction sections is also 100%, and the water quality standard for drinking water sources at levels above the county remains stable at 100%.

"Green-Water-Action" initiative has transformed Beizhuangbang, located in Zhongdai Street, Pinghu City, into an aesthetically and environmentally appealing area. In addition to the construction of ecological revetments, an underwater forest has been planted, and both a water stage and a cloud bridge have been built along the river course. Standing on the bridge, one can enjoy a picturesque view of the entire village. For the villagers, the phrase "people live in the scenery" has become a vivid reality.

By implementing measures such as enhancing management and protection mechanisms, restoring the ecological environment, and improving the cultural landscape, the Village has embodied the charm of a Jiangnan water town, with its rippling blue waves and harmonious integration of people and water. In the village, river dredging, water system connectivity, bank slope stabilization, ecological restoration, and other renovations has been undertaken, giving the river a revitalized appearance. This area has not only become a popular leisure and recreational space for nearby residents but also a picturesque addition to the region's scenic rural tourism routes.

2.5. Domestic Sewage Treatment and Its Combination of Rainwater Collection

(1) Crisscrossed rivers for floodwater storage, quick drainage and flood discharge

In Hangjiahu region, a complex network of rivers is densely interwoven, and ponds and lagoons are dispersed throughout the area. Over the past fifty years, occurrences of drought and flooding have been minimal, primarily due to the extensive distribution of rivers and the region's efficient drainage systems. Hangjiahu region is characterized as a low-lying plain with a shallow water table and gentle topography, which supports extensive rice cultivation. The rural population has a long-standing agricultural tradition, spanning thousands of years, and possesses considerable expertise in managing the challenges posed by floods and droughts. Typically, small ditches and streams are excavated adjacent to residences or along contour lines to create ponds or lagoons. These structures serve to collect rainwater, mitigate flooding, store precipitation, and utilize cofferdams to retain both rainwater and floodwater.

Historically, Hangjiahu Plain has faced significant environmental challenges. In 1909, the region was severely impacted by catastrophic flooding. This was followed by a prolonged drought in 1934, during which the cracks in the riverbed were reported to be as large as a human palm. The year 1954 witnessed the most intense plum rain in a century, resulting in extensive flooding of rice fields and a complete loss of harvest. Records indicate that between 1949 and 1978, Hangjiahu Plain experienced five major floods and eight

significant droughts, leading to substantial economic losses. In response to these recurring issues, a comprehensive planning initiative known as "South-to-North Water Diversion" project was proposed for Hangjiahu Plain. This initiative included the construction of a drainage outlet in Hangzhou Bay, aimed at addressing the dual challenges of waterlogging and drought in the region. The infrastructure comprises four drainage gates, one large pumping station, four main drainage rivers, several auxiliary channels, bridges, control gates, and revetments. The primary river channel extends 66.7 km in length. On 15 November 1978, a workforce of 300,000 laborers commenced operations at the construction site, which spanned 41.29 km. Following 43 days of intensive labor, Changshan River dam was breached, marking the completion of the first phase of the river channel excavation. Changshan River, which measures over 40 km in length, more than 80 m in width, and exceeds 3 m in depth, was thereby established.

In 1980, Changshan Gate was inaugurated to facilitate the drainage of water from Hangjiahu Plain into Qiantang River. Subsequently, in 1984, construction commenced on the second phase of "Changshan River" project. By 1985, the third phase of "Changshan River" dredging project was completed, establishing a connection to the Beijing-Hangzhou Grand Canal. At this juncture, over 200 km of primary river channels had been constructed.

Changshan Sluice serves as the principal drainage facility within "South Drainage" project, managing 40% of the flood drainage capacity for the South Drainage of Hangjiahu Plain. In 1991, Taihu Basin experienced a significant flood event. During this occurrence, Changshan Sluice utilized all seven openings to facilitate flood drainage, achieving a volume that was more than 50% less than that recorded during the major rainy season of 1954, thereby contributing to a successful grain harvest. In 2023, Changshan River Hub was operational for 94 days, during which it released water on 40 occasions, addressing 12 flood events and draining a cumulative total of 873 million m^3, a volume equivalent to that of 61 West Lakes.

Changshan River Hub, in conjunction with various interconnected tributaries, effectively manages water flow during periods of flooding and conserves water during droughts. This system ensures that agricultural yields can be maintained in Hangjiahu plains, irrespective of adverse weather conditions. Furthermore, each village, community, and settlement is equipped with a flood management system. Ditches and ponds are excavated along contour lines to maximize the collection of rainfall within residential areas, thereby facilitating the storage of floodwater. Typically, these ditches and ponds function as oxidation ponds, purifying the domestic wastewater generated by community residents, while also enhancing the aesthetic appeal of the residential environment. A diverse array of aquatic plants, flowers, and other vegetation is cultivated along the banks of the ditches and ponds, contributing to the overall beauty of the landscape.

In Figure 5, rainwater and pollutants are initially segregated. The initial rainwater is captured within the residential landscape area, which is approximately 10~20 cm lower than the road surface or surrounding ground. A small volume of rainwater is retained in this landscape area at the onset of rainfall. As precipitation intensifies, rainwater that exceeds the height of the road curbs within the landscape area is directed to the pond or lagoon using a siphon or drain. This pond or lagoon is situated at a height comparable to that of the road surfaces, thereby preventing the roads from becoming inundated.

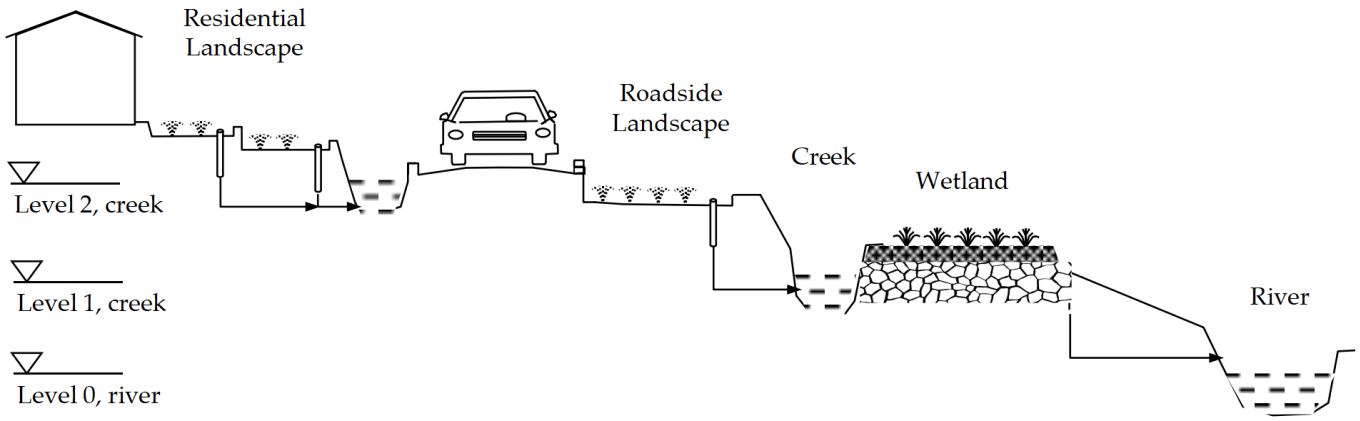


Figure 5. Schematic of rainwater collection and storage systems in Hangjiahu region.

(2) Curbs design and the recycled water used for landscape irrigations.

