

**EVALUATING OPERATIONAL  
EFFICIENCY OF URBAN WATER SECTOR IN  
CHINA BASED ON NETWORK DEA METHODS**

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CHINA BASED ON NETWORK DEA METHODS**

by

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Ever since I made the decision to pursue a doctorate, I have recognized the need to commit myself to exploring and addressing various challenges. I frequently experienced confusion and self-doubt. However, there were moments of delight as I successfully navigated numerous challenges, and I opted to confront them as an optimistic researcher. Studying at the School of Distance Education, Universiti Sains Malaysia, is a valuable experience and a sentimental memory accompanied with me into the future. This reflects the journey of self-improvement and serves as a unique representation of the personal growth I accomplished.

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## LIST OF ABBREVIATIONS

CAE	Chinese Academy of Engineering
CNY	Chinese Yuan
COD	Chemical oxygen demand
CRS	Constant returns-to-scale
CUCSY	China Urban Construction Statistical Yearbook
CUWA	China Urban Water Association
DEA	Data envelopment analysis
DNDEA	Dynamic network DEA
DRCMWR	Development Research Center of the Ministry of Water Resource
IRI	Industry Research Institute of China
MOHURD	Ministry of Housing and Urban-Rural Development of China
MEE	Ministry of Ecology and Environment of China
MWR	Ministry of Water Resources of China
NA	Ammonia nitrogen
NBS	National Bureau of Statistics of China
NDRC	National Development and Reform Commission of China
SDG	Sustainable development goals
TGR	Technology gap ratio
UN	United Nations
UWS	Urban water sector
UWSI	Urban water supply industry
UWSU	Urban water supply utility
VRS	Variable returns-to-scale
WaSCs	Water and sewerage companies
WoCs	Water-Only companies
WWTP	Wastewater treatment plant
WREW	Water Resources Engineering and Management of China
WRI	World Resource Institute

# **PENILAIAN KECEKAPAN OPERASI SEKTOR AIR BANDAR DI CHINA BERDASARKAN KAEDAH RANGKAIAN DEA**

## **ABSTRAK**

Perbandaran yang pesat dan pembangunan sosioekonomi telah memperburuk kekurangan air dan pencemaran air sisa, menimbulkan cabaran besar bagi sektor air bandar (UWS), terutamanya di negara-negara yang kurang maju. Di China, Sektor Air Perbandaran (UWS), yang dicirikan oleh monopoli semula jadi dan pemulaan pasaran, menghadapi ketidakcekapan akibat daripada pengembangan bandar yang pesat, pencemaran air, tarif air yang rendah, subsidi fiskal, dan infrastruktur yang uzur. Sehingga kini, banyak literatur telah memberi tumpuan kepada utiliti air dari negara lain dan penggunaan air industri di China. Tiada penyelidikan serupa yang telah menyiasat secara sistematik operasi holistik untuk UWS. Kajian ini secara sistematik menilai kecekapan teknikal UWS di China menggunakan model DEA rangkaian dinamik merentasi tiga dimensi: peringkat firma (246 utiliti bekalan air bandar, 2016–2018), peringkat industri (industri bekalan air bandar di 159 bandar, 2013–2018), dan peringkat sektor holistik (UWS di 56 bandar utama, 2013–2017). Operasi UWS dipecahkan kepada empat substage, iaitu pengeluaran air, pengedaran air, rawatan air sisa, dan kitar semula air sisa, untuk membolehkan penanda aras yang terperinci. Keputusan menunjukkan ketidakcekapan yang ketara, terutamanya dalam pengeluaran air dan kitar semula air sisa, yang didorong oleh struktur monopoli, tarif yang tidak selaras, dan kelewatan teknologi. Implikasi dasar termasuk kepelbagaian pemilikan, reform tarif, peningkatan infrastruktur, dan pengambilan teknologi yang lebih baik. Penyelidikan ini menyumbang rangka kerja penilaian kecekapan yang baru dan komprehensif serta alat penanda aras baru untuk UWS China.

# **EVALUATING OPERATIONAL EFFICIENCY OF URBAN WATER SECTOR IN CHINA BASED ON NETWORK DEA METHODS**

## **ABSTRACT**

Rapid urbanization and socioeconomic development have intensified water scarcity and wastewater pollution, posing significant challenges for urban water sectors (UWS), especially in less-developed countries. In China, the UWS, characterized by natural monopoly and initial marketization, faces inefficiencies due to fast urban expansion, water pollution, low water tariffs, fiscal subsidies, and aging infrastructure. Until now, extensive literature has shed light on water utilities from other countries and industrial water use in China. No similar research has systematically investigated the holistic operation for the UWS. This study systematically evaluates the technical efficiency of China's UWS using dynamic network DEA models across three dimensions: firm-level (246 urban water supply utilities, 2016–2018), industry-level (urban water supply industry in 159 cities, 2013–2018), and holistic sector-level (UWS in 56 major cities, 2013–2017). The UWS operation is decomposed into four substages, namely water production, water distribution, wastewater treatment, and wastewater recycling, to enable detailed benchmarking. Results reveal significant inefficiencies, particularly in water production and wastewater recycling, driven by monopolistic structures, misaligned tariffs, and technological lag. Policy implications include ownership diversification, tariff reform, infrastructure upgrades, and enhanced technological adoption. This research contributes a novel, comprehensive efficiency assessment framework and new benchmarking tool for China's UWS.

# CHAPTER 1

## INTRODUCTION

### 1.1 Overview

Of the 1.4 billion km<sup>3</sup> of water on the earth, only 2.5% is freshwater, and 0.34% of it is accessible to humans (Maidment, 1992). Water is limited and essential for human survival and the economy. Population growth, urban expansion, and consumption patterns contribute to decreasing water resources per capita while spreading freshwater pollution. Global water consumption has increased sixfold and has been rising at a rate of 1% annually for the past 40 years, which is predicted to continue until 2050. Nearly 26% of the global population (2.2 billion) lacks access to clean water. An estimated 80% of wastewater flows into rivers and oceans without adequate treatment (United Nations, 2023). Thus, a crucial effort is needed to deliver water and sanitation services to billions of people. This converges with SDG 6 “Clean Water and Sanitation”, which conveys an urgent global call to ensure the availability and sustainability of water supply and sanitation services (United Nations, 2019).

Nearly 80% of the global GDP is produced in cities (WRI, 2022). Cities are uniquely positioned to produce prosperity and innovation, whereas urban expansion gains millions of new residents every month and leads to an accelerated contradiction between resource-constrained water supply and population-driven water demand (Cosgrove & Loucks, 2015). The population density in cities and rural-to-urban migration are the primary causes of the world’s water crisis (Mysiak, 2010). Over 56% of the global population currently lives in urban areas, which would rise to 75% by 2055 (around 7.3 billion people). Nearly one third of city dwellers (1.2 billion) were daily underserved by clean water in 2022, and that population is anticipated to grow to 2.1 billion by 2050 (United Nations, 2023).

