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Research Article

A Data-Driven Framework for Smart Urban Domestic Wastewater: A Sustainability Perspective

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With the continuous advancement of urbanization, the problem of urban domestic wastewater has become increasingly serious. Furthermore, information and communication technologies (ICTs) have flourished, providing smart ideas for the governance of urban problems, including smart urban domestic wastewater (SUDW), to improve efficiency and deliver smart cities. The framework of smart governance is vital for urban planning and development, but existing frameworks lack systematic characteristics. Therefore, this study aimed to systematically analyze the functions that SUDW can achieve from a sustainability perspective and to construct a framework of SUDW. This paper articulated the objectives of SUDW from the perspectives of service providers (mainly wastewater treatment plants, WWTPs), government, and public based on the goals of smart cities and sustainable development. Moreover, seven functions of SUDW were identified based on systematic literature analysis, such as the automation of WWTPs and operation and maintenance of sewer assets. Then, the information needed for the above functions was analyzed to clarify communication between the main stakeholders and functions, which were illustrated by an information chain model. The functions are interrelated and closely related to sustainable development, where information sharing is the foundation and key component. Based on the above analyses, a data-driven framework of SUDW consisting of five layers was proposed. The paper indicated that the core of SUDW is the perception, transmission, storage, analysis, and application of relevant data. The study not only contributes to the body of knowledge relating to smart cities but can also guide the planning of cities to realize SUDW, smart cities, and sustainable development.

1. Introduction

With the continuous development of the economy and the advancement of urbanization, the problem of urban domestic wastewater has become increasingly serious. In China (the latest Environmental Statistics Annual Report is the 2015-year version), the total discharge of wastewater was 73.53 billion tons in 2015, where urban domestic wastewater accounted for 53.52 billion tons (71.05% of the total) and increased annually, and chemical oxygen demand (COD) and ammonia-nitrogen (NH3-N) of urban domestic wastewater accounted for 38.09% and 58.33% of the corresponding volume of pollutants in wastewater, respectively [1]. Therefore, urban domestic wastewater has a considerable impact on the water environment. Faced with a large quantity of urban domestic wastewater, it has become important to govern domestic wastewater. In 2015, the urban domestic wastewater treatment rate reached 92%; however, problems remain in the field of domestic wastewater, such as the quality of the treated water and the sludge of disposal not meeting the corresponding standards, serious leakages of wastewater pipes, low rate of wastewater reuse, and large gap between the expectations of the public for improving the water environment and reality [2]. One of the sustainable development goals (SDGs) proposed by the United Nations is to ensure access to and sustainable management of water and sanitation for everyone. The specific targets include reducing pollution, increasing wastewater treatment rates, promoting waste recycling and safe reuse, and strengthening the involvement of local communities [3]. Thus, the governance of domestic wastewater is closely linked to sustainable development.

Meanwhile, information communication technologies (ICTs), such as the Internet of Things (IoT) and big data, are booming [4]. In this context, to solve urban problems such as transportation, domestic wastewater, and pollution, relevant scholars and organizations have proposed the concept of smart city [5, 6]. The rapid development of smart cities has provided new ideas for the governance of urban problems as well as a new paradigm for urban development and sustainable social and economic growth [7]. Scholars have also proposed ways to achieve smart wastewater, such as managing the collection and treatment of wastewater and the final discharge of processed wastewater intelligently [8], warnings about floods, leakages of sewer networks and pollution [9], and reuse of wastewater [10]. However, most studies are fragmented. Besides, the lack of a systematic framework is one dilemma restricting the development of smart cities [11]. And most current architectures for smart cities are based on data [12], where we can extract useful information to support relevant decisions [13]. However, the water industry has lagged in utilizing the value of existing data [14]. Specifically, a large amount of data are collected and stored to meet operation and regulatory requirements; unfortunately, many of them are never accessed, and the potential capability of instruments is often unrealized [15], which goes against sustainable development.

Therefore, this study aimed to systematically construct the framework for smart urban domestic wastewater (SUDW) from a sustainability perspective to guide the planning and delivery of SUDW. This paper addresses the gap arising from the scattering of current research studies among different areas of smart wastewater and contributes to the body of knowledge relating to smart cities. Moreover, the proposed framework will help the government, urban developers, and service providers understand solutions for the development of SUDW and can be used to guide the planning of urban domestic wastewater to promote the realization of SUDW, eventually delivering smart cities and achieving sustainable development.

2. Literature Review

2.1. Sustainable Development and Smart City

2.1.1. Sustainable Development. The idea of sustainable development is originated from the World Commission on Environment and Development (WCED) and is defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [16]. Then, development is divided into the social and economic aspects, and the environment, economy, and society are called the three pillars of sustainable development [17].

With the development of cities, problems such as social conflicts, natural corruption, and breakdown of essential services will gradually emerge. Basiago [18] maintained that the practices of economic, social, and environmental planning reflecting "urban sustainability" are the antidotes to these negative problems. Moreover, cities have become the main point of sustainable development due to the huge number of citizens in urban communities [19]. From the perspective of the city, considering the idea of sustainable development, the relevant sectors focus primarily on urban metabolic infrastructure, like water, energy, sewerage, and waste management [20]. Urban domestic wastewater belongs to this field.

2.1.2. Smart City. Various scholars have depicted the smart city from different perspectives. Based on applications of ICTs, Cretu [21] viewed the smart city as the collection of real-time data, sensors, intelligent devices, and other ICTs, which are integrated into all areas of our life. However, Xia and Wang [22] stated that to understand the smart city, we should focus on the city itself, rather than ICT, and smart cities aim to alleviate or resolve various problems to improve the performance and the quality of life. Molina-Giménez [10] also held that smart cities, with the assistant of new technologies, should solve their fundamental problems and their policies are supposed to concentrate on realizing economic productivity, social development, and environmental sustainability. The concept of the smart city is therefore argued to encapsulate user-centric considerations for improving quality of life, besides the ICT-driven development paradigm [23].

2.1.3. Relation between Sustainable Development and Smart City. Sustainable development is closely linked to smart city. Caragliu et al. [24] proposed that social and environmental sustainability are major strategic components of smart cities. Bătăgan [19] maintained that the goals of sustainable development are similar to those of smart cities and that smart systems support sustainable urban development. Analyzing eight smart cities and eight urban sustainability assessment frameworks, Ahvenniemi et al. [25] found that the frameworks of urban sustainability contained more environmental indicators than those of smart cities and emphasized the importance of the deployment of smart solutions towards economic, environmental, and social sustainability, where ICT plays a decisive role. In the context of smart cities, ICT assists to optimize production and consumption and has the potential to contribute to sustainability [26].

In summary, both sustainable development and smart city aim to improve the quality of life, of which ICT plays an important role in achieving smart cities and sustainability. From the perspective of the city, sustainable development focuses on the metabolism of cities, and smart cities are close to solving urban problems, including urban domestic wastewater. Therefore, in the context of smart cities, we can deploy ICTs to solve the problem of urban domestic wastewater to improve efficiency and thus deliver smart cities and achieve sustainability.