Curbs, commonly referred to as "road curbs" or "curb stones", are precast concrete blocks or masonry structures positioned between the roadway and the sidewalk, elevated above the road surface and approximately level with the sidewalk. Their primary function is to safeguard pedestrians and to facilitate the formation of drainage ditches along the edge of the roadway. For water conservancy projects, curbs are also identified as "wheel guards", which denote the convex ridges located on both sides of pier-type and narrower jetty-type docks. This section does not aim to address the topic of curbstones; rather, it focuses on the design of roadside landscape belts and rainwater collection systems.

In Hangjiahu region, the design of roadside landscape belts incorporates a gradient that positions them 10~20 cm lower than the adjacent road surface. This design consideration primarily addresses the management of rainwater runoff; during precipitation events, rainwater from the road surface is directed into the lower landscape area. The initial runoff may transport various pollutants, including particulate matter and harmful substances that are adsorbed onto these particulates. As the rainwater flows into the roadside landscape area, these pollutants are intercepted and deposited within the underlying soil. As rainfall continues and the volume of water increases, the landscape area eventually reaches capacity, leading to overflow. To facilitate effective drainage, a siphon or floor drain is installed within the landscape area. The siphons are positioned 10~20 cm above the landscape belt, aligning with the road surface but remaining lower than the curbstone. Once the rainwater level reaches the siphon height, it is evacuated from the landscape area. At this stage, the volume of rainwater is substantial, and the water that is siphoned away contains a reduced concentration of pollutants, thereby allowing it to be directed into recycled water systems.

To facilitate the unobstructed flow of rainwater into the roadside landscape, the design of the road curbstone is of paramount importance. Typically, the height of the road curbstone on the side adjacent to the vehicle is approximately 10~15 cm higher than the road surface. Conversely, the landscape area on the opposite side, corresponding to the vehicle, is designed to be approximately 10~15 cm lower than the road surface. To ensure that rainwater can flow directly and efficiently into the landscape area, the road curbstone incorporates a gap or opening at specified intervals, which is set to the same elevation as the road surface. This design allows rainwater to enter the landscape area through the gap. The width of the gap is generally two to four times the height of the road curbstone (Figures 6 and 7).

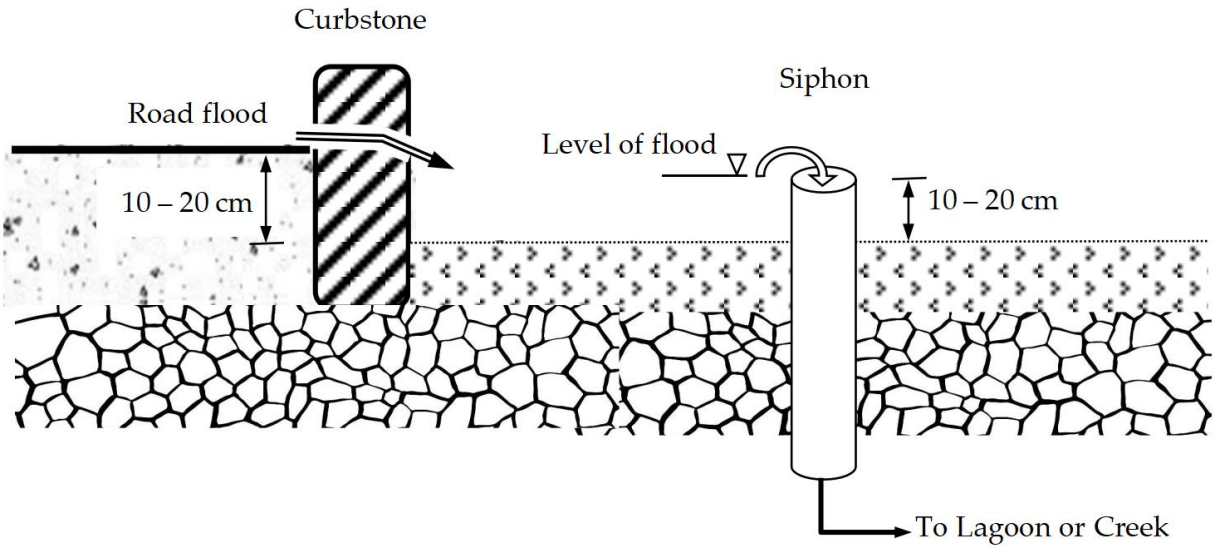


Figure 6. Roadside landscape design for rainwater retention and flood collection.

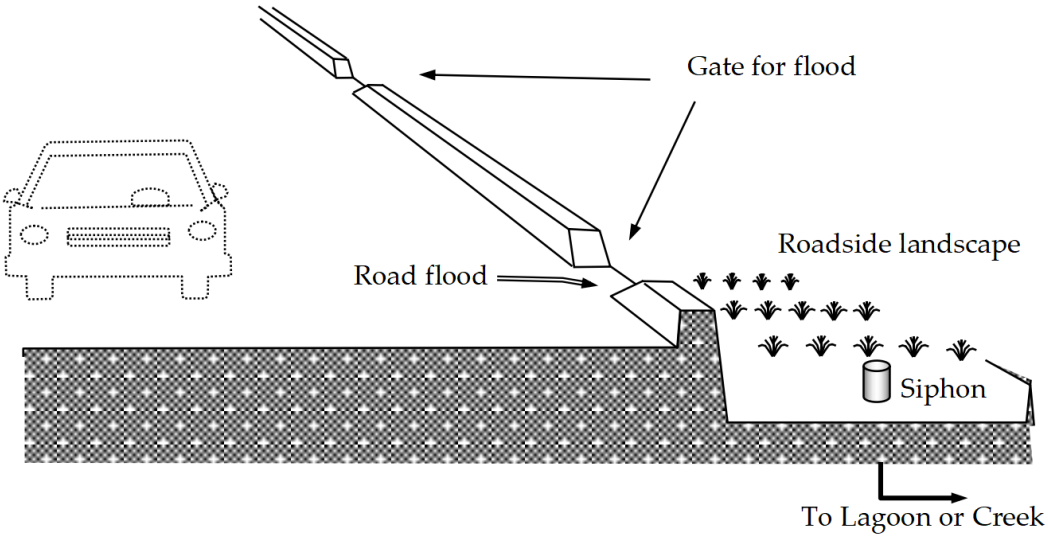


Figure 7. Gate design between curbstones for facilitating rainwater and floodwater flow.

(3) Domestic sewage reclaimed and replenishment

Jiaxing is actively pursuing the designation of a national pilot city for water ecological restoration and is currently undergoing the approval process. As part of the initial cohort of pilot cities for this initiative, Jiaxing has commenced construction on 59 projects, with a total investment amounting to 3.314 billion yuan. The city plans to implement comprehensive ecological restoration efforts for its rivers and lakes, develop Key Points of Jiaxing City's 2022 Green Water Action, and issue Technical Guidelines for the Ecological Restoration of Plain River Networks. Additionally, the construction of 419 km of green water rivers is set to be completed. The city is committed to vigorously advancing the water ecological restoration project, which includes three initiatives supported by central ecological environment protection funds, notably in the eastern region of Jiashan.

Water quality management is an ongoing endeavor, with current achievements laying the groundwork for future benefits. Moving forward, Jiaxing will commit to a scientific, systematic, precise, and comprehensive approach to water management. The region aims to address existing deficiencies in water control by establishing high standards, creating

quality benchmarks, and developing a comprehensive vision for water management. These efforts are intended to enhance the sense of well-being and satisfaction among the populace.