The urban water crisis is not simply due to water scarcity but also to the poor operational efficiency or a lack of competent governance (Worthington, 2014). The urban water sector (UWS) undertakes the formidable task of providing drinking water supply and sanitation services for urbanites (Wang et al., 2017). Under these existing and emerging pressures, particular focus has been placed on the UWS to achieve greater operational efficiency in response to the water crisis and the provision of clean water in a sustainable manner (Abbott & Cohen, 2009).

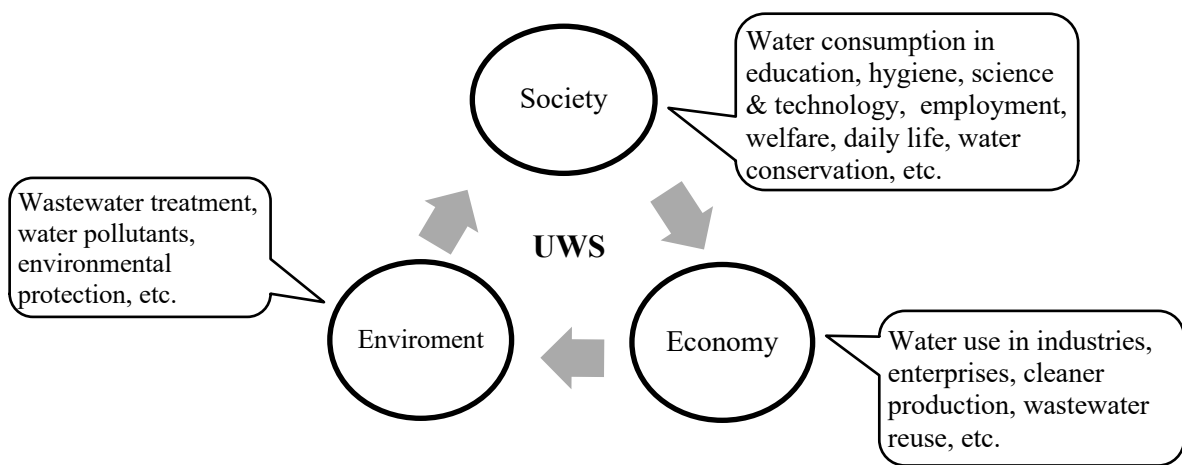


Figure 1.1 Urban water sector's interaction with socio-economy  
 Note: Modified Fu et al. (2008)

The UWS is the industry that is responsible for the universality and providing potable water supply and wastewater treatment services (Abbott et al., 2012; Fu et al., 2008; Cetrulo et al., 2019). As shown in Figure 1.1, the services provided by the UWS inextricably underpin the production of the entire society and economy. However, the wastewater discharged with pollutants from water utilities deteriorates the ecosystem. The quantity and quality of raw water extracted from the environment are strongly affected by wastewater discharged. Inhabitants' daily lives also affect the UWS. Water needs to be rationally supplied on the basis of enterprises requirements and population served, while clean production and wastewater reuse can reduce wastewater discharge and conserve water resources (Bronner et al., 2022).

Natural monopolism is the common characteristic in UWS due to the water scarcity, capital intensity, economies of scale, regional exclusivity, and public service, which make the industry subject to regulations (Hayes, 1987; Marques et al., 2011). Market competition must be initiated by governments. Normal performance indicators such as profit or return rates become problematic because the input and output prices is not asymmetrical in the absence of market force. Thus, measuring the operational efficiency of the UWS by a reliable metric and establishing benchmarking baselines are crucial (Ananda, 2014). Assessing the past performance by a well-established evaluation system and improving the efficiency of the UWS is a robust support to achieve optimal allocation of resources. This serves as the motive for this study.

Currently, the bulk of urban water crisis is concentrated in middle-income countries or emerging economies, as they absorb most of the intensive growth impact (WRI, 2022). An estimated 90% of urbanization is happening in Africa and Asia (United Nations, 2018). As the largest developing country, China is experiencing a surge in urban growth. Agglomeration from rural areas to cities exposes the UWS in China to challenges due to its large population (18.8% of the global total) and limited water resources. The total water resources in China amount to 2.7 trillion m<sup>3</sup> (6% of the global total). However, water resources per capita stand at 1918.2 m<sup>3</sup>, which is 1/4 of the world average (MWR, 2022). From 1978–2022, the urbanization rate increased from 17.92% to 65.22%, while the number of cities increased by 502 from 193 in 1978 to 695 in 2022 (NBS, 2023). In 2022, more than 400 of the 695 cities in China supplied water insufficiently, and 110 of them suffered from incurable water scarcity.

Thousands of water utilities are scattered throughout cities in China, which try to cope with the severe water demand and serve the well-being of citizens. The UWS

in China, which is also referred to as a natural monopoly, is regulated by local governments. Marketization is still in the early stages. Urbanites have inexpensive access to tap water. Operation costs that exceed water tariffs are compensated for by fiscal aid for water utilities. These factors lead to inefficient operations in the UWS.

To date, the majority of efficiency analyses on the water industry in China have focused on industrial water use. Operational efficiency of the holistic UWS remains largely unmeasured scientifically. Less is known about water utilities. The UWS in China still lacks a reliable metric to assess how well it performs (Du et al., 2023). In this research, network data envelopment analysis (NDEA) and metafrontier approach are combined to develop fine-grained methodologies to evaluate the efficiency of the UWS in China from multiple dimensions. Efficiency analysis at the firm-level, industry-level, sector-level will all be present, and policy implications will be provided.

This chapter introduces the context of this thesis by not only introducing the research background for the UWS in China but also outlining the research problem, the scope of the study, the research questions and objectives, the methodology, the significance of the research, definitions of key terms, and, how the thesis is organized.

## **1.2 Background of Study**

The background of the study is motivated to conduct a systematic efficiency evaluation for the operation of UWS in China. The research background is related to water stress, institution structure, operation system, marketization reform, water tariff, the status quo of the UWS in China, and the DEA methods.

### **1.2.1 Water Stress and Surging Demands for Urban Water Service**

According to the National Bureau of Statistics of China (NBS, 2023), in 2022, the total water resources in China equated 2708.8 km<sup>3</sup>. The surface water resources

covered 2598.4 km<sup>3</sup>, the groundwater resources covered 792.4 km<sup>3</sup>, and the overlapping area between surface water resources and groundwater covered 682.1 km<sup>3</sup>. However, the water resources per capita in China were 1918.2 m<sup>3</sup> (1/4 of the world average), which is at the global moderate water scarcity level<sup>1</sup>.