2.2. Smart Governance and Smart Urban Domestic Wastewater

2.2.1. Smart Governance and the Framework of Smart City. "*Governance is the sum of the many ways that individuals and institutions, both public and private, manage their* *common affairs*" [27]. Giffinger and Gudrun [28] stated smart and transparent governance, including stakeholder participation in strategic decision-making and public and social services, as an essential part in the six divided dimensions of the smart city concept. Meijer and Bolívar [29] claimed that smart governance includes new types of collaboration by using ICTs to empower open governance processes and to acquire better results. Pereira et al. [30] also emphasized the role of ICT in smart governance to achieve collaboration among various stakeholders for better decisions. Therefore, ICT and stakeholder collaboration have been perceived as essential for smart governance.

In addition, to guide the realization of smart cities, some studies have examined frameworks of smart cities, including a general framework of smart cities [31]; different areas of smart cities, such as smart grids [32] and smart traffic [33]; and the specific application functions, like energy efficiency monitoring and short-term load forecasting [11] and water quality monitoring and management within smart drinking water and wastewater networks [9]. Specifically, Wenge et al. [31] presented a six-layer framework: data acquisition, data transmission, data storage and vitalization, support service, domain service, and event-driven application. Massana et al. [11] also proposed a six-layer framework, but the specific functions of each layer were acquisition, transmission, storage, preprocessing, service, and application. Ye et al. [34] built a three-layer framework with a sensing layer, network layer, and application layer. However, most current frameworks are limited to a single function or service and lack a systematic design and development for the field of SUDW. Although the number of layers and the function of each layer are not unified, the framework for smart cities is clearly data-oriented, and the collection, transmission, processing, and application of data are the basic components.

2.2.2. Smart Urban Domestic Wastewater. In the context of smart cities, some scholars have proposed applying the notion of smart governance to different infrastructures and public services, of which water and wastewater are important areas [35]. Currently, no uniform definition of smart water or smart wastewater exists, but researchers have realized the importance of ICTs in the water/wastewater sector. Perciavalle et al. [14] proposed an intelligent platform, deployed to collect real-time and other data from a multitude of source systems together, can produce significant results and improvements in digital water/wastewater, particularly in the fields of sewer, stormwater monitoring, and water production. Fattoruso et al. [9] also maintained that smart water network technology arms the operators with an exhaustive and effective set of capabilities of decision-making for sustainable water management.

In the field of SUDW, previous studies have explored different aspects of domestic wastewater. Edmondson et al. [36] proposed a smart sewer asset information model of sewerage networks that can provide real-time information and build towards the capacity to predict the performance of sewerage network with the help of real-time monitoring and reporting. Chow et al. [15] developed a web-based prototype portal for complex online data sets to provide real-time warnings to support treatment plant operation. Khatri et al. [37] considered the recycling of wastewater, and Saputra et al. [38] focused on the collaboration of stakeholders.

The value of relevant data on domestic wastewater has also received attention, and data-driven methods have been widely used in the wastewater and water industry. Specifically, Wei [39] proposed that traditional physics-based and mathematical models have limitations in predicting the behavior of wastewater processing and the optimization of wastewater plant operations, and deployed a data-driven approach to model and optimize the wastewater treatment process in a wastewater treatment plant (WWTP). Savic [40] studied data-driven methodologies to predict the failures of water and wastewater asset. Dürrenmatt and Gujer [41] also applied this method to process data from WWTPs to provide valuable information for optimal plant control. However, the potential value of wastewater-related data and the possible functions of SUDW are scattered in different areas of wastewater, which are fragmented and not systematic. In addition, less research has addressed the communication of related information between various fields, which is not conducive to the realization of smart governance.

Considering the above characteristics, the concept of smart governance, highlighting the deployment of ICTs and the involvement of stakeholders, has been applied to infrastructure and public utilities, such as urban domestic wastewater. SUDW has been studied, but the fields of most studies are scattered and lack systematic consideration. In addition, the existing frameworks are limited to a single function or service, which is not beneficial to the implementation of smart governance. Therefore, this study is based on a systematic literature analysis to identify the potential functions that can be realized by SUDW and analyzes the information needed by the corresponding functions, as well as the main stakeholders and information communication paths involved. Finally, based on the above analyses, a data-driven framework is proposed to facilitate the implementation of SUDW.

3. Methodology

The existing studies on SUDW are scattered and lack a systematic framework to guide practice. To compensate for this gap, this paper, based on the existing literature, identifies the achievable functions of SUDW by means of systematic literature analysis and then incorporates stakeholder involvement to analyze the information needed for each function. Finally, the information chain of SUDW is constructed, and the data-driven framework is proposed based on the above analysis. The process for developing the framework is shown in Figure 1.

A systematic literature review is *"a means of identifying, evaluating, and interpreting all available studies relevant to a particular research question, topic area, or phenomenon of interest to present a fair evaluation of a research topic by using a trustworthy, rigorous, and auditable methodology"* [42].

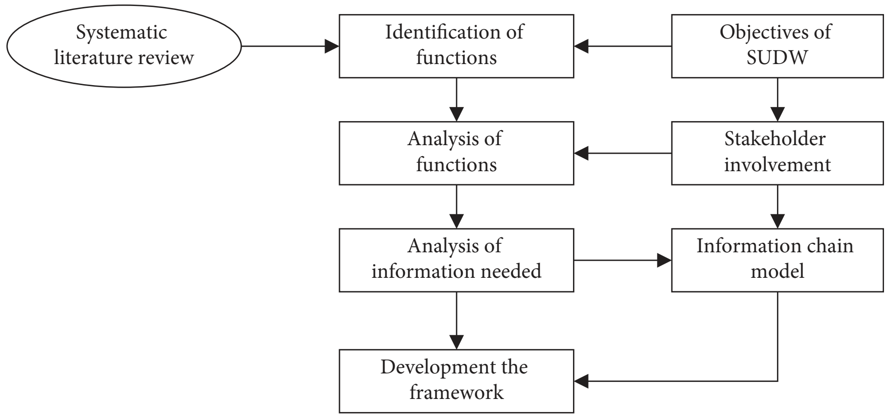

Figure 1: Process for developing the SUDW framework.

This method is a good approach to understand the diversity and complexity of smart cities [43]. Previous studies of smart wastewater provide a foundation for a systematic literature review. Some scholars have used this method to construct frameworks, like Chen et al. [44], who applied this method to build a conceptual framework for bridging BIM and building; Heaton and Parlikad [43] also applied this method to build a framework for the alignment of infrastructure assets to citizen requirements. As shown in Figure 2, this study identified the potential functions of SUDW through the following steps.

First, the study used the combination of "smart," "intelligent," "wastewater," and "sewerage" as keywords to search in SCOPUS, and the China Knowledge Network Index (CNKI) database was searched with "smart" and "wastewater" (in Chinese) as keywords. More than 1000 relevant Chinese and English studies were found covering many databases, such as the Science Citation Index and Social Science Citation Index. Then, after reading the abstract of each study to understand the core content, more than 100 Chinese and English studies closely related to the research topic were selected, and the rest of the literature with low relevance to the study was omitted. Next, 51 key articles were identified by reading and systematic analysis of the literature in order to refine the content and core viewpoints related to the tasks and functions of SUDW in combination with the objectives of SUDW to identify the potential application functions of SUDW. Finally, by screening and sorting the identified application functions, we obtained 7 application functions.