The integration of recycled water from sewage treatment, along with natural precipitation, is directed into oxidation ponds or lagoons to facilitate the safe utilization of recycled water. In Section 2, domestic wastewater undergoes pre-treatment and homogenization prior to its introduction into oxidation ponds for natural purification. Subsequently, it is further refined through artificial wetlands before being discharged and reintroduced into the river network. All processes related to the reclamation and replenishment of domestic sewage must adhere to the relevant regulations.

The most recent regulations on the reclamation and replenishment of domestic sewage are "Groundwater Management Regulations", issued as Order No. 748 by State Council of People's Republic of China. These regulations were adopted at the 149th Executive Meeting of State Council on 15 September 2021, and were promulgated to come into force on 1 December 2021. Developed in accordance with Water Law of People's Republic of China, Water Pollution Prevention and Control Law, and other relevant laws, these regulations aim to strengthen groundwater management, prevent overexploitation and pollution, ensure the quality and sustainable use of groundwater, and promote the development of ecological civilization.

After undergoing treatment, domestic sewage is categorized as recycled water. There are several methods for recharging recycled water, primarily including the utilization of surface water, water sourced from rivers and ditches, water from reservoirs and ponds, and the injection of water into wells. These methods may be employed individually or in combination. The examples are listed as follows:

(a) Surface water recharge: This category of recharge can be further subdivided into two types. The first type occurs in agricultural fields or recreational areas, where surface water is utilized for recharge in conjunction with conventional irrigation practices. This approach not only diminishes the volume of groundwater extraction but also contributes to the conservation of groundwater resources. When surface water is employed for irrigation, the resultant seepage from various channels and irrigated fields also serves to replenish groundwater supplies. Consequently, the most effective and simple method of recharge involves the use of surface water for supplementary irrigation in areas reliant on well irrigation. The second type involves the diversion of floodwaters during the flood season or the diversion of river base flow during the non-irrigation season, specifically aimed at enhancing groundwater recharge. To facilitate the replenishment of substantial water volumes within a limited timeframe, it is essential to identify appropriate topographical features and highly permeable land as recharge sites. This process may require the construction of water diversion channels and land edge ridges, as well as the implementation of deep or extensive flooding techniques.

(b) Recharge using river channels and ditches: Dry riverbanks composed of gravel, sand, or sandy soil, as well as abandoned ancient river channels visible on the surface, and irrigation canals and drainage ditches constructed in sandy and loamy regions, exhibit a high capacity for water infiltration. Utilizing these ditches for water conveyance or developing engineered water storage systems can substantially enhance groundwater replenishment along the coastal areas.

(c) Recharge through reservoir and pond water storage: In hilly regions, mountain pond reservoirs are constructed utilizing valley topography, while in flat areas, plain reservoirs are established in depressions. Many of these projects may lack the necessary conditions for effective water storage due to leakage in the reservoir area. However, such projects serve important functions in flood control and retention, and the water

that escapes can contribute to the replenishment of groundwater in the surrounding and downstream regions. Tiankai Reservoir, a medium-sized valley reservoir, and Daning Reservoir, a plain reservoir located on the right bank of the lower reaches of Lugou Bridge on Yongding River in Fangshan District, Beijing, exemplify such initiatives, which play a crucial role in groundwater replenishment.

(d) Recharge through injection of water into well: This approach is particularly suitable for urban and industrial areas due to its localized effect. Additionally, it serves as an effective means of replenishing deep confined aquifers. However, the limited flow area of the well's filter pipe poses a risk of clogging, which can complicate maintenance efforts. Consequently, the recharge water undergoes disinfection and filtration prior to injection.

3. Processes Case Study

3.1. Materials and Methods

(1) Scope of investigation

Regional scope: 13 districts and counties in Hangjiahu region, including Hangzhou (Jianggan District, Xihu District), Lin'an District, Yuhang District, Huzhou (Nanxun District, Wuxing District), Deqing County, Changxing County, Anji County, Jiaxing (Xiuzhou District, Nanhu District), Jiashan County, Haining City, Haiyan County, Pinghu City, Tongxiang City.

Process scope: according to the proportion of main processes of rural sewage treatment facilities in Hangjiahu area, select typical processes in Hangjiahu area—anaerobic-anoxic-aerobic (A^2/O) biological nitrogen and phosphorus removal process, anaerobic-aerobic (A/O) process, membrane bioreactor (MBR) process, anaerobic biological treatment process, and constructed wetland treatment process.

Monitoring time was from November 2018 to October 2019, and the monitoring frequency is conducted daily and the data plotted in the work is the average of a month.

(2) Sampling method

Randomly select 80 rural sewage treatment terminal facilities in Hangjiahu region. Collect water samples at the inlet and outlet of the facility respectively, and the number of samples collected shall not be less than 3, and measure the average value after mixing. In order to avoid the impact of surface runoff, the sampling period should avoid moderate rain and above. During the sampling process, the inlet and outlet water is in the dynamic process of continuous flow. After mixing, the sample is sealed and stored in a 1 L white plastic sealing bottle. The test and analysis are carried out within 12 h. The sample is sampled once a month.

(3) Sampling method and emission standard

Water samples were collected and stored at 4 °C. The test items were chemical oxygen demand (COD_{Cr}), ammonia nitrogen (NH_3-N) and total phosphorus (TP). COD_{Cr} was determined by rapid digestion spectrophotometry [63], ammonia nitrogen was determined by salicylic acid spectrophotometry [64], and total phosphorus was determined by ammonium molybdate spectrophotometry [65].

The discharge standard shall be in accordance with the pollutant discharge limit specified in the Discharge Standard of Water Pollutants at Rural Domestic Sewage Treatment Sites in Zhejiang Province [66]. The new facilities located in important water system sources, important lake and reservoir catchment areas and other areas with important water environment functions and Pingyuan river network areas with small water environment capacity shall be in accordance with the Class I standard, and those located in other areas shall be in accordance with the Class II standard.

(4) Data acquisitions

Monitoring data processing statistics, with confidence interval of 95%, calculate the compliance rate and removal rate, and use Origin 2018 to draw the data chart. The seasonal variation coefficient of compliance rate is calculated by the following formula:

$$C_v = \sigma / \mu \quad (1)$$

where: C_v is the seasonal variation coefficient of the rate of reaching the standard, dimensionless; σ is the standard deviation of the compliance rate in the four seasons; and μ is the average of the rate of reaching the standard in the four seasons.

3.2. Overview of Rural Domestic Sewage Treatment in Hangjiahu Region

According to statistical data, in 2019, the total volume of rural sewage generated in Hangjiahu region amounted to 83.23 million ton/year. Among the municipalities, Huzhou reported the highest sewage output, totaling 13.97 million ton/year, followed by Yuhang District and Jiaxing, which produced 9.03 million ton/year and 8.11 million ton/year, respectively (Figure 8). In contrast, due to the limited number of rural areas in Hangzhou, the amount of rural sewage generated was the lowest, at only 340,000 ton/year.