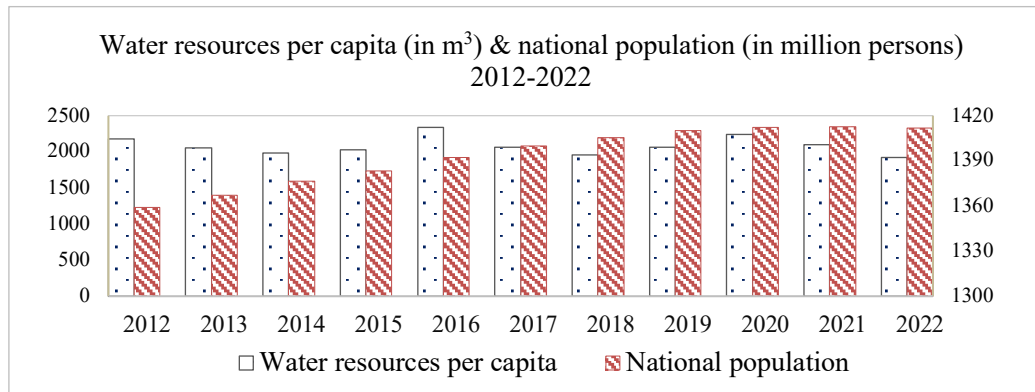


Figure 1.2 Water resources per capita and national population  
Source: China Statistical Yearbook (2023)

The water resources in China are characterized by limited water resources per capita, uneven distributions, and asynchrony with economic development levels. As depicted in Figure 1.2, from 2012-2022, the national population increased each year, whereas the water resources per capita fluctuated between 1900 m<sup>3</sup> and 2200 m<sup>3</sup> and even experienced a downward trend. China's total water resources rank sixth globally, with water resources per capita ranking 152<sup>nd</sup> (World Bank, 2020).

Water resources are unevenly distributed among regions in China, with more resources in the southern region than in the northern region. As shown in Figure 1.3, the most dominant main river baselines in China are the Yangtze River and the Yellow River, characterized by longest distance sources, substantial runoff volumes, and significant hydropower potential. Only 19% of the water resources are in Northern

<sup>1</sup> Based on the classification criteria of water scarcity levels by the United Nations, sufficient water sources refers to a situation where the water resources per capita are more than 3000 m<sup>3</sup>. Mild water shortage refers to a situation where the water resources per capita are between 2000 m<sup>3</sup> and 3000 m<sup>3</sup>. Moderate water shortage refers to a situation where the water resources per capita are between 1000 m<sup>3</sup> and 2000 m<sup>3</sup>. Severe water shortage refers to a situation where the water resources per capita are between 500 m<sup>3</sup> and 1000 m<sup>3</sup>, and extreme water shortage refers to a situation where the water resources per capita are less than 500 m<sup>3</sup> (Du et al., 2023).

China (the north region of the Yangtze River), which comprises 64% of the territory, 46% of the population, and 44% of the GDP. Southern China, with only 36% of the country's territory, 54% of the population, and 56% of the GDP, contributes 81% of the total water resources (NBS, 2023). The shades of dark red in Figure 1.3 shows that the Yellow River basin is the most significant area regarding the water supply and demand conflicts, along which many districts are facing severe water stress.

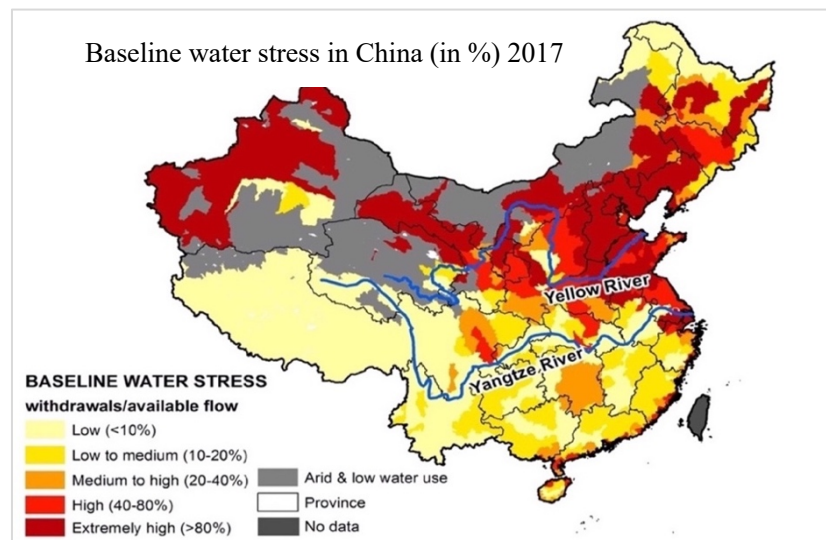


Figure 1.3 Spatial distribution of river baseline water stress<sup>2</sup> in China  
Source: World Resource Institution (2017)

As illustrated in Figure 1.4, the distribution of water resources per capita in China does not match its economic development levels. Eastern coastal provinces with higher gross regional products per capita such as Beijing, Shanghai, Tianjin, and Jiangsu, have extremely lower water resources per capita, whereas western undeveloped provinces such as Tibet, Qinghai, Guangxi, Yunnan and Xinjiang have sufficient water resources. The water resources per capita in 10 provinces (autonomous regions or municipalities) are below the severe water shortage level (<1000 m<sup>3</sup>).

<sup>2</sup> The river baseline water stress is a measurement of the chronic level of competition and depletion of available water serving as an effective indicator for assessing water-related risks. The shade of dark signify increased competition for water among consumers and the depletion of water resources.

Among them, the water resources per capita in Beijing, Tianjin, Ningxia, Shanghai, Jiangsu, Henan, and Hebei are below the extreme water shortage level (<500 m<sup>3</sup>).

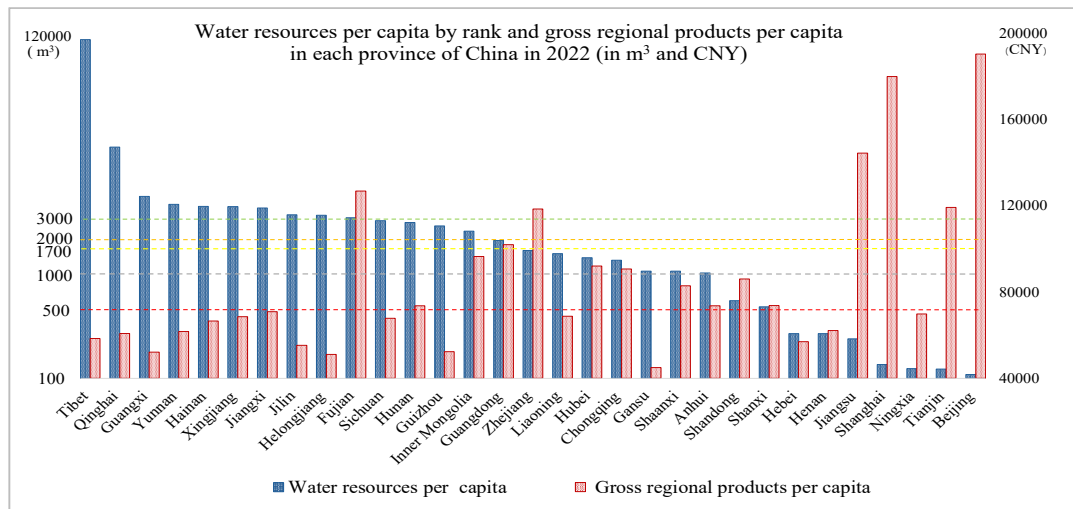


Figure 1.4 Water resources per capita and gross regional product per capita in each province  
Source: China Statistical Yearbook 2023