4. Identification and Analysis of Functions of SUDW from a Sustainability Perspective

4.1. Objectives of SUDW from a Sustainability Perspective. Urban domestic wastewater is an urban problem, and the governance of wastewater has a vital role in promoting sustainable development. Economic, environmental, and social sustainability are the three pillars of sustainable development [17], and both sustainable development and smart city aim to promote the quality of citizens' life. SUDW is an important part of smart cities that involves various stakeholders. The Organization for Economic Co-operation and Development (OECD) [45] noted that the core stakeholders in the water industry are the government, service providers, and public. The service providers include WWTPs and sewer asset O&M departments. Therefore, based on the goals of the smart city and sustainable development, this study analyzes the objectives of SUDW from the perspectives of the service providers, the government, and the public.

Service providers play an important role in domestic wastewater treatment. Taking WWTPs as an example, WWTPs shoulder the important task of mitigating the environmental impact caused by organizations and households at the end-of-pipe [46]. Ensuring that the effluent quality meets the standards, which is a vital part of the compliance objectives [14], is the main goal of the operation and management of the WWTP. In addition, the compliance objectives also include compliance with the production process and the quality of operation [47, 48]. Moreover, during the process, the WWTP consumes a large amount of energy and chemicals. Therefore, in the context of SUDW, the WWTP should optimize the process and improve the efficiency of wastewater treatment to reduce energy and chemical consumption without sacrificing the quality of effluent to reduce operation costs and the impact on the environment [49], which reflects the great economic value and environmental sustainability.

In China, the government has the responsibility for planning, supervision, financing, etc., in the supply of wastewater treatment services [50]. In the context of smart cities, the government and the relevant authorities are finding ways to reorient their information technology and policies to guide smart growth and address the needs of their citizens and businesses with the use of ICT and by incorporating more critical agents throughout the process [51]. Moreover, in the water sector, the smart city must equip itself with instruments to ensure universal, continuous, regular, and high-quality public services [10]. From the perspective of sustainability, the government optimizes resource allocation by implementing public policies to promote social, economic, and environmental sustainability. Therefore, in SUDW, the goal of the government is to

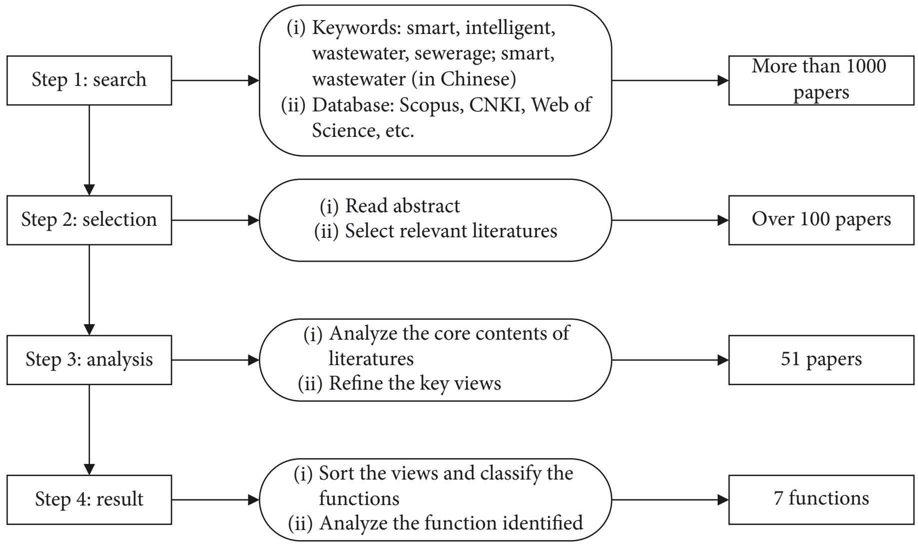

Figure 2: Process of systematic literature analysis.

improve the efficiency of public services, specifically improving the formulation of policies relating to domestic wastewater and achieving real-time and efficient supervision and performance evaluation.

The public is one of the most important subjects in smart cities [5]. Improving the quality of public life is a common goal of smart cities and sustainable development [19]. For SUDW, perception and participation platforms allow the public to obtain and understand information relating to domestic wastewater, provide feedback on their demands, or participate in SUDW decision-making; this can increase public participation and solve the problems of domestic wastewater in more satisfactory ways. In addition, the social and living environment can be improved by realizing SUDW, which can increase public satisfaction and improve their life as well. Therefore, the public's goal is to improve their quality of life.

In summary, the objectives of the SUDW are shown in Figure 3. Environmental, economic, and social sustainability are the three pillars of sustainable development. From a sustainability perspective, SUDW can not only improve the efficiency of wastewater treatment but also mitigate the pollution of domestic wastewater to the environment and reduce energy and chemical consumption, which would reduce the impact on the environment and promote economic sustainability. In addition, it can also improve the efficiency of public services and increase the quality of public life to promote sustainable social development. Therefore, the goals of SUDW are consistent with those of sustainable development.

4.2. Identification of the Functions of SUDW Based on a Systematic Literature Analysis. Through the systematic literature analysis, we identified seven functions: automation of WWTP, operation and maintenance (O&M) of sewer assets, alert and control of disasters, reuse of wastewater, public communication and participation, smart supervision and evaluation, and information sharing. The frequencies of the seven functions identified in the 51 studies are shown in Figure 4.

The results of the analysis show that among the 51 papers, the number of studies on the automation of WWTP is the highest, with 33 (65%), followed by alert and control of disasters and O&M of sewer assets, which are also important functions of SUDW, with 31 and 26 studies, respectively. In addition, public communication and participation and information sharing have also attracted the attention of some scholars, with 16 studies analyzing these two functions. Smart supervision and evaluation are considered in 12 papers. Some of the results of the systematic literature analysis are shown in Table 1.

4.3. Analysis of the Functions of SUDW from a Sustainability Perspective. This study analyzes the contents of the seven functions identified from a sustainability perspective.

4.3.1. Automation of WWTP. The WWTP deploys an automatic control system consisting of online detection and analysis instruments, monitoring systems, real-time transmission networks, etc. According to the characteristics of the influent water, such as the quality and quantity of domestic wastewater, and the standards of the treated effluent, the operating conditions of the key processes of wastewater treatment are analyzed and controlled intelligently to operate and manage in an automated and intelligent manner. Analysis of the collected data can help the WWTP to understand its operation conditions, support relevant decisions, and achieve real-time control of the operating parameters of critical equipment and the volume of chemicals, which can reduce reliance on engineers' experience [57]. These steps can not only ensure that the quality of the effluent water meets the standards but also save energy and chemical consumption, which can reduce operational costs. In addition, this function can also monitor the entire treatment process and detect