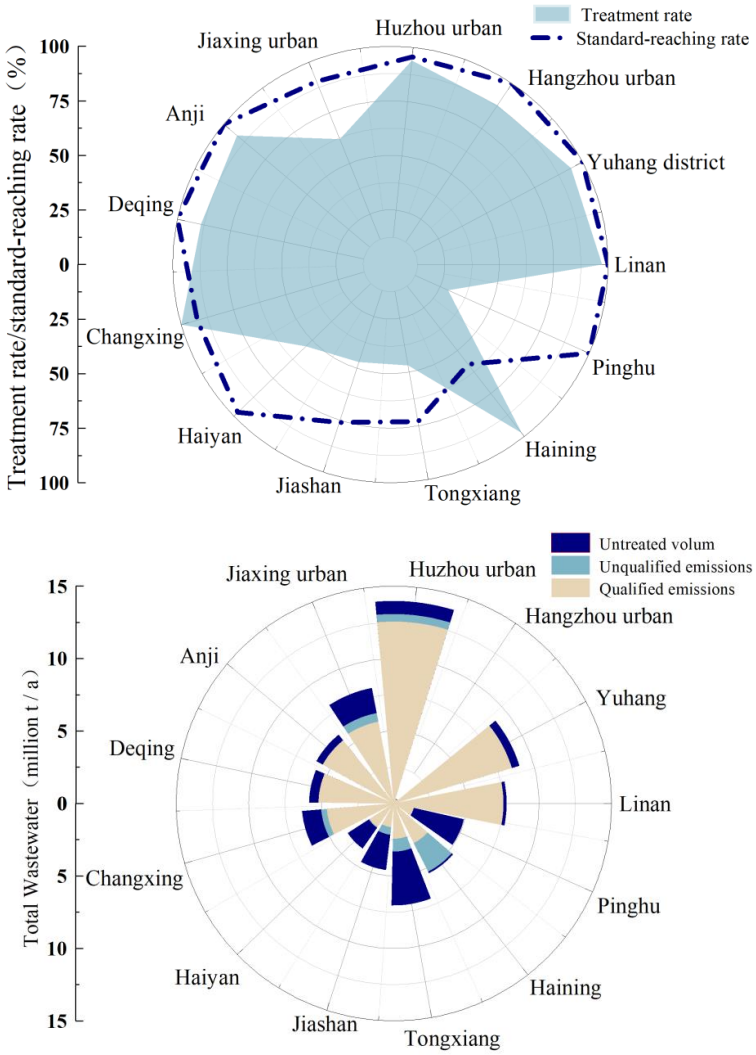


Figure 8. Status of rural sewage treatment in Hangjiahu region (2018–2019).

The total amount of rural sewage treated in Hangjiahu region amounts to 65.73 million ton/year, achieving a treatment rate of 79%. Notably, Changxing County exhibits the highest rural sewage treatment rate at 100%, followed by Lin'an City and Haining City, with treatment rates of 97% and 98%, respectively. In contrast, the treatment rate in Jiaxing is comparatively low, with Pinghu City recording the lowest rate at only 29%. Additionally, the treatment rates in Tongxiang City, Jiashan County, Haiyan County, and Jiaxing are all below 60%.

The treatment rate in Haining is the highest. However, the operational effectiveness of the facilities is suboptimal, with a compliance rate for meeting the National Standard ranking lowest at only 58%. Tongxiang City and Jiashan County follow in second place, with compliance rates of 73% and 76%, respectively. The compliance rates for the remaining ten districts and counties are commendable, exceeding 90%.

In summary, the rates of rural sewage treatment and compliance in Hangzhou and Huzhou are generally high. However, the corresponding rates in Jiaxing, which encompasses Pinghu City, Haining City, Tongxiang City, Jiashan County, Haiyan District, and Jiaxing, are significantly lower than those observed in Hangzhou and Huzhou. It is recommended that a systematic upgrade and transformation be implemented to address this disparity.

An investigation into rural sewage treatment facilities in Hangjiahu region reveals that the predominant treatment processes employed include A^2/O process, A/O process, anaerobic biological treatment process, CW process, and Membrane Bioreactor (MBR) process. Notably, A^2/O process exhibits the highest utilization rate, comprising 58.1% of the total treatment facilities, attributable to its adaptable scale and comprehensive functionality (Figure 9) [67]. A/O process, which is often integrated with chemical phosphorus removal and electrolytic phosphorus removal methods [68], offers advantages such as ease of operation, stable performance, and effective treatment results. This process is particularly well-suited for rural sewage treatment, representing 17.07% of the facilities.

Additionally, the anaerobic biological treatment process and CW treatment process offer advantages such as low energy consumption and ease of management [69]. These processes are particularly suitable for areas with low effluent standards, achieving a utilization rate of 18.19%. MBR represents an innovative approach that integrates membrane treatment with biological treatment, characterized by a compact footprint and high treatment efficiency. The effluent produced can meet or exceed Grade I A standards as outlined in "Discharge Standard of Pollutants for Urban Sewage Treatment Plants" [22,70]. In recent years, MBR technology has gained traction in rural sewage treatment applications. However, the high capital investment and operational maintenance challenges associated with this process [71] have resulted in a relatively low adoption rate in Hangjiahu region, which stands at only 0.76%. In conclusion, A^2/O process and A/O process are the two predominant methods employed in rural sewage treatment within Hangjiahu region.

The rural sewage treatment facilities in Hangjiahu region predominantly possess a treatment capacity of less than 30 ton/day, which constitutes approximately 88% of the total number of facilities. Typically, the service population served by a single facility is approximately 400 individuals within a community. Furthermore, only 1.5% of the facilities have a treatment capacity exceeding 100 ton/day.

The results indicate that rural sewage treatment in Hangjiahu region primarily relies on small-scale decentralized facilities. The decentralized approach to domestic wastewater treatment is increasingly recognized as a viable trend for sewage reclamation in small villages and towns, as it significantly diminishes the need for extensive pipe networks in rural sewage systems. However, a notable drawback of decentralized systems is the potentially

high number of facilities required, which can substantially complicate the operation and maintenance management of these decentralized agricultural sewage treatment systems.

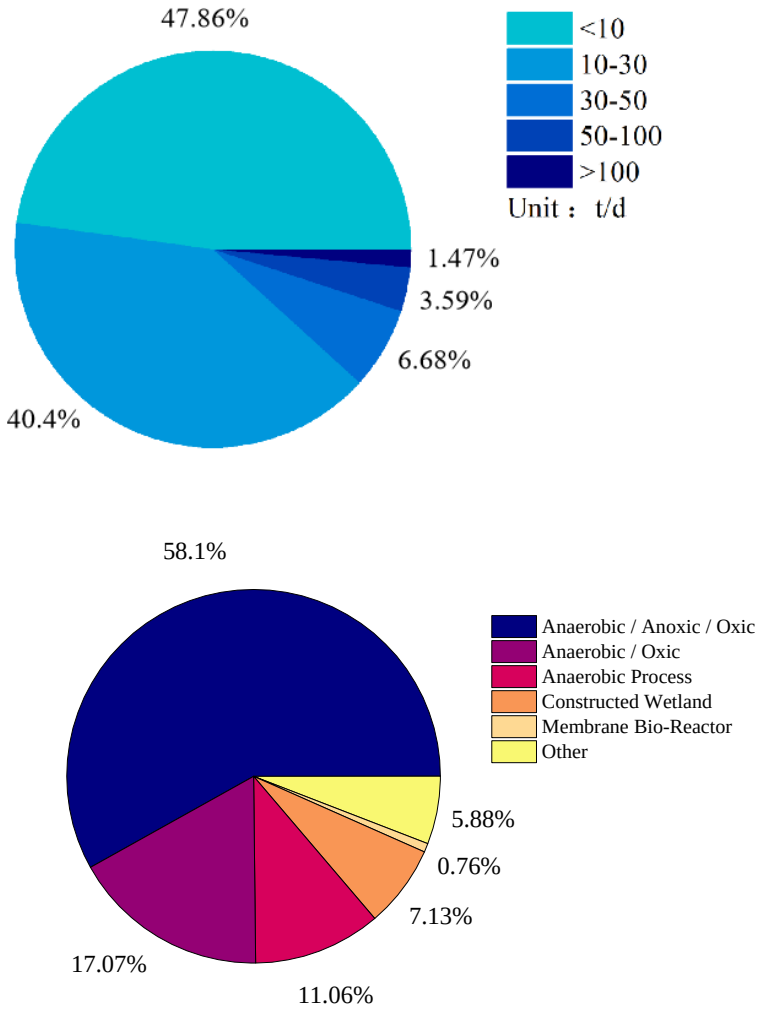


Figure 9. Distribution characteristics of rural domestic sewage treatment facilities in Hangjiahu region.