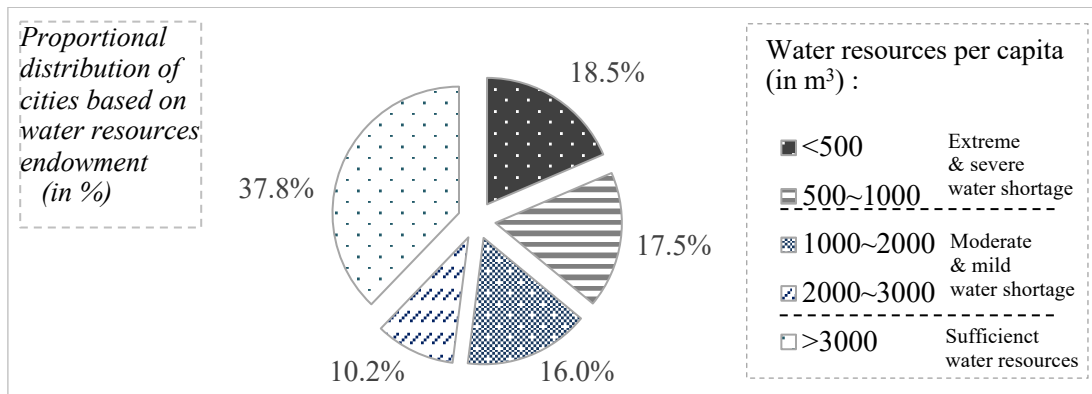


Figure 1.5 Proportion distribution of Chinese cities based on water resources per capita  
Source: China Urban Construction Statistics Yearbook (2022)

Owing to the fast urban expansion and dense population, the freshwater resources per capita in cities are even scarcer. According to data from the China Urban Construction Statistics Yearbook (2022), nearly 62.1% of the cities do not have sufficient water resources per capita (<3000 m<sup>3</sup>) (Figure 1.5). The water resources per capita in 18.5% of cities are less than 500 m<sup>3</sup>, which indicates extreme water shortages. A total of 17.5% of the cities' water resources per capita are within the range of 500~1000 m<sup>3</sup>, which indicates severe water shortages. The water resources per capita in Beijing are only 108.4 m<sup>3</sup>, whereas that in Shanghai and Tianjin are 133.4 m<sup>3</sup> and

121.3 m<sup>3</sup> respectively. The uneven distribution of water resources becomes the constraint for the development of the UWS in China.

Meanwhile, the market demand for urban water services in China has increased dramatically over the past 40 years since the reform and opening up. From 1978 to 2022, the urbanization rate in China increased from 17.92% to 65.22%. The number of cities increased by 502, from 193 in 1978 to 695 in 2022. The urban population (excluding the county) accelerated from 76.82 million in 1978 to 564.88 million in 2022 (MOHURD, 2023). According to the “Statistic Bulletin on China Urban Construction for 2022”, the total national urban water supply and consumption in 2022 amounted to 67.44 km<sup>3</sup>, with an increase of 59.56 km<sup>3</sup> from 7.87 km<sup>3</sup> in 1978. The daily water consumption per capita increased from 120.6 litre to 184.7 litre in 1978-2022. The investment in urban water networks increased more than 370 times (from CNY 7.2 million to 2618.4 million) during this period. On the basis of the “Sustainable Water Development Report for China” (CAE, 2001), the urban water demand is predicted to reach 122 km<sup>3</sup> in 2030 and 154 km<sup>3</sup> in 2050.

Owing to the increase in water demand, urban water stress is an extremely serious issue. To date, the annual water deficiency across cities exceeds 6 km<sup>3</sup> (WREM, 2023). Nearly 400 of China’s 695 jurisdictional cities supply water insufficiently, and 110 of them suffer from incurable water shortages. More than 30 megacities (Beijing, Shanghai, Tianjin, Guangzhou, Shenzhen, Wuhan, Xian, etc.) have been experiencing severe water scarcity. During the peak water consumption season, certain cities are forced to limit their water supply, which seriously impedes economic development.

Even more seriously, the pollution scale of rivers in urban areas is expanding. The discharge of chemical oxygen demand (COD) and ammonia nitrogen (NA) are

normally used as primary pollutant indicators for assessing wastewater emission (Wu et al., 2019). According to the China Ecological Environment Statistical Yearbook (MEE, 2022), the COD and NA emissions from industrial and household wastewater equal 8.09 billion kilograms and 0.54 billion kilograms, respectively, accounting for 31.1% and 65.7% of the national emissions. The water resources in more than 90% of cities across the country has been polluted, and nearly 50% of urban water sources do meet drinking water source criteria. According to the China Urban and Rural Construction Statistical Yearbook (MOHURD, 2023), the wastewater discharged in cities increases at a rate of nearly 1.7% annually. In 2022, wastewater from cities amounted to 63.9 km<sup>3</sup>, accounting for 64.9% of the national volume. The recycled and reused wastewater amounted to 17.9 km<sup>3</sup>, with a reused rate of only 28%.

Facing the water stress in the severe situation of water pollution and surging urban water demand, the operation of the UWS inevitably require efficiency improvement to ensure qualified services for water supply, wastewater treatment and a larger scale of wastewater reuse. An examination of the efficiency of the UWS is undoubtedly a heuristic prerequisite for addressing these urban water crises.

### **1.2.2 Operation System of the Urban Water Sector**

Literature related to UWS, is derived from the appellations of water utilities as those which provide urban potable water and sanitation services since the pioneering work of Ford and Warford (1969). Following the definition and operation activities elaborated in González-Gómez and García-Rubio (2008), Fu et al. (2008), Kakwani and Kalbar (2020), Wang et al. (2017), the term “urban water sector (UWS)” refers to the service industry that is responsible for providing water services from water operators to urbanites in a city, including raw water extraction, clean water production,

water distribution, drainage system, wastewater treatment, water recycling and reuse, and related supporting devices (as shown in Figure 1.6).