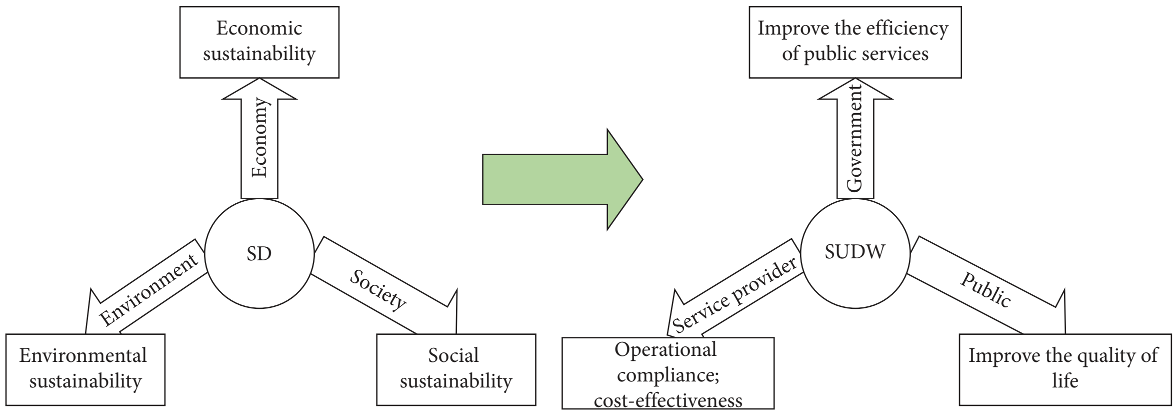

Figure 3: Objectives of SUDW (SD = sustainable development).

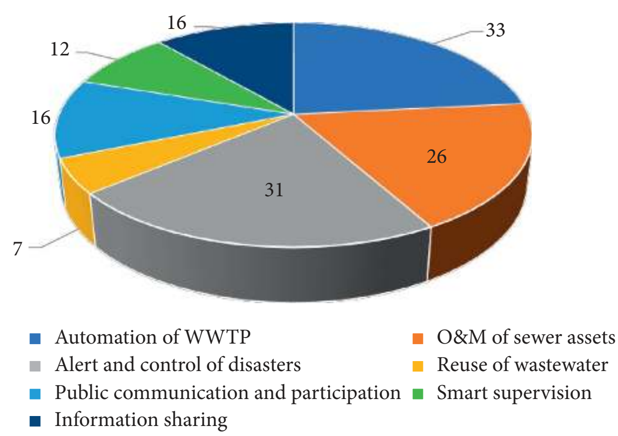

Figure 4: Frequencies of functions in 51 papers.

Table 1: Partial results of systematic literature analysis.

No.	References	Functions of SUDW						
		Automation of WWTP	O&M of sewer assets	Alert and control of disasters	Reuse of wastewater	Public communication and participation	Smart supervision and evaluation	Information sharing
1	[8]	√		√				√
2	[36]	√	√	√		√		
3	[52]		√	√		√	√	
4	[53]		√	√	√	√	√	
5	[14]	√	√	√		√	√	√
6	[10]			√	√	√		√
7	[9]		√	√				
8	[54]	√	√	√				
9	[55]	√			√			
10	[56]		√	√		√	√	√

anomalies to provide early alerts to ensure continuous and stable operation of the system.

4.3.2. O&M of Sewer Assets. Sewer assets comprise the physical infrastructure of pipes, manholes, pumps, and channels that convey wastewater to WWTPs for cleaning [36]. Inadequate upgrading, maintenance, and repairs over time will result in increased stress, decreased efficiency, and rapid deterioration and failure of infrastructure [52]. Therefore, the O&M of sewer assets is critical to the integrity and sustainability of the sewer system. The relevant O&M departments of sewer assets can deploy intelligent sensors, IoT, and other ICTs to monitor and report the performance of sewerage networks in real-time and present them in a visual form to assist operational decision-making, such as replacement and repair plans, monitoring and early alert of failures, and emergency plans for faults. In addition, the efficient O&M of the key assets can maintain their service level with the lowest life cycle cost, and the saved funds can be reinvested in other infrastructure to help reduce gaps in infrastructure and promote economic and social sustainability [58].

4.3.3. Alert and Control of Disasters. Flooding and pollution are the main disasters related to wastewater [36]. The function, based on the integration and analysis of relevant historical data, combined with the perception of relevant real-time or near real-time data, such as water quality, water level, and precipitation, calculates and predicts disaster risks to support the disaster decision-making. This process enables early identification and warning of avoidable disasters and emergency response to unavoidable events, such as reminding the WWTPs and the public, and conceiving and evaluating reliable mitigation strategies. It can also improve the resilience of cities and thus reduce damage to urban wastewater treatment systems and the impact on the environment.

4.3.4. Reuse of Wastewater. Reclaimed water is highly treated wastewater that can be reused for other purposes, such as gardening, flushing toilets, watering plants and vegetables, washing cars, cleaning houses, and firefighting [55]. In smart cities, water governance should extend to the efficient management of wastewater, which reflects the circular economy [10] and reduces the impact on natural water sources. Smart cities can build reclaimed water networks and determine the overall status with the help of ICTs in real-time. Thus, the control center can make decisions, regulate the relationship between supply and demand, ensure the stable operation of the reclaimed water network system, and promote the recycling and reuse of wastewater, which is conducive to environmental and social sustainable development.

4.3.5. Public Communication and Participation. Public participation is an important feature of SUDW that embodies the notion of "bottom-up" and supports co-creation and social innovation [38]. Public participation can facilitate citizen involvement and support informed and sustainability-aware decisions based on an extended awareness of the environment and the consequences of human actions [59]. The government or enterprises disclose relevant information through the information channel, and the public can also use the information channel to express their own demands. This function can strengthen communication between different stakeholders, especially the public, and increase public participation. In addition, through propaganda and publicity of information related to reclaimed water, the public's acceptance of reclaimed water, as well as the awareness of water savings and the reuse of wastewater, can be enhanced to promote sustainable development.

4.3.6. Smart Supervision and Evaluation. An important function of SUDW is smart supervision and evaluation. Wastewater treatment, as necessary infrastructure, should assure reliability and compliance [14]. Moreover, most current wastewater treatment projects in China are public-private partnerships [50]. Therefore, the government bears the responsibility for operational supervision and performance evaluation. Corresponding government authorities obtain and analyze accurate monitoring data through ICT technologies and multiple intelligent detection methods to realize real-time supervision and evaluation of WWTPs and the departments of sewer assets operation, which can improve the accuracy of the evaluation results. In addition, smart supervision and evaluation are conducive to the effective allocation of resources, thereby improving the efficiency of public services and promoting sustainable development.

4.3.7. Information Sharing. Shared, timely, and actionable information is the kingpin of smart governance [60]. Planning and execution of the governance of wastewater involve coordinated efforts from different stakeholders and includes the collection of data, identification of appropriate authorities for their sources, and development of effective communication to these authorities [61]. The subjects of information sharing services and sources are diverse, and information sharing is the foundation for the realization of the above functions. In SUDW, data interaction and sharing among various stakeholders are realized by an information sharing platform, and the stakeholders can find potential value from a large amount of data to promote the realization of related functions. Data interaction and sharing can reduce the repeated collection of data and improve the utilization of data, which is favorable for sustainable development.