The statistical data pertaining to the influent water quality monitoring of rural sewage treatment facilities in Hangjiahu region is illustrated in Figure 10. The average concentrations of Chemical Oxygen Demand (COD), ammonia nitrogen, and total phosphorus in domestic sewage within Hangjiahu region are recorded at 196 mg/L, 41.6 mg/L, and 4.62 mg/L, respectively. Furthermore, the distribution of these concentrations exhibits regional variations. Notably, the concentrations of COD and ammonia nitrogen in rural sewage from Hangzhou are significantly higher than those in other areas, ranging from 250 mg/L to 400 mg/L and 40 mg/L to 70 mg/L, respectively. This is followed by Huzhou and Jiaxing, where COD levels range from 150 mg/L to 250 mg/L and ammonia nitrogen levels range from 10 mg/L to 50 mg/L. Other counties and cities exhibit slightly lower concentrations than those observed in Huzhou and Jiaxing. The overall fluctuation in total phosphorus concentrations is considerable, with Hangzhou displaying relatively high levels, while no significant differences are noted among the other counties and cities. Additionally, analysis of monitoring results across different seasons indicates that seasonal fluctuations in the quality of rural sewage in Hangjiahu region are not pronounced.

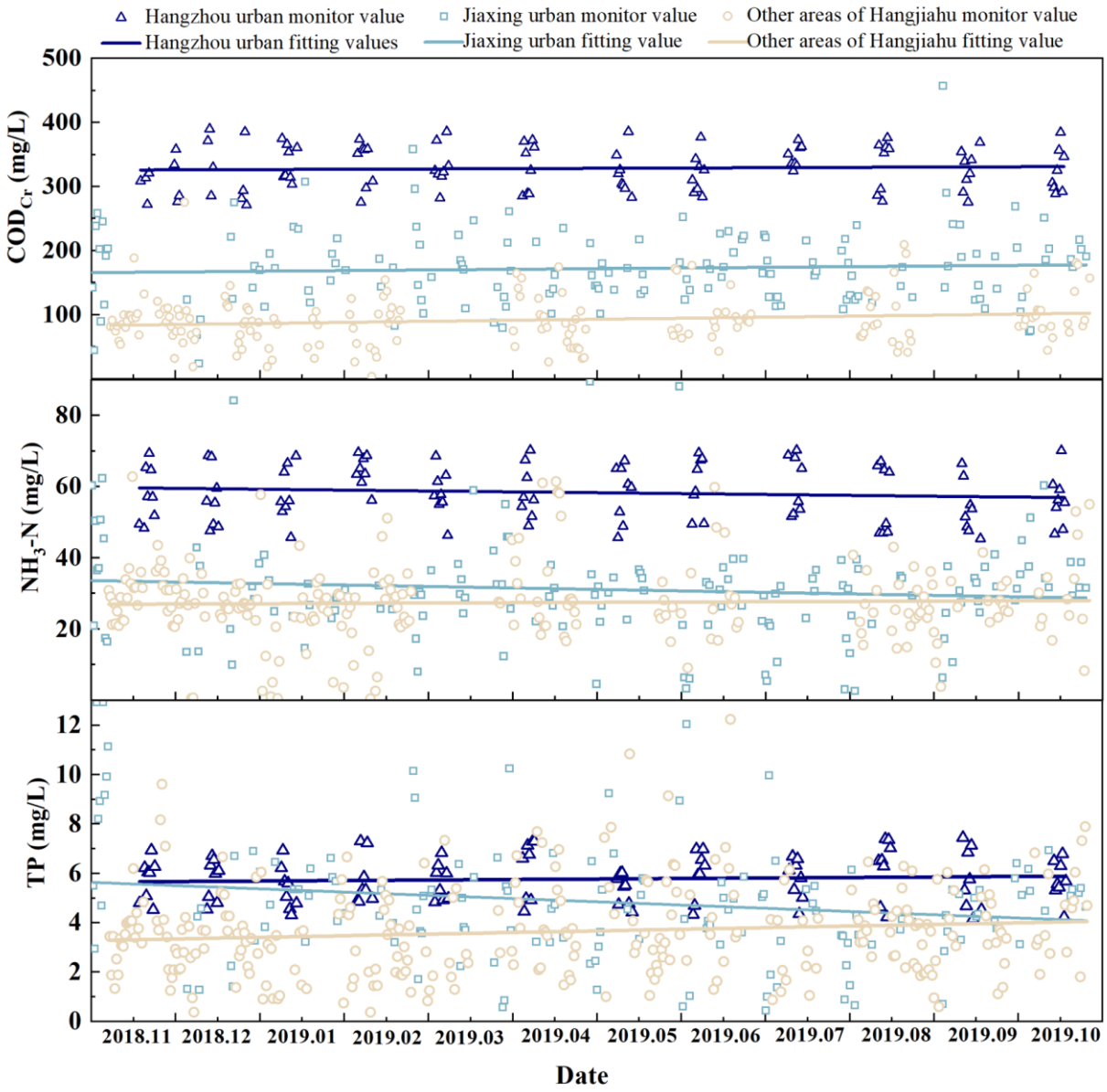


Figure 10. Inlet water qualities of agricultural sewage facilities in Hangjiahu region.

3.3. Operation Status of Rural Domestic Sewage Treatment Facilities in Hangjiahu Region

(1) Different treatment processes

The operational effectiveness and stability of sewage treatment facilities employing various processes exhibit significant variability. In Figure 11, the overall compliance rates for A^2/O process, A/O process, MBR process, and CW process are comparable, ranging from 94.3% to 96.7%. However, the attainment of different compliance standards varies markedly among these processes. The first-level compliance rates for A^2/O and A/O processes are notably higher, at 51% and 47.7%, respectively. In contrast, only 37.1% of MBR facilities achieve first-level standards, while CW process demonstrates the lowest first-level compliance rate at a mere 6.9%. Furthermore, the total compliance rate for ATT process is significantly lower than that of the other processes, standing at only 53.3%. Within this category, the secondary compliance rate is 45.8%, but the primary compliance rate is alarmingly low at 7.5%, positioning its treatment capacity as the least effective among all evaluated processes.