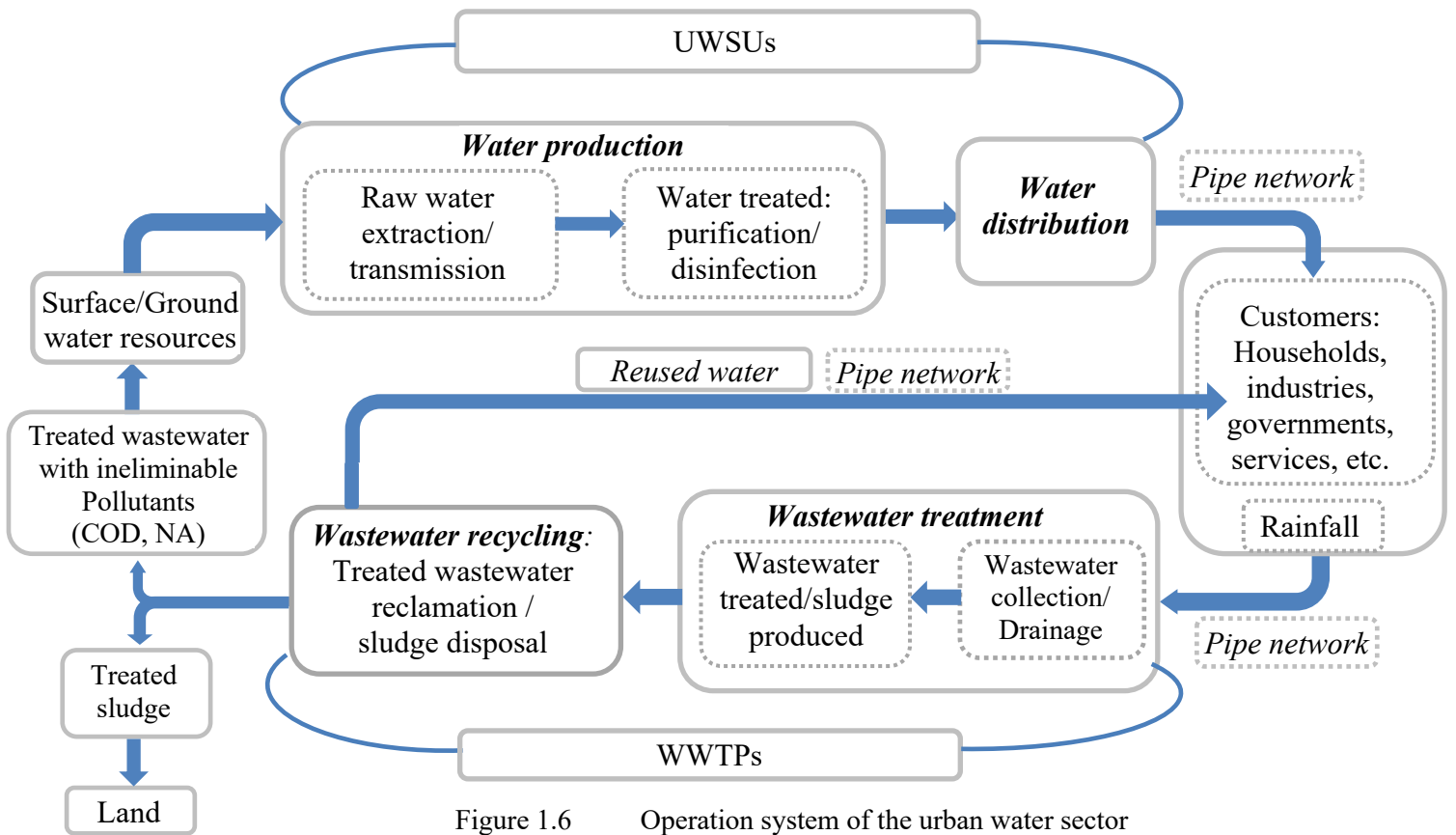


Figure 1.6 Operation system of the urban water sector  
 Note: Modified Wang et al. (2017)

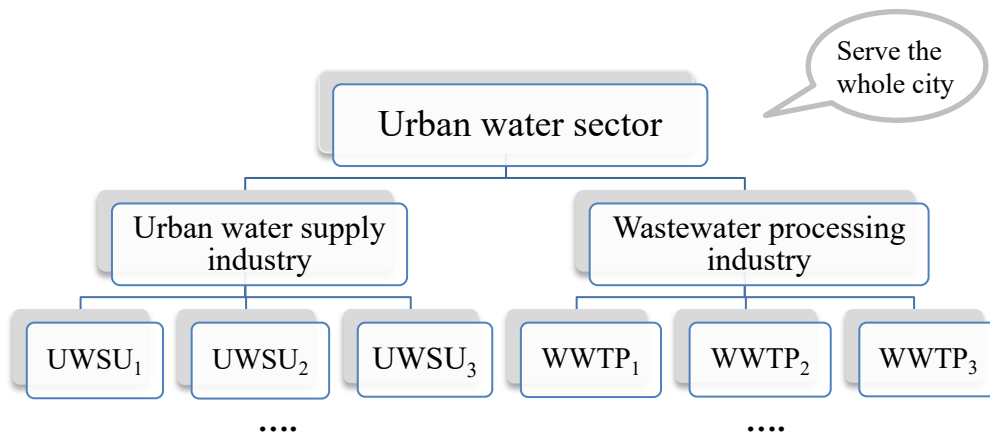


Figure 1.7 Subsystem of the urban water sector  
 Note: Developed by Author

In general, the operators in the UWS include urban water supply utilities (UWSUs) and wastewater treatment plants (WWTPs), which provide different water

services in their respective industry (Abbott et al., 2012; González-Gómez & García-Rubio, 2008; Wang et al., 2017). Figure 1.6 depicts the water services provided by the UWSUs and WWTPs. The UWSUs are normally in charge of clean water production (raw water extraction and treatments) and water distribution (González-Gómez & García-Rubio, 2008). They extract raw water from water resources such as rivers, lakes, dams, or groundwater aquifers and transmit it to the water plants. In the water plants, the raw water is disinfected and purified to meet the potable water criteria and then distributed to customers (industries, households, municipal services, etc.).

Afterwards, the industrial wastewater, domestic sewage and rainfall are collected to the WWTPs through the drainage system, which is a sewerage network to collect and convey the wastewater and rainfall runoff in cities. The WWTPs are in charge of the wastewater treatment services (i.e. sewerage drainage, dirty water disposal, water recycling and reuse, sludge disposal) (Io Storto, 2020). Sludge is used in flocculent sedimentation to eliminate hazardous organic pollutants. Pollutants in wastewater are removed at an environmentally safe threshold. Treated wastewater will be discharged back into the nature. With more advanced treatments, a portion of the treated wastewater can be recycled and then reused directly for non-household purposes (landscaping, industry use, roadside, irrigation, etc). The treated sludge as a byproduct can be reutilized in agriculture.

Figure 1.7 depicts the subsystems of UWS. The water supply services provided by UWSUs constitute the urban water supply industry (UWSI), and wastewater processing provided by WWTPs form the wastewater processing industry respectively (Goksu et al. 2019). The UWSI refers to the entire industry responsible for providing clean and safe potable water to urbanites, including residential, industrial users, and

governments in each city. The wastewater processing industry involves the collection, treatment, and safe discharge or reuse of municipal and industrial wastewater. These two subsystems together form the core of the UWS. Notably, the UWS is a multiactivity industry. The sound operational efficiency of both subsystems contribute to the joint efforts to achieve higher efficiency of the entire UWS in cities.

### **1.2.3 Reform of the Urban Water Sector in China**

#### **1.2.3(a) Market-oriented Reform**

The UWS in China has gradually gone through four marketization reform phases since the “*Water Law*” in 1988: the first phase was characterized by the complete public welfare of water services (before 1992); the second phase was characterized by state-held water corporation establishment and admission for non-state capital (1992-2002); the third phase was characterized by the “build-operate-transfer (BOT)” franchise for non-state entities (2002-2016); and the fourth one was characterized by public-private partnership (PPP) (2016-present).