5. Development and Analysis of the Framework for SUDW Based on a Data-Driven Approach

Data-driven approaches can be used to extract valuable information and discover knowledge from static as well as operational data of infrastructure and public services and are suitable for real-time diagnosis and prediction [62]. Data-driven optimal techniques, without the need of skilled engineers and expensive instruments, are thus attractive in practice [57]. Besides, these strategies are widely used in areas where the speed of collection and recording of data exceed the ability of information processing [63]. In the wastewater sector, this strategy has been applied to process data from WWTPs to provide insightful information for optimal control [41]. SUDW utilizes data, namely, through data perception, transmission, and analysis, to support relevant decisions and achieve the corresponding functions. Based on the data-driven approach, this study analyzes the information needed for the above functions, the main stakeholders, and the information flows among different stakeholders and functions and builds a framework for SUDW.

5.1. Analysis of Information Demands for the Functions of SUDW

5.1.1. Information Needed for Automation of WWTP. The automation of WWTP is based on real-time monitoring and analysis of the quantity and quality of wastewater of the inlet, outlet, and each reaction pool of WWTP, the operational status, and other parameters of the equipment combined with historical data to assist in the formulation of relevant decisions and to adjust the operational strategies of WWTP in real-time. This study considers the wastewater treatment process in the WWTP (as shown in Figure 5) to analyze the information needed for automation of the WWTP.

An online detector is installed at the inlet of the WWTP to monitor and analyze the data of influents in real-time, mainly the quantity and quality of wastewater, including COD, NH3-N, total nitrogen (TN), total phosphorus (TP), and other indicators. Then, the data are transmitted to the automation control system for analysis to facilitate control of the switches, running duration, rotation speed, and other parameters of the filtering grid, the lifting pump, the blower, and other relevant equipment to optimize equipment operation and achieve precise control. In terms of chemical management, real-time data, such as flow rate, phosphate concentration, volume of sludge, and moisture content, of each reaction tank are sent to the chemical management control system, and the number of chemicals, such as iron salt and aluminum salt, is calculated to adjust the dosing pump automatically to reduce the use of chemicals without affecting the quality of the WWTP effluent. In addition, by means of the fault diagnosis system and the analysis of historical data, potential faults or abnormalities can be identified. In the case of an adverse impact on the wastewater treatment system, an early alert is provided to prompt the relevant personnel to take corresponding measures to ensure the good operation of the WWTP.

5.1.2. Information Needed for O&M of Sewer Assets. Asset condition and real-time performance are important foundations for formulating decisions related to the O&M of sewer assets [36]. From the perspective of the information demand, the static project information of the sewer networks, such as the age of the sewerage pipelines and the locations of the control pump and the different diversion structures, are important foundations for O&M decision-making. In addition, the performance of the pipe networks must be monitored in real-time so that the departments can judge the damage degree of the networks and formulate short-term and long-term sewer asset replacement and maintenance plans, which can perform maintenance and improvement of the networks in stages and improve the performance of the sewerage network system. Based on various continuous and online sensors installed in sewage networks and historical data, such as the sewage network overflow duration, overflow probability, and overflow sequence, the network conditions, and weather data are collected and analyzed in real-time to predict sewerage overflow risk and provide early warning of failures in the network. This process can help managers address potential and real-time problems and ensure the smooth operation of the networks.

5.1.3. Information Needed for Alert and Control of Disasters. The alert and control of disasters is similar to the O&M of sewer assets. To achieve risk warning and emergency management for pollution and flooding, the real-time status of the networks must be monitored and meteorological data must be collected and analyzed in real-time to facilitate timely detection of pollution sources and predict flood risks to make corresponding control decisions to improve the resilience of the urban network system.

Continuous and real-time monitoring of various parameters of water quality along the sewerage network can be used to identify pollution caused by unregulated or abnormal, malicious discharge to the pipe network early, and warn pollution incidents to avoid serious pollution incidents and reduce the impact on the wastewater treatment system and the destruction of the environment. Real-time monitoring and analyses of the water level, volume, flow rate, etc., of sewerage networks are required for the early alert and control of floods and other disasters. Predicting and judging the volume of flow and the capacity of networks can provide decentralized and real-time control of the storage capacity of the combined sewerage system with the help of automatic smart valves, that is, controlling the amount of stormwater runoff in large reservoirs of wastewater networks to prevent the occurrence of sewage overflows.

5.1.4. Information Needed for Reuse of Wastewater. Improvement of the reuse of wastewater should be analyzed from the supply and demand sides [64]. On the supply side, through the deployment of ICTs, a smart network for urban reclaimed water reuse is constructed to perceive, analyze, and address the reclaimed water resources within the scope of the city and to determine the quality, quantity, and pressure of the reclaimed water in the network in real-time. Smart networks facilitate relevant decision-making and rational coordination of the supply-demand relationship to ensure the stable operation of the reclaimed water network system and the supply of the reclaimed water.

In terms of demand, the success of this practice depends on public acceptance and involvement [65], and water quality is an important concern for the utilization of reclaimed water [37]. Therefore, to promote the reuse of wastewater, WWTPs and the agency of reclaimed water should actively disclose information about reclaimed water. Meanwhile, the government plays a guiding and coordinating role, such as publicizing knowledge about reclaimed water, organizing convenient and comprehensive communications with users of reclaimed water, and coordinating the relationship between relevant departments and users, to increase public acceptance of reclaimed water and promote the reuse of wastewater.

5.1.5. Information Needed for Public Communication and Participation. Members of the public are both recipients and providers of information. The public can directly see the information disclosed by the government or relevant enterprises through information disclosure, such as disaster warning information, the water quality of reclaimed water and effluent of WWTP, to understand urban domestic wastewater. If the services provided by the government or relevant enterprises are not appropriate or cannot satisfy the

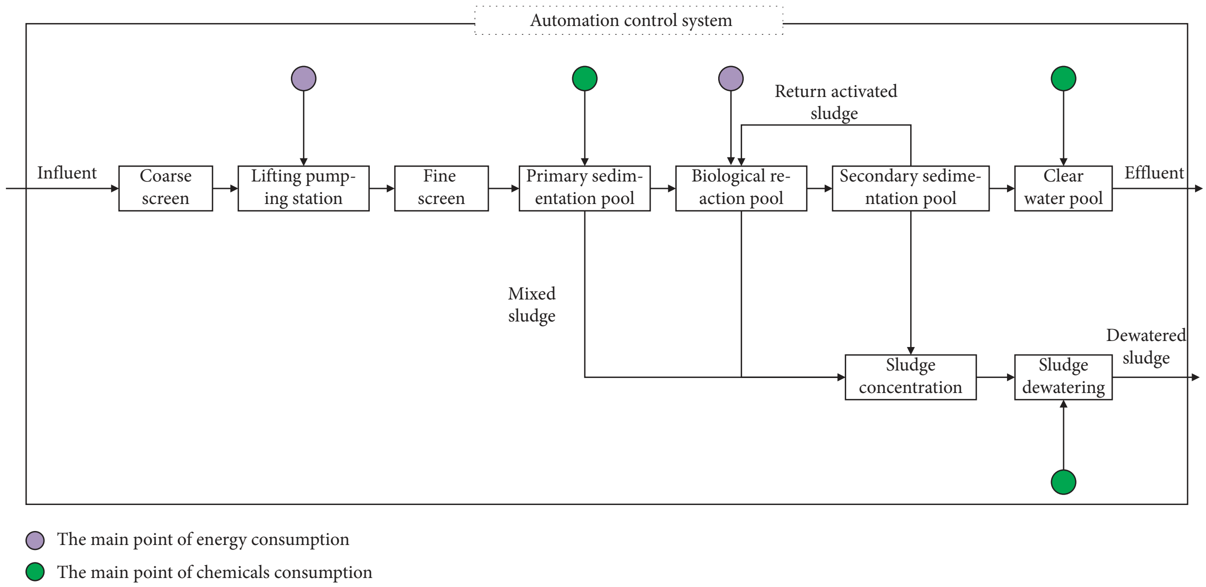

Figure 5: The process flow diagram of domestic wastewater treatment.

public's requirements, the public can express their claims through the online reporting system, including complaints about network leakage, water pollution reports, complaints about noise or odor of WWTPs, or request to disclose relevant information.