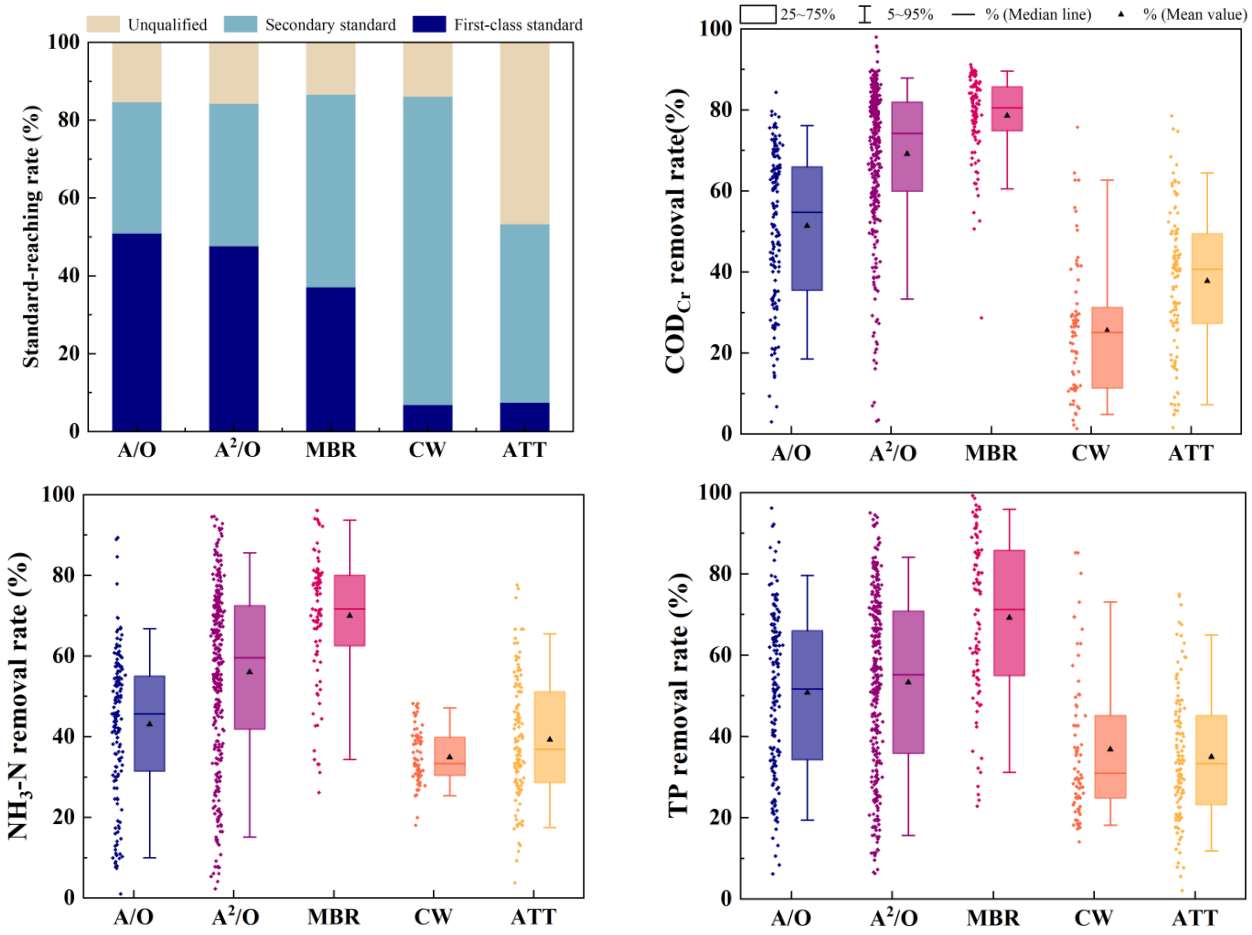


Figure 11. Variations in removal efficiency across different rural sewage treatment processes.

From the analysis of individual pollutant factors, MBR process demonstrates the highest removal efficiencies for COD, ammonia nitrogen, and total phosphorus, achieving rates of 80%, 70%, and 71%, respectively. However, MBR process is characterized by its high load capacity and efficiency, making it more suitable for regions with well-developed pipe networks and elevated influent concentrations. Additionally, MBR membrane module and the chemical phosphorus removal dosing system require frequent maintenance, which contributes to the instability of effluent water quality. Therefore, MBR process exhibits variability in its phosphorus removal effectiveness, resulting in a relatively low overall first-level compliance rate. In comparison, A/O and A^2/O processes achieve removal rates for COD, ammonia nitrogen, and total phosphorus that are only slightly lower than those of MBR process. However, due to the limitations in total phosphorus removal associated with both A^2/O and A/O processes, there is no significant difference observed between the total compliance rates and primary compliance rates of these two processes.

CW demonstrates a limited efficacy in the removal of three specific pollutants, achieving a removal rate of less than 30%. Additionally, ATT process exhibits suboptimal performance in the reduction of COD, ammonia nitrogen, and total phosphorus, with removal rates ranging from 30% to 40%. Notably, this study reveals that the influent sewage concentration in CW facility is frequently low, resulting in a higher effluent compliance rate compared to ATT process. This discrepancy may be attributed to the condition of the pipe network. In regions characterized by underdeveloped pipe network infrastructure, treatment methods that require minimal operation and maintenance, such as artificial wetlands, are often favored.

In conclusion, the processes currently employed in rural areas exhibit certain deficiencies. Among these, MBR, A^2/O, and A/O processes demonstrate relatively effective performance. However, they require robust operation and maintenance, particularly in the management and safeguarding of the phosphorus removal process. Conversely, the anaerobic process and CW process show inadequate pollutant removal efficiency and are unsuitable for scenarios with stringent discharge requirements and elevated influent concentrations.

(2) Different processing scales

In this study, A^2/O process, which is characterized by its high frequency of application, has been selected to investigate the effects of treatment scale on the efficacy and stability of sewage treatment. In Figure 12, the pollutant removal rates for both small-scale (<10 ton/day) and large-scale (>100 ton/day) treatment facilities are notably high, significantly surpassing those of medium-scale facilities. Specifically, small-scale facilities (<10 ton/day) exhibit the highest removal rates for COD, ammonia nitrogen, and total phosphorus, achieving rates of 78%, 79%, and 81%, respectively. In contrast, large-scale facilities (>100 ton/day) demonstrate removal rates of 81% for COD, 66% for ammonia nitrogen, and 62% for total phosphorus.