Before 1992, the local municipal government completely undertook the dual tasks of water service providers and regulators. Tap water was provided as a public good. Charging water tariffs in China can date back to 1985 (Jiang et al., 2022). The commodity characteristic of water was initially recognized. The low water tariffs were set by the state authorities, which did not reflect the intrinsic value of the water and led to irrecoverable operating costs. The related financial pressure acted as a burden on governments. By 1992, the urban water supplied was 42.98 km<sup>3</sup>, with an access rate of 56.2%, and the population served was 172.81 million. The urban wastewater treated amounted 5.22 km<sup>3</sup>, with a treatment rate of 17.29% (MOHURD, 2022).

From 1992 to 2002, amid the rapid urbanization and opening up of China, the UWS experienced rapid progress. As the “*Acts on the Restructure of the Institutional Mechanism of Public-Owned Enterprises*” and “*Corporation Law*” (State Council of the People’s Republic of China, 1992, 1993) stipulated, the formation of state-held water companies commenced. The UWSUs were restructured to corporation format. This was a groundbreaking move regarding the separation of water service providers and regulators by governments. State-owned water companies took over the responsibilities for operation. International water companies began to invest and engage in China, such as Veolia Water, Suez of France, Thames Water of UK, who are the front-runners in the UWS (Zhong et al. 2008).

Since 2002, i.e., after China’s accession to the WTO, the curtain of market-oriented reform for the UWS in China has been lifted. The UWS requires high costs for infrastructure construction and maintenance. Governments alone cannot afford the investment created by the fast urbanization. External funding sources, such as the private sector and international capital, are thus allowed to participate to solve the problem of inadequate investment. Authorities have enacted more guidelines for commercial involvement. In 2004, the MOHURD issued “*Management for Concessions Franchise for the Public Utility Industry*”, in which the “build-operate-transfer (BOT)” operation franchise was introduced. Under a BOT concession, non-state entities receive a delegated management contract from the government, invest in and run the water companies for a specified time and transfer the entire project, including intellectual property back to the government when it ends. These contracts give companies incentives to invest in and share risk in exchange for greater decision rights and more interests. This provides for competition to stimulate higher efficiency (Jiang & Zheng, 2014).

Since 2016, diversified investment patterns in the UWS have increased dramatically. The “*Guidelines on Further Encouraging and Guiding Private Capital to Enter the Urban Water Supply, Gas, Heating, Wastewater, and Garbage Treatment Sectors*” were enacted in 2016 (MOHURD, 2016), which highlighted “public-private partnership (PPP)” cooperation in the field of municipal utility projects. New forms of co-management and joint investment with the public and private sectors have been advocated. However, governments still set standards for services and participate in the investment and supervision for major project matters.

Currently, the BOT concession, or PPP authorized by the governments, has been the leading operating model in the UWS of China. Notable achievements have been made in the market-oriented reforms. However, the main body in the UWS has still been state-owned water companies (Du et al., 2023). According to the Urban Water Supply Statistical Yearbook (CUWA, 2019), among the 627 large and medium-sized water companies surveyed across the cities in China, state-owned enterprises account for 50.96% of the total, and public-private joint ventures (PPPs) account for 38.69%. Private enterprises account for only 6.05%, and Sino-foreign joint ventures account for 4.30%. The UWS is still lacking competition and diversified investment.

### **1.2.3(b) Water Tariff**

The water tariff constitutes the main revenue source for the UWSUs and functions as an essential micro-tool for balancing demand and supply in the UWS. According to the “*Regulations on Urban Water Supply*” (MOHURD, 1994), urban water tariffs in China are predominantly set by the local municipal governments following the state acts and are supposed to cover the operation expenses, authorized return rate (8%-10%), and taxes. By a separate procedure, the municipal governments also set the wastewater fees for the WWTPs. The UWSUs are entrusted with the

collection of water tariffs together with the wastewater treatment fees from end-users and transfer the fees to WWTPs.

Water tariffs in China have been ascending gradually over the past decades but still remain comparatively lower than those in other countries. Based on “*Statistics on the Water Tariff of Urban Residents in China in 2020*” (DRCMWR, 2021), the water tariff from 36 major cities ranged from CNY 2.34~5.23/m<sup>3</sup> (\$0.32~0.73/m<sup>3</sup>), with an average of CNY 3.44/m<sup>3</sup> (\$0.47/m<sup>3</sup>), whereas the wastewater treatment fee was about CNY 1.1/m<sup>3</sup> (\$0.15/m<sup>3</sup>). The ratio of the water tariff to the disposable income per capita varied from 0.21% to 0.67% in China. As stated in the “*Economic Evaluation of Water Conservancy Construction Projects*” (MWR, 2013), this ratio should be between 1.5% and 3%. Below this threshold, residents are not incentivized to conserve water. As stated by the “*Report of Market Prospects and Investment Analysis on Tap Water Production and Supply Industry in China*” (IRI, 2020), the ratio of the water tariff to the disposable income per capita of urban residents in China is far below the international average range of 2.5%-3%. In addition, the water tariff in China is only 16% of the world average, while the wastewater treatment fee is 14% of the world average. Thus, the scarcity and intrinsic value of water are not adequately reflected.

Furthermore, water tariffs are set primarily on the basis of the “cost-plus regulated profit” in China, which is similar with the “rate-of-return” principal in many other countries. The “regulated profit” may result in the “A-J effect” in which the sector inevitably cause overcapitalization risk and a substantial lack of efficiency (Averch & Johnson, 1962). Water companies are allowed to be compensated by fiscal subsidy if the “reported cost” exceeds the water tariff. The water tariff setting prevents

water operators from obtaining excess profits but does not provide enough incentives to improve efficiency.

#### **1.2.4 Efficiency Evaluation Methods for the Urban Water Sector**

“Efficiency” which is originated from Koopmans (1951) and Debreu (1951), is frequently used to denote the most optimal utilization of all production factors in an operation process. It commonly indicates a comparative analysis of the observations and optimal values of their inputs or outputs, or a combination of the two (Fried et al., 1993). To quantify efficiency, two mainstream alternative methods are available, namely, parametric and nonparametric methods. The primary difference between these methods is that parametric approaches need to specify a priori function with parameters for production technology, while nonparametric approaches need to define certain properties that the observations in the production possibility set are presumed to satisfy (e.g., convexity, homogeneous). For studies on the efficiency analysis related to the UWS, nonparametric methods (54.4%) are preponderant over parametric methods (39.1%), and only 6.5% of the studies use both methods (Cetrulo et al., 2019).