5.1.6. Information Needed for Smart Supervision and Evaluation. The government supervises and evaluates the processes and operation quality of wastewater treatment-related services offered by service providers, including the operation of WWTP, sludge disposal, management of malodors and environmental noise of the plant, consumption of energy and other materials, O&M of sewage networks, and reuse of reclaimed water [47, 48]. The WWTP uploads the quality and quantity of the influent and effluent of the plant and other information about its operation, through real-time online monitoring and transmission equipment, to report the operation status to the government. The government can supervise its operation management and pollutant discharge in a smart way. Moreover, the government can conduct performance evaluation, according to the water quality and quantity and other assessment information reported, to calculate pollutant reduction (COD, NH3-N, TN, TP, etc.) and other evaluation results to ensure that the load rate, quality of operation, and effluent water quality of the WWTP meet the standards and to improve the efficiency of public services. Similarly, sewer asset O&M departments upload water quality, water quantity, and other performance indicators of the sewage networks in real-time to report the real-time status of the networks, which can contribute to the regulation of sewer assets and improve the integrity of the sewerage network system. In terms of the reuse of wastewater, the government monitors the quality of reclaimed water in real-time and can combine the reported condition of the reuse of reclaimed water and other information to evaluate the status of wastewater reuse.

5.1.7. Information Needed for Information Sharing. Information sharing is the foundation for the realization of the above functions. Information sharing should determine the scope of information based on the source of information and the authorities who need it, as well as their confidentiality. According to the scope of shared information, information sharing includes intraorganizational and cross-organizational sharing. For example, in a WWTP, the biotechnology department and the laboratory department should share wastewater-related information, such as the water quality of the influent and effluent of the WWTP and each reaction pool, to improve operational management.

In terms of cross-organizational sharing, the operation status of the WWTP is supervised by the Ministry of Ecology and Environment, Ministry of Housing and Urban-Rural Development, etc.; therefore, information about the quality and quantity of wastewater, the process of treatment, etc., should be shared between the WWTP and the government. The O&M of sewer assets is closely related to weather-related data. Therefore, weather data, such as precipitation, are also an important source of cross-organizational sharing. Information sharing also includes the release of disaster alerts and the active disclosure of environmental regulatory data. In the release of disaster information, the real-time and continuous sensors of the sewage networks can quickly assess the occurrence of pollution or flooding to notify the WWTP and facilitate the development of an effective operation plan, which can ensure the stability of the wastewater treatment system. Potential areas affected by floods or overflows can also be notified by sharing disaster alert information to ensure the safety of the population, prevent loss of life, and reduce the social and environmental impacts.

5.2. Information Chain of SUDW. The functions of SUDW are interrelated. Specifically, the WWTP not only considers the water quality and condition of the equipment but also accepts supervision and evaluation from the government and considers complaints of noise and odor of the WWTP from the surrounding residents or other citizens. In addition, when a network failure or disaster occurs, relevant information should be shared with the WWTPs so that the operators of plants can take relevant measures in advance to maintain the stability of the wastewater treatment system. The early alert and control of disasters require the O&M departments of sewer assets to provide information such as the real-time status of the pipeline networks, which is convenient for detecting pollution, floods, and other disasters. The alert is also based on weather-related information. The reuse of wastewater is closely related to other functions as well. The status of wastewater reuse is also a vital component of the evaluation by the government. Therefore, government departments must monitor the usage of reclaimed water, such as information about the quantity and quality. Moreover, the reuse of wastewater is an important issue in public communication.

The components of the smart city information chain model contain information, nodes, and paths, where the nodes are the senders and receivers of the information and the paths are the roads of the information flow [66]. The realization of each function of SUDW is based on the perception of data, through information transmission to the corresponding system or platform for analysis, and the output of relevant data to provide valuable operational information for the corresponding service providers. To clearly represent the information communication between the main stakeholders and functions, this study regards the above seven functions as corresponding functional platforms to complete information analysis and processing. By combining the analyses of the information needed for each function, this study constructs an information chain of SUDW, as shown in Figure 6.

This information chain model illustrates the information communication between the main stakeholders and the functions of SUDW and the information interaction among various functions. Taking the automation of WWTP as an example, the WWTP detects the quality and quantity and other useful data of domestic wastewater in real-time and transmits the data to the automation platform of the WWTP. Eventually, the operational control parameters of the equipment and the dosage of chemicals are the outputs of the functional platform. The public expresses complaints or other appeals to the WWTP or to the government, and the WWTP or the government receives the information and provides feedback on the implementation results to the public. In addition, by analyzing the real-time monitoring and uploaded evaluation information, the government can assess the WWTP and deliver feedback to the plant. In return, the plant can adjust its operational strategy based on complaints and feedback.

5.3. Data-Driven Framework of SUDW. The above analyses illustrated the functions of SUDW, the main stakeholders involved in each function, and the data required. The main stakeholders are service providers (including the WWTP, O&M departments of sewer assets, and the agency of reclaimed water), the government, and the public. The data required to realize the corresponding functions include wastewater-related data, such as wastewater quality, water quantity, water level, and flow rate; equipment-related data, such as the switch status of the equipment, running duration, current, energy consumption, noise, and other indicators; sewer assets-related data, such as the locations of facilities, age, and storage capacity of the pipeline network; real-time status of the networks, such as water level and quality of wastewater in the network; weather-related data, such as precipitation and temperature; and public feedback data, such as requests or complaints from the public and other descriptive data of life and activities recorded through social networks.

Different types of data are provided by different stakeholders, and they should be acquired by different technologies [67]. Water quality sensors, water level sensors, and water velocity sensors are used to collect real-time wastewater-related data and determine the real-time status of networks. Weather-related data are obtained by weather radar. Video surveillance is used to collect data about the equipment and pipeline network status. In addition, manual reporting, such as feedback from relevant departments in response to public demands, is an important source of data for SUDW.

Based on the above analyses, this study develops a data-driven framework for SUDW, as shown in Figure 7. With data as the core, the framework aims to explore the potential value and to support decision-making through the collection and the analysis of online and offline data to achieve the functions of SUDW. The framework consists of five layers, from bottom to top: data perception layer, data transmission layer, data storage layer, data analysis and application layer, and user interface layer.