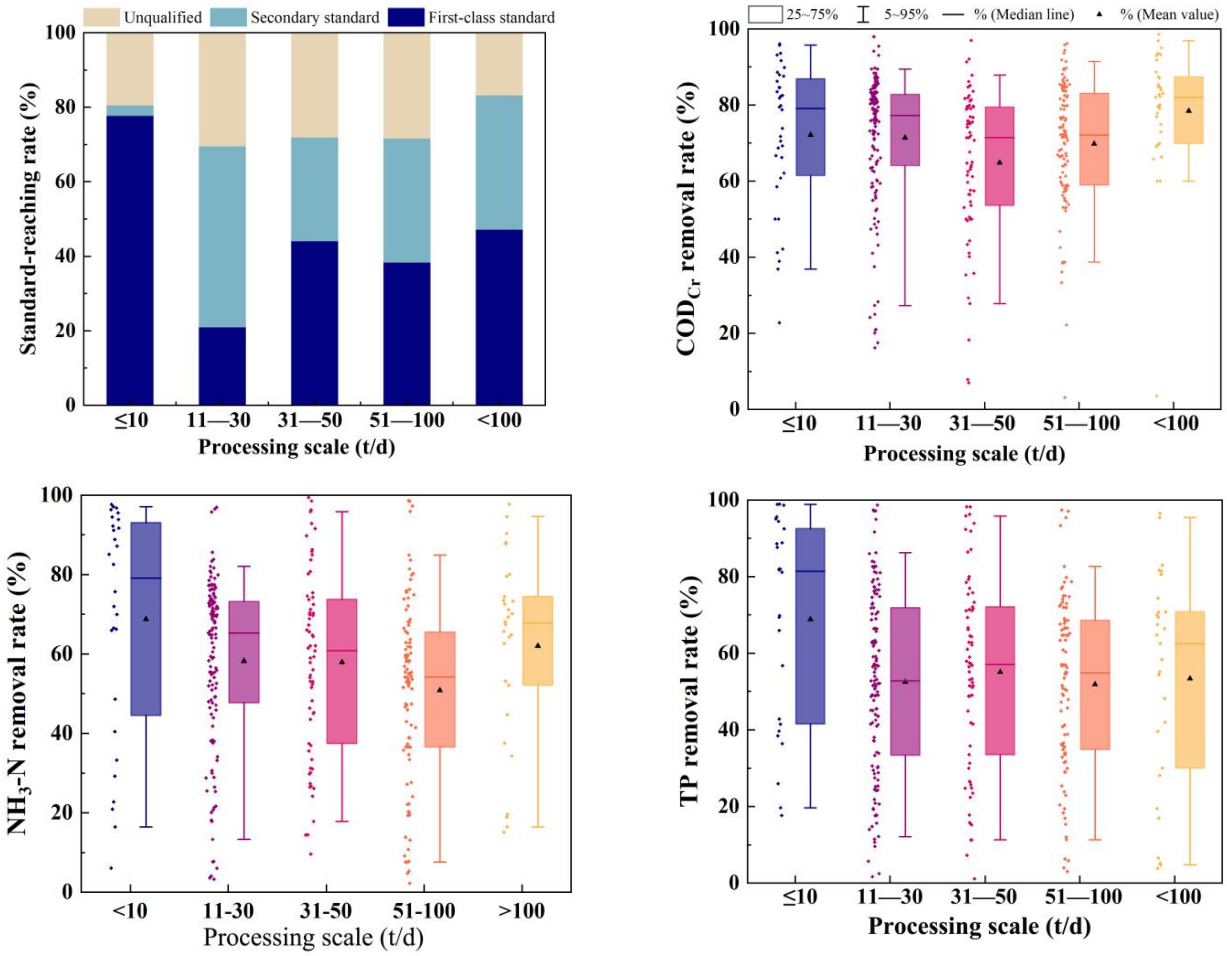


Figure 12. Variations in removal efficiency across facilities of different treatment scales.

In Hangjiahu region, small-scale treatment facilities (<10 ton/day) are frequently utilized in areas where numerous households are situated, particularly in locations lacking centralized sewage systems from catering services, public restrooms, and small workshops

that do not generate significant wastewater. The concentration of influent water in these areas is relatively low, which facilitates the treatment process.

(3) Effect of different seasons

During the period from November 2018 to December 2019, this study conducted continuous monitoring of the sewage treatment facilities in Hangjiahu region to investigate the relationship between compliance rates and seasonal effects. Figure 13 shows the C_v vs. different processes employed. In the figure, it can be seen that the seasonal variation coefficients for A/O process and A^2/O process are 3.61% and 5.69%, respectively, indicating that both processes are not significantly impacted by seasonal changes. The operational effectiveness of MBR process and CW process is relatively stable and less affected by seasonal variations, with coefficients of variation of 11% and 11.2%, respectively. Conversely, ATT process is most affected by seasonal changes, exhibiting a variation coefficient of 20.74%. The seasonal variation trend in compliance rates across the five processes is consistent, with the highest compliance rates observed in summer and a significant decline in winter, corroborating previous reports [72–74]. As water temperatures rise in summer, the activity of nitrifying bacteria increases, thereby enhancing the removal rate of ammonia nitrogen and the rate of compliance with standards. Notably, the total compliance rates for A/O process, A^2/O process, MBR process, and CW process are similar, with A/O process demonstrating the most stability. Furthermore, the compliance rates for CW and ATT processes experience a slight decline in summer, potentially due to increased temperature fluctuations and variations in target pollutant concentrations. The activities of microorganisms contribute to this decline in compliance rates, while the bacteria in MBR process remain isolated and fixed.

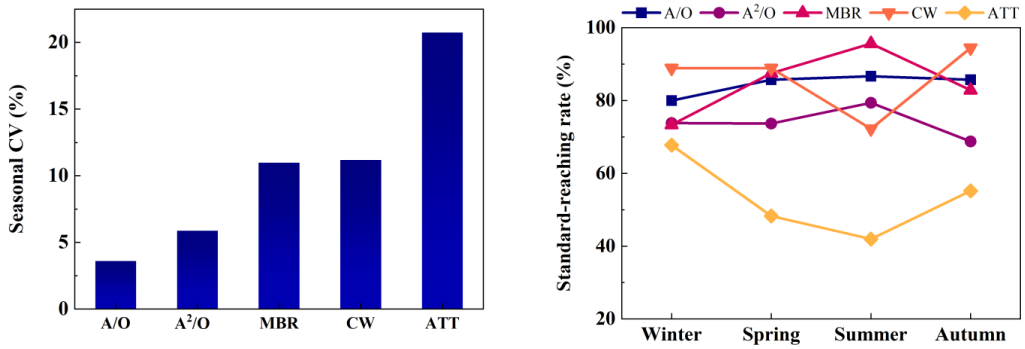


Figure 13. Seasonal variations in compliance rates of rural sewage treatment processes.

4. Conclusions

China faces a significant challenge with uneven water resource distribution and severe water shortages. As an agricultural nation with 509 million rural residents, it frequently experiences major disasters such as droughts and floods, which adversely impact agricultural productivity and harvests. In rural areas, domestic sewage has further exacerbated concerns about drinking water safety. The rising water demand and wastewater discharge have spurred the development of domestic wastewater reclamation and reuse strategies. The reclamation of domestic sewage, coupled with the comprehensive utilization of rainwater and floodwater, offers numerous environmental and economic benefits. These include alleviating water shortages, reducing pollutant emissions, improving soil quality, and lowering production costs. While these efforts remain in their infancy in many regions of China, Hangjiahu region stands as a notable success story. Over the past three decades, the region has effectively resolved challenges related to floods, droughts, and wastewater reclamation. Since 1991, no severe floods or droughts have occurred, showcasing a rare and

exemplary model that can guide other regions facing similar challenges. Key takeaways from Hangjiahu's experience include:

(1) Capturing and storing rainwater and floodwater for use during drought seasons;
(2) Combining treated wastewater with stored rainwater to create a sustainable supply for agricultural irrigation and other uses, addressing water shortages and replenishment;
(3) Utilizing initial rainwater to irrigate local flower beds for landscaping purposes, with overflow rainwater stored and recycled for agricultural applications;
(4) Implementing separate urine collection systems to provide valuable plant nutrients for agriculture, while simultaneously reducing wastewater discharge.
(5) Executing "five water co-governance" strategy within river network areas together with continuous water treatment, ecological restoration, and quality monitoring will be essential to ensuring long-term sustainability. The overall treatment rate of rural sewage in Hangjiahu region is 79% and the average standard rate of effluent from sewage treatment facilities is 86% (Grade II landmark) in 2018–2019. However, since the "five water co-governance" action promoted it has gradually reaches national standards 100% in most of the region in 2022.
(6) Enhancing investment is the key to ensuring the maintenance of high environmental quality. The reclamation of water and sludge fertilizers has further improved the water quality within the whole region. Environmental protection platform promoted environmental quality and helped to solve the worries of enterprises.
(7) Reallocating ponds or lagoons and enlarging rivers are beneficial for efficient storage of rainwater for drought preparedness, and provides habitats for wild animals and establishes ecological diversity as well as scenery.
(8) Restoring the ecological environment and improving the cultural landscape, giving the river a revitalized appearance, the area has not only become a popular leisure and recreational space for nearby residents but also a picturesque addition to the region's scenery.
(9) Combining domestic sewage treatment and rainwater collection, the crisscrossing river channels can regulate flood flow and enable rapid flood discharge. The curbstone design not only implements initial rainwater interception for roadside landscape, but also enables the collected clean recycled water to be used for irrigation and replenishment.