Among the non-parametric approaches, data envelopment Analysis (DEA), which was the pioneer work of Charnes et al. in 1978, a leading method for efficiency benchmarking in the water sector (Ananda, 2019; Cetrulo et al., 2019; De Witte & Marques, 2010; Goh & See, 2021). DEA applies a linear programming technique to construct a piecewise linear frontier for the decision-making units (DMUs). The data are subsequently “enveloped” by determining whether or not each observed point is within the interior of the frontier, rather than by the graph of a priori function with estimated parameters (Debreu, 1951). The input and output data used in DEA are more well-defined than the price data used in parametric methods (Cooper et al., 2007)..

Since Byrnes et al. (1986), DEA models in the vast quantity of worldwide literature for UWS have been developed from basic standard DEA (Byrnes et al., 2010; Liu et al., 2013; Wang et al., 2018) to modified conventional DEA, such as the directional distance function (DDF) (Goh & See, 2023; Li et al. 2021; Ma et al., 2016; Zhou et al., 2019), double-bootstrap DEA<sup>3</sup> (Guerrini et al., 2018; Molinos-Senante et al., 2018; See, 2015), slack-based measures (SBM) (Bronner et al., 2022; Deng et al., 2016; Liu et al., 2020), common set weights (CSW)-DEA (Sala-Garrido et al., 2023a), dynamic DEA (Li et al., 2021; Yang et al. 2021), metafrontier DEA (Molinos-Senante et al., 2015, 2017; Suárez-Varela et al., 2017; Sala-Garrido et al., 2011; Du et al., 2023), to static network DEA (Gidion et al., 2019; Hu et al., 2018; lo Storto, 2018, 2020; Wang et al., 2021; Zhou et al., 2018).

Referring to Figure 1.6, when analysing the UWS, which is a multi-product system, decomposing the internal operation and revealing the inefficiency of subdivisions in the system necessitates the adoption of network data envelopment analysis (NDEA) (firstly proposed by Färe & Grosskopf, 2000). A large number of the existing studies adopted the conventional DEA models regarding the water service as a “black box” in which inputs are transformed to outputs in all one step. This would cause the system’s efficiency to be overestimated or biased (Kao, 2014). Although few studies have applied static NDEA for water industry efficiency without dynamic consideration. Accordingly, to complement the existing DEA approaches, this study seeks to develop novel dynamic multiactivity NDEA models and evaluate the operational efficiency of the UWS comprehensively and precisely.

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<sup>3</sup> Efron (1992) proposed the bootstrapping approach, which is essentially a statistical resampling methodology to produce robustness conclusions. Simar and Wilson (2007) combined double bootstrapping algorithm within the framework of the DEA, which would yield a set of bias-corrected estimates for all chosen explanatory variables.

### **1.3 Problem Statement**

Due to the water scarcity and a surge in urban water demand, the UWSUs in China are under increasing pressure as they have to satisfy increasing water needs against urban growth. Although China has made remarkable reform progress, the UWS is still essentially monopolized by state-owned water companies, with a lack of market competition. The large capital costs create barriers to new entrants. The inexpensive access to water and the “A-J” effect from the water tariff setting result in an absence of incentives for efficiency. UWSUs has been in a status of break-even or losses for a long time. Operation costs that exceed water tariffs are allowed to be compensated for the UWSUs by fiscal subsidies. Moreover, the water leakage rate of UWSUs has been around 15% in China, which lags behind the rate of 8% in developed countries (Chen et al., 2022). Thus, improving the operational efficiency of UWSUs is urgent.

The existing research in China has focused mainly on efficiency in water use and wastewater mitigation (Bian et al., 2014; Yang et al., 2021; Wang et al., 2021; Xu et al., 2019; Yao et al., 2018; Zhao et al., 2017; Zhou et al., 2019), economic growth (Chen et al., 2019; Yang et al., 2021), or the influencing factors (Liang et al., 2021; Song et al., 2018) at province-level. No prior studies have investigated water supply efficiency based on micro-operational data of UWSUs in China. Macro-performance depends on micro-performance (Fried et al., 1993). To help the weak UWSUs catch up with the outperforming ones, the firm-level efficiency examination is required.

Numerous studies from other countries have provided valuable reference resources on efficiency analysis of water utilities pertaining to ownership, regulations, economy of scales, service quality, influence factors. (e.g., Cetrulo et al., 2019; Goh & See, 2021; Worthington, 2014 for a corresponding overview of the literature).

However, most of them treat water services as a “black box” and measure a system’s efficiency. Because the UWSUs provide multiproduct services (refer to Figure 1.8), breaking down the internal operation into components can identify the inefficiency source in specific subprocess. The efficiency improvement from each subprocess contributes to the overall efficiency of an UWSU. Thus, the NDEA is required.

Limited studies have decomposed and examined the efficiency for the internal operation of water utilities based on static NDEA (Norbaizura et al., 2015, 2018; Gidion et al., 2019; Io Storto, 2018, 2020). They treated the water services as an instantaneous conversion of the input flow into the output flow, thereby ignoring the consecutive impact of fixed assets in time dimensions. Ignoring the continuity feature of a capital-intensive industry may result in biased efficiency (Färe & Grosskopf, 1996). Thus, considering the capital-intensive feature is needed to assess the efficiency of the UWSUs precisely. No prior studies conducted the efficiency analysis for UWSUs under a dynamic measurement. *All these trigger to assess accurately how well the UWSUs perform in China by the dynamic NDEA model.*

Second, from industry-level aspect, the UWSI underpins the livelihood and socio-economic development for a whole city. China is characterized by vast territory and uneven distribution of water resources (as refer to Figure 1.3 and 1.5). The water resources in Chinese cities tend to vary significantly, which affect the availability and efficiency of water supply (Carvalho & Marques, 2011; Chen et al., 2022; Yang et al., 2021). Water suppliers that are located in cities with more rivers or rainfall are deemed to incur lower operation expenses, but their efficiency may not be necessarily higher without advanced technology. The arid climate conditions with low precipitation hinder the development of the water provision in certain cities, but the water suppliers

in those cities may not be the worst performer if possessing better technology. There is no one-size-fits-all solution to improving the efficiency of the UWSI for a country as large as China. Cities need to search their own suitable strategies for strengthening the water supply services based on their heterogeneities in water resources.

Although heterogeneity is an issue worthy of consideration, most existing DEA studies overlooked it and measure efficiency under the assumption of a shared technology frontier. This may distort the efficiency and impede cross-comparison for observations with heterogeneity (Hayami & Ruttan, 1970). Metafrontier DEA is a well-established approach to relax the constraint of heterogeneity and conduct the efficiency comparison (Battese et al., 2004). Few conventional DEA studies adopted the metafrontier technique for efficiency evaluation based on the heterogeneities of ownership or business (Molinos-Senante et al., 2015, 2017; Suárez-Varela et al., 2017; De Witte & Marques, 2009; Sala-Garrido et al., 2023). Metafrontier DEA applications for UWSI in China are even rare (i.e., Chen et al., 2022; Du et al., 2023; Li et al., 2021). No prior studies have combined the metafrontier approach with NDEA in efficiency analysis for the UWSI in cities at industry-level. *Thus, this study aims to adopt the metafrontier NDEA to analyse the performance and technology gap of the UWSI in Chinese cities taking into account the heterogeneity of water resources.*

Third, owing to severe water pollution in China, there has been an urgency for a greater efficiency in alleviating wastewater pollution and increasing the water reuse besides the clean water supply (Wu et al., 2019; Yang et al., 2021). As shown in Figure 1.6, wastewater discharged with chemical pollutants would deteriorate the quality of the water, while the recycled wastewater has been recognized as a great alternate with water resource (Voulvoulis, 2018; Tsani et al., 2020). The reused wastewater rate is

only about 28% in China (MOHURD, 2023). To reduce the burden on the environment and support the target of SDG6, integrating water pollutants and reused water into the efficiency evaluation framework of UWS is imperative.