The data perception layer collects relevant wastewater treatment data through sensing devices, such as precipitation gauges, sensors, and videos. Wired or wireless networks (such as TCP/IP, bluetooth, Zigbee, and other protocols) are used to transmit and exchange the perceived information and data in the data transmission layer. In the data storage layer, by means of data warehousing technology, databases are established to store structured, semistructured, and unstructured data [68], such as perceived wastewater-related data, equipment-related data, and sewer asset-related data. In the data analysis and application layer, the original data are denoised and cleaned via data processing and integration to obtain reliable data [69]. Then, artificial intelligence algorithms, such as neural networks and machine learning, are used to analyze and extract the potential value from the data to provide relevant information and support relevant decision-making to achieve the corresponding functions [67]. Finally, through the user interface layer, in the form of visualization, the relevant information is transmitted to stakeholders to strengthen the stakeholders' participation.

6. Discussion

From the perspective of the realizable functions of SUDW, this study proposed that SUDW is based on the application of ICT technologies; involves the collection and analysis of wastewater-related data, equipment-related data, sewer assets-related data, weather-related data, etc.; and helps

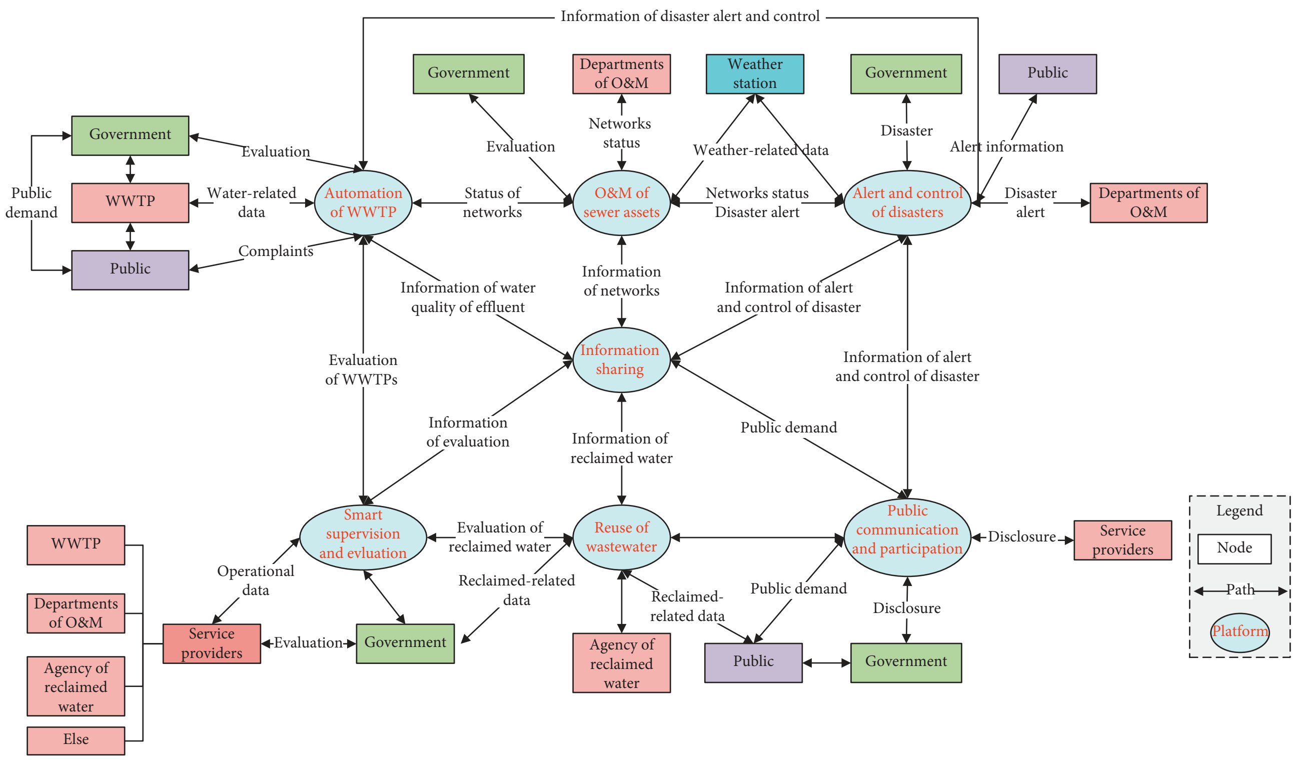

Figure 6: Information chain model of SUDW.

stakeholders obtain accurate information in real-time or near real-time to support relevant decision-making and realize relevant functions, thereby promoting the delivery of sustainable development and smart cities and improving the quality of public life.

This paper studied the framework for SUDW from the perspective of sustainability. A data-driven framework was constructed on the basis of the identification and analysis of the achievable functions, main stakeholders, information needed, and information transmission paths of SUDW. The proposed framework consists of five layers: data perception layer, data transmission layer, data storage layer, data analysis and application layer, and user interface layer. By means of perception, transmission, storage, analysis, and application of relevant data, the framework supports decision-making and helps achieve the corresponding functions. Finally, the relevant information is transmitted to the corresponding stakeholders in the user interface layer. The data are the core element of the framework. Therefore, the timeliness and validity of the data are important guarantees for the realization of SUDW [69, 70]. To ensure the timeliness and validity of the data throughout the process, in the data perception layer, the accuracy of the sensors should be guaranteed to ensure that the perceived data can be used to support decision-making [71]. Additionally, the timeliness of data collection, such as real-time monitoring of important water quality indicators, including BOD, PH, TN, and TP, and daily statistics of sludge quantity, should be ensured. In the data transmission layer, the perceived data should be transmitted securely through the transmission protocols to avoid data lag or data loss [72]. Therefore, a strong demand exists for related transmission technologies. Moreover, the storage of data should ensure the stability of the databases and facilitate the real-time read-in and accessing of data [70]. In addition, the database should be extensible to ensure the development of other functions. In the data analysis and application layer, data cleaning and preprocessing are important to ensure data validity, delete duplicate information, correct errors, and improve data reliability and effectiveness of the results [73]. The designed algorithm should be stable and applicable to the corresponding functions and provide correct and valuable information for decision-making to promote the realization of functions. Finally, the data are interpreted and visualized in the form of tables and images and transmitted to stakeholders to facilitate the understanding of relevant data.

In contrast to architectures built from a single service or function perspective, such as studies conducted by Fattoruso et al. [9] and Ye et al. [34], this paper proposed a comprehensive framework for SUDW that can facilitate an understanding of the achievable functions of SUDW systematically and noted the premise of achieving this goal, i.e., the perception, transmission, storage, and analysis of the corresponding data. Moreover, a holistic and comprehensive framework is conducive to clarifying and coordinating the relationships among stakeholders and between stakeholders and related functions, which can strengthen the utilization of existing resources and promote the planning and implementation of smart cities [74].