In future, the continuity and sustainability of environmental protection policies, such as "five water co-governance" initiative, are critical. These policies have significantly reduced pollution emissions and promoted regional environmental quality. Additionally, the reclamation of water and sludge fertilizers has further enhanced water quality across the region. The establishment of environmental protection platforms has also facilitated improvements in environmental quality and alleviated concerns for enterprises. Hangjiahu's success provides a compelling reference for other regions seeking to address similar challenges, paving the way for sustainable and resilient water management practices.

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Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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

Appendix A

Table A1. Series water quality standards for different reclaimed water use in China.

The Reuse of Urban Recycling Water	Industrial Use [i]		Urban Miscellaneous Use [ii]		Scenic Environment Use [iii]						Green Irrigation Use [iv]			Farmland Irrigating Use [v]				Groundwater Recharge Use [vi]	
Indexes	Recirculating Cooling, Boiler, Process, Product	Once-Through Cooling, Washing	Toilet Flushing, Car Washing	Urban Landscaping, Street Sweeping, Fire, Construction	Aesthetic			Recreational			Wetland	Unrestricted	Restricted	Irrigation Crop Types				Surface Recharge	Injection Recharge
					Watercourse	Impoundment	Waterscape	Watercourse	Impoundment	Waterscape				Fibre Crops	Dry Grain and Oil Crop	Wet Grain	Open-Air Vegetables		
Basic Requirements	-		-		No floating materials, no unpleasant odors or tastes						-			-				-	
pH	6.0~9.0		6.0~9.0		6.0~9.0						6.0~9.0			5.5~8.5				6.5~8.5	
Chroma	20°		≤15 Pt-Co	≤30 Pt-Co	≤20°						≤30°			-				30DF	15DF
olfaction	-		No displeasure		No displeasure						No displeasure			-				-	
Turbidity (NTU)	5	-	≤5	≤10	≤10	≤5		≤10	≤5		≤10	≤5	10	-				10	5
BOD_5 (mg/L)	10		≤10	≤10	≤10	≤6		≤10	≤6		≤10	≤20		100	80	60	40	10	4
COD (mg/L)	50		-	-	-						-			200	180	150	100	40	15
SS (mg/L)	-		-		-						-			100	90	80	60	-	
DO (mg/L)	-		≥2.0	≥2.0	-						-			≥0.5				-	
NH_3-N (mg/L)	5		≤5	≤8	≤5	≤3		≤5	≤3		≤5	≤20		-				-	
N (mg/L)	15		-	-	≤15	≤10		≤15	≤10		≤15	-		-				1.0	0.2
P (mg/L)	0.5		-	-	≤0.5	≤0.3		≤0.5	≤0.3		≤0.5	-		-				1.0	
LAS (mg/L)	0.5		≤0.5	≤0.5	-						-	≤1.0		8.0			5.0	0.3	
Animal and vegetable oils (mg/L)	-		-	-	-						-			-				0.5	0.05
petroleum (mg/L)	1.0		-	-	-						-			10		5.0	1.0	0.5	0.05
C_6H_5OH (mg/L)	-		-	-	-						-				1.0			0.5	0.002
Alkalinity (mg/L)	350		-	-	-						-			-					
total hardness (mg/L)	450		-	-	-						-			-				450	
TDS (mg/L)	1000	1500	≤1000 (2000)	≤1000 (2000)	-						-	≤1000		nonsaline-lands 1000, saline-lands 2000			1000	1000	
chloride (mg/L)	250	400	-	-	-						-	≤250		350				250	
SO_4^{2-} (mg/L)	250	600	-	-	-						-	-		-				250	
sulphide (mg/L)	-		-	-	-						-	-		1.0				0.2	
cyanide (mg/L)	-		-	-	-						-	-		-				0.05	
fluoride (mg/L)	-		-	-	-						-	-		-				1.0	
nitrate (mg/L)	-		-	-	-						-	-		-				15	

Table A1. *Cont.*

The Reuse of Urban Recycling Water	Industrial Use [i]		Urban Miscellaneous Use [ii]		Scenic Environment Use [iii]						Green Irrigation Use [iv]			Farmland Irrigating Use [v]				Groundwater Recharge Use [vi]	
					Aesthetic			Recreational						Irrigation Crop Types					
Indexes	Recirculating Cooling, Boiler, Process, Product	Once-Through Cooling, Washing	Toilet Flushing, Car Washing	Urban Landscaping, Street Sweeping, Fire, Construction	Watercourse	Impoundment	Waterscape	Watercourse	Impoundment	Waterscape	Wetland	Unrestricted	Restricted	Fibre Crops	Dry Grain and Oil Crop	Wet Grain	Open-Air Vegetables	Surface Recharge	Injection Recharge
nitrite (mg/L)	-		-	-				-				-				-		0.02	
Fe (mg/L)	0.3	0.5	≤0.3	-				-				-				-		-	
Mn (mg/L)	0.1	0.2	≤0.1	-				-				-				-		-	
Hg (mg/L)	-		-	-				-				-				0.001		-	
Cd (mg/L)	-		-	-				-				-				0.01		-	
As (mg/L)	-		-	-				-				-		0.1			0.05	-	
Cr (VI) (mg/L)	-		-	-				-				-				0.1		-	
Pb (mg/L)	-		-	-				-				-				0.2		-	
SiO_2 (mg/L)	30	50	-	-				-				-				-		-	
Fecal coliform groups	1000 MPN/L		-	-		≤1000/L		≤1000/L		≤3/L	≤1000/L	≤200/L	≤1000/L	40,000/L			20,000/L	1000/L	3/L
Ascaris egg count (/L)	-		-	-				-				≤1	≤2			2		-	
Total residual chlorine (mg/L)	0.1~0.2		-	-		-				0.05~0.1	-	0.2 ≤ End-of-Pipe ≤ 0.5		1.5			1.0	-	
Total Chlorine (mg/L)	-		≥1.0 (leave the factory), 0.2 (End-of-Pipe)	≥1.0 (leave the factory, 0.2 (End-of-Pipe)				-				-				-		-	

[i] GB/T 19923-2024 Reuse of urban recycling water-Water quality standard for industrial uses [75]; [ii] GB/T 18920-2020 The reuse of urban recycling water-Water quality standard for urban miscellaneous use [23]; [iii] GB/T 18921-2019 Reuse of urban recycling water-Water quality standard for scenic environment use [76]; [iv] GB/T 25499-2010 The reuse of urban recycling water-Water quality standard for green space irrigation [77]; [v] GB/T 20922-2007 The reuse of urban recycling water-Quality of farmland irrigation water [78]; [vi] GB/T 19772-2005 The reuse of urban recycling water-Water quality standard for groundwater recharge [79].

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