Despite the great interest in efficiency analysis for wastewater mitigation in China (Bian et al., 2014; Ding et al., 2019; Feng et al., 2019; Wu et al., 2019; Hu et al., 2018; Xu et al., 2019; Yang, 2021; Zhou et al., 2018; Jiang et al., 2020) and a large number of the studies from other countries focused on the performance of UWSUs or the WWTPs separately, no similar studies have decomposed the UWS and conducted the performance analysis for the whole industry chain. The reliable services from both the UWSUs and WWTPs constitute a well-run UWS. No studies have investigated the full range of water services of the UWS, unifying water production, water distribution, wastewater treatment, and wastewater recycling, considering wastewater pollutants and water reuse simultaneously. *The third problem is to establish a suitable NDEA to analyse both the global and substage efficiencies of the UWS in China systematically.*

#### **1.4 Research Questions**

As discussed above, the foremost research question in this study is “How does the UWS perform in China?”. The following sub-questions will be addressed:

- i) RQ1: What is the operational efficiency of the UWSUs in China? Which substages contribute most to inefficiencies?
- ii) RQ2: a) What is the relative performance of the UWSI across different groups of Chinese cities? b) What technological gaps exist between these groups? c) What strategies can be proposed to enhance UWSI efficiency within each group?

- iii) RQ3: a) What is the overall efficiency of the holistic UWS in Chinese cities? b) “Which substages contribute most significantly to system inefficiency? c) What measures can be implemented to improve both system and substage efficiencies?

## **1.5 Research Objectives**

The objective of this study is to evaluate the operational efficiency for the UWS at firm-level and city-level in China. On the basis of the general objective and the questions addressed, the corresponding sub-objectives are as follows:

- i) RO1: To accurately assess the overall and substage efficiencies for the UWSUs at firm-level in China.
- ii) RO2: To analysis the efficiency and the technology gap for the UWSI in different group of Chinese cities at industry-level.
- iii) RO3: To investigate the system and substage efficiencies of the holistic UWS in China at sector-level.

## **1.6 Scope of the Study**

As this study aims to address the three abovementioned research problems, three empirical analyses will be conducted in sequence:

To analysis the performance of the UWSUs, an efficiency analysis of 246 UWSUs in China was conducted using a dynamic NDEA method in 2016-2018.

To investigate the performance of the UWSI and technology gap analysis at industry-level, the focus was on three groups of 159 cities across China in 2013-2018 based on a novel union NDEA approach. The cities were grouped based on their water resources per capita.

To explore the performance of the holistic UWS, an efficiency evaluation was conducted for both water supply and wastewater treatment operations in 56 cities across China in 2013-2017 based on a mixed NDEA model.

### **1.7 Significance of the Study**

This research provides not only novel modelling for efficiency assessment and performance-related insights into the UWS in China but also provides a solid basis for the formulation of water governance to address the urban water crisis.

This study conducts a comprehensive technical efficiency analysis of China's urban water sector at multiple levels. At the firm level, it introduces a novel dynamic NDEA model to evaluate the performance of the UWSUs and identify managerial inefficiencies. At the industry level, it proposes an integrated approach combining network DEA and metafrontier techniques to account for heterogeneity in water resource endowments, providing policy implications based on inter-city technology gaps. At the sector level, the study establishes a multi-dimensional framework encompassing water supply, wastewater treatment, and water reuse, offering novel practical insights to enhance the operational efficiency of the entire UWS.

A comprehensive analysis of the performance of the UWS value chain in China is conducted, along with an in-depth exploration of inefficiency sources. Beyond methodological innovation, the study offers valuable managerial insights aimed at improving system-wide water services and assists in the design of specific policies across different Chinese cities in China.

## 1.8 Definition of Key Terms

The following definitions are provided for the terms used in this study. The DEA concepts and model variables are further defined in literature review (Chapter 2) and the methodology (Chapter 3).

Table 1.1 Definition of key terms

Terms	Definition
Urbanization rate	Refers to urban population divided by national population (China Statistical Yearbook).
Water resource per capita	Defined as total volume of surface water and groundwater (measured as the summation of run-off for surface water and recharge of groundwater from local precipitation) divided by population of the national or city (China Statistical Yearbook).
Urban water supply utilities	The urban water supply utilities are normally in charge of services like clean water production (raw water extraction and treatments) and water distribution. They extract raw water from water resources such as rivers, lakes, dams, or groundwater aquifers and transmit it to the water plants. In the water plants, the raw water is disinfected and purified to meet the potable water criteria and then distributed to customers (industries, households, municipal services, etc.) (González-Gómez & García-Rubio, 2008; Wang et al., 2017).
Urban water supply industry	This system integrate operational management of the whole water supply system including water resources intake, water treatment and water distribution (Fu et al., 2008).
Urban water sector	The “urban water sector (UWS)” refers to a service industry that is responsible for providing services from water utilities to end-users, including raw water intake, water treatments, water distribution, sewerage drainage, wastewater treatments, water recycling, with related supporting devices. The primary function of the UWS is the urban water services delivery based on network, not the construction or finance (Fu et al., 2008; Wang et al., 2017).
Efficiency	The term “efficiency” of a production unit primarily denotes a comparison between the observed DMU and optimal values of its inputs and outputs. This comparison is expressed as the ratio of the maximum outputs that can be obtained from the given inputs, the ratio of the minimum inputs that are necessary to produce the given output, or a combination of the two. (Friedet al., 1993).
Wastewater recycling and reuse	With more targeted treatment than the discharged treated wastewater, a portion of the treated wastewater can be recycled by diminishing more pollutants and contaminants in sewage effluents and delivered to its recipients (industrial use, landscaping, wetland parks, irrigation, etc.) through the recycled water pipelines independent from the tap water distribution pipelines (Wang et al., 2017).
DEA	Data Envelopment Analysis (DEA) is a nonparametric approach that applies a linear programming technique to construct a piecewise linear frontier for the decision-making units (Charnes et al., 1978).
Network DEA	It is the term describing the DEA approach used to evaluate the performance of systems with a network structure. The “internal production” of the “black box” can be investigated in both static and dynamic status using network DEA models. The network structures include series structure, parallel structure, or a combination of these. The fundamental concept of the network DEA is to “connect” divisions, thereby establishing a unified modelling framework for multi-product system with multi-stage links or multiperiod production (Färe & Grosskopf, 2000).