Under the guidance of this framework, the realization of SUDW can develop functions gradually and vertically and then realize information sharing among functions through

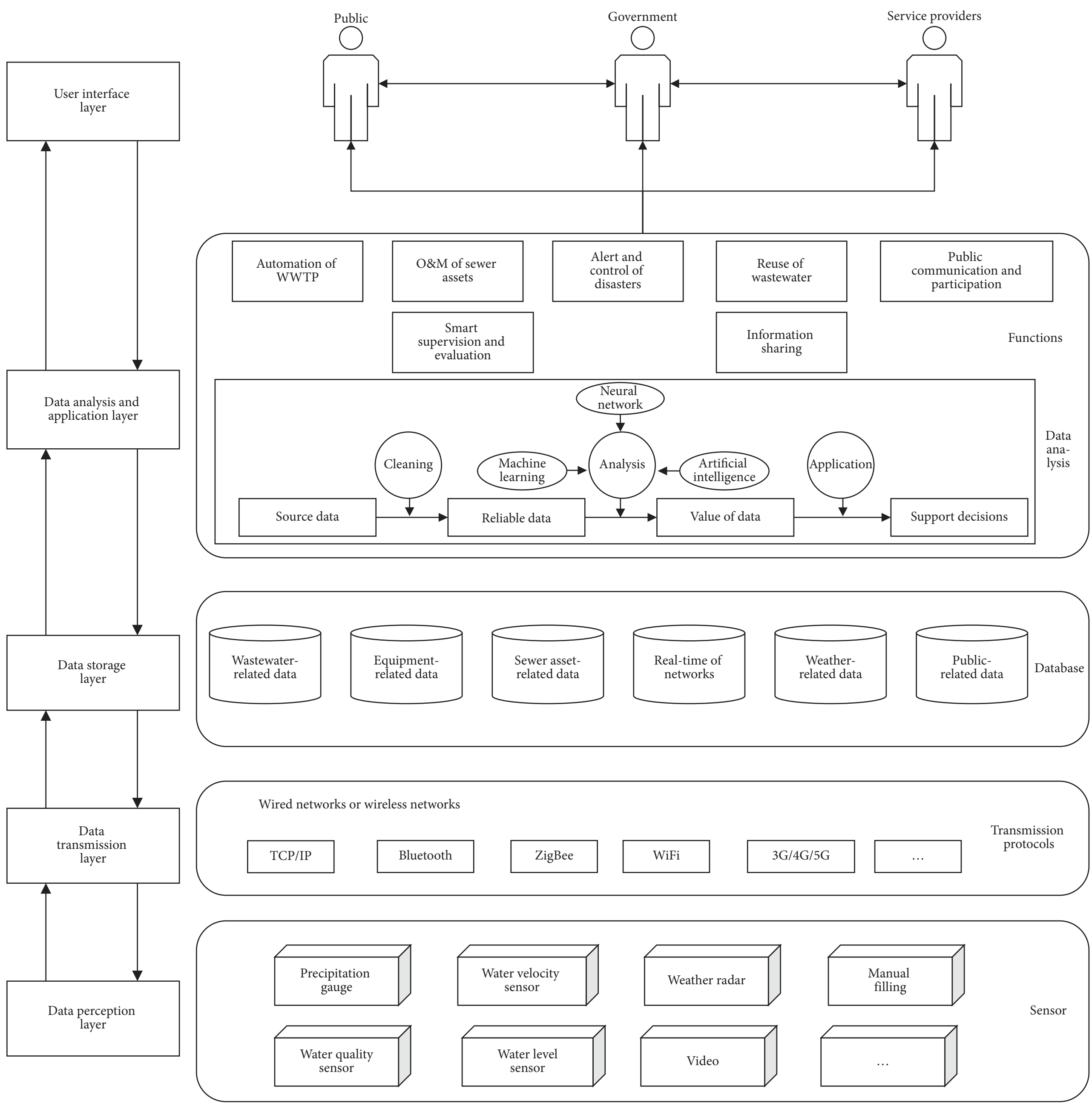

Figure 7: The data-driven framework of SUDW.

an information synthesis platform [74]. Alternatively, the planning of each function and their relationships can be achieved horizontally, gradually improving each function to ultimately realize SUDW.

After realization of SUDW, from the perspective of environmental benefits, the WWTP can improve the efficiency of wastewater treatment to ensure that the discharged treated wastewater meets the standards and can also reduce the consumption of energy and chemicals, eventually mitigating the impact on the environment [14, 75]. Early alert of sewage network overflows or disasters related to domestic wastewater reduces the impact on the public living environment as well [9]. Reuse of wastewater also reduces the use and destruction of water resources [10]. From an economic point of view, the use of ICTs and other technologies can improve the service efficiency of service providers and lead to greater cost-effectiveness [51]. Moreover, for the government and society, the improved infrastructure operation efficiency can more effectively realize the allocation of resources and facilitate economic sustainability. From the perspective of social benefits, the rational allocation of resources can also help narrow the gap between infrastructures and promote social equity and social sustainable development [58]. In addition, after the improvement of the living environment and promotion of public participation, it can improve the satisfaction of the public and eventually improve the quality of life [59]. Therefore, from the perspectives of the environment, economy, and society, the objectives of SUDW are consistent with the goals of sustainable development. Guided by the goals of sustainable development, the framework for SUDW is designed to conduct the planning and development of SUDW, which in turn promotes sustainable development.

7. Conclusion

This research studied the framework for SUDW from the perspective of sustainability. Based on the goals of sustainable development, the objectives of SUDW, which are consistent with those of sustainable development, were assessed from the perspectives of service providers (mainly WWTPs), the government, and the public. Based on a systematic literature analysis, seven functions of SUDW were identified: (i) automation of WWTP, (ii) O&M of sewer assets, (iii) alert and control of disasters, (iv) reuse of wastewater, (v) public communication and participation, (vi) smart supervision and evaluation, and (vii) information sharing. These functions are interrelated and closely related to sustainable development, where information sharing is the foundation and key component. Then, an information chain model of SUDW was constructed to express the transmission paths of information between stakeholders and functions, which also highlighted the information interaction between functions and emphasized the importance of stakeholders. Finally, based on the above analyses, a data-driven framework for SUDW was developed systematically that consists of the following five layers, from bottom to top: (i) data perception layer, (ii) data transmission layer, (iii) data storage layer, (iv) data analysis and application layer, and (v) user interface layer. The premise of SUDW is defined as the perception, transmission, storage, analysis, and application of corresponding data. This paper also proposed data as the core element of the framework, and we should ensure the validity and timeliness of the data to provide valuable information for relevant decision-making.

Despite achieving the research objectives, some limitations remain. Because of different functions in different contexts or the use of different data analysis methods, the required data can vary. This paper did not define all the data required by SUDW, but the basic form of the indicators and the ways to obtain them were analyzed, thereby providing a reference for follow-up research and practice. Additionally, due to the complexity of the components of the framework, such as the transmission protocols and analysis algorithms, this study did not use actual cases to analyze the framework.

Nevertheless, this study, through the systematic analysis of the achievable functions of SUDW, compensates for the gap arising from the scattering of current research studies among different areas of smart wastewater and contributes to the body of knowledge relating to smart cities. In addition, the proposed smart framework can help the government, urban developers, and service providers understand solutions for the development of SUDW and can be used to guide the planning of urban domestic wastewater to promote the realization of SUDW, eventually delivering smart cities and achieving sustainable development.

Subsequent studies will consider specific cases to demonstrate and revise the framework. In future research, scholars can study the specific data indicators that must be obtained, the ICT technologies needed for the entire process, the data transmission protocols, and the data analysis algorithms to implement the application, which involve many disciplines and various fields.

Data Availability

The results of a systematic literature analysis used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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