Centralized water reuse system with multiple applications in urban areas: lessons from China's experience

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Abstract: In the context of rapid urbanization and water shortage, many cities of the world, especially megacities in rapidly developing zones, have urgent needs in improving their sustainable water management without compromising the local socioeconomic development. Water reuse has been increasingly recognized as a sustainable water management strategy. The results of this paper have shown that the development of water reuse in China is found to have positive correlations to local water resource availability and GDP levels, and the water reuse rate in some megacities has already reached 35-60%. Centralized water reuse systems have widely gained favor. Thus, a centralized water reuse framework with three utilization patterns is proposed. Particularly, a multiple-utilization model that applies a hierarchical use structure is found to be viable for meeting multiple water quality requirements. Other patterns address environmental and cascading ways in maximizing the value of reclaimed water use. A case study in a Chinese megacity, Tianjin, is demonstrated where a large-scale centralized water reuse project with a multiple barrier treatment approach and a hierarchical distribution and use structure has contributed to water reuse development in a safe, reliable and economical manner. This paper can be beneficial to water authorities and practitioners for long-term urban water management in other rapidly developing cities and regions that have encountered similar water-related problems.

Key words: Water reuse; urban areas; megacities; centralized water reuse systems; urban water management

1. Introduction

Population growth, climate change, industrialization, social and economic growth,

along with elevated living standards, have generated ever-increasing demands for water resources around the globe (Jiménez- Cisneros, 2014; UNWWAP, 2015). In 2014, 3.9 billion people, or 54% of the global population, lived in cities. With a continuing social and economic development trend, two-thirds of the global population will be urban dwellers by 2050 when global water demand is projected to increase by 55% (WRG, 2009; UNWWAP, 2015). Notably, the number of megacities has nearly tripled since 1990 and about one in eight urban dwellers live in megacities. By 2030, 41 urban agglomerations are projected to exist, serving at least 10 million inhabitants each (UNDESA, 2014). Hence, water-related challenges including water scarcity and water quality deterioration issues will be increasingly concentrated in urban areas, particularly in the lower-middle income countries (e.g. Asia and Africa) where the pace of urbanization is fastest and the local governments have limited capacity to deal with the rising water supply and sanitation challenges (Cobbinah et al., 2015; UNDESA, 2015; Li et al., 2016). As a major emerging economy and a developing country with the largest population base of the world, China also faces a myriad of urban water challenges (UNESCO, 2015; Hsu et al., 2014). Most of urban cities in the country are densely populated and 7 out of 34 megacities¹ in the world are located in mainland China (NBSC, 2016). Highly agglomerated urban population requires reliable, efficient and cost-effective urban water management systems (WWF, 2008; UNESCO, 2015). Water reuse has been increasingly considered as a promising alternative water resource for sustainable water supply and management practices (Garcia and Pargament, 2015). It has proven useful in increasing the reliability of long-term water supplies in many water-scarce areas of China (Hu et al., 2015). Thus, the construction and upgradation of wastewater treatment and reuse facilities have come into a high-speed development period across the country (Chang and Ma, 2012; Zheng et al., 2015).

In China, there is a population trend of gathering in megacities, very large cities and

¹Urban areas with a population of more than 10 million

big cities². In 2014, China's total population reached to 1.4 billion and 56% of the people are urban dwellers (NBSC, 2016). According to the National New Urbanization Plan (2014-2020), China's urbanization level in 2020 will reach to 60%, and a population of about 100 million rural residents will be new urban residents (Gu et al., 2015). The continuing urbanization and industrialization requires significant product, material and natural resources input and can lead to considerable waste streams and emissions. Meanwhile, China's Gross Domestic Product (GDP) has increased steadily, with an average growth rate of 6.9% and a figure of 68,000 billion Yuan³ (\$10,200 billion US dollars) in 2015 (Lyu et al., 2015; NBSC, 2016). Migration from rural to urban areas has resulted in high incomes and thus a substantial increase in household consumption and more resource intensive living standards (Feng et al., 2014). Hence, there has been increasing awareness on China's environmental capacity, water and food security, and resource shift and management in urban areas (Chen et al., 2015; Sun et al., 2016). Noticeably, water-related issues are considered as one of the most serious threats to the sustainable development of society (UNESCO, 2015). Approximately two thirds of China's 661 cities encountered water shortage problems and among which, over 100 cities faced acute shortages and megacities, though pioneers of urban development, have various water stress and eco-environmental problems (Lieberthal, 2011). In the long-term, water supply and demand pressure is a serious concern for China's urban population (Brubaker, 2015).

The fast-growing urban societies increased the quantity of water consumption and wastewater discharge while accelerating the development of wastewater treatment and reuse in both cities and counties of China (Hu et al., 2016). Consequently, the amount

²According to the State Council of China (2014 No.51), the administrative divisions in China are generally classified into cities, counties, townships, towns and villages. Cities are further grouped by size, including megacities (10 million), very large cities (5-10 million), big cities I (3-5 million), big cities II (1-3 million), medium-sized cities (0.5-1 million), and small cities and towns (0.5 million or less) (Gu et al., 2015). Individuals, who live in cities, counties or areas with over 50% of residents are non-agricultural population, are generally considered as urban residents. By the end of 2014, China has 653 designated cities (including 361 county-level cities), 1596 counties, and 20401 townships (MOHURC, 2015).

³1 Yuan (RMB) roughly equals to 0.15 US dollar or 0.13 Euro.

of total wastewater discharge had experienced steady growth over the years with an annual increase rate of 4%, which reached $7.2 \times 10^{10} \text{ m}^3$ in 2014. The increase was largely accounted for by domestic effluent discharge (MOEP, 2014). At the same time, with a great deal of investment by the government, wastewater treatment facilities were extended dramatically in both cities and counties of China, where the overall treatment rate achieved a high level of over 82% by the end of 2014 (Table 1).

Table 1 Wastewater treatment in China*

Year	Number of WWTP**		Treatment capacity of WWTP ($\times 10^8 \text{ m}^3/\text{d}$)		Wastewater treatment rate (%)		
	In cities	In counties	In cities	In counties	In cities	In counties	National
2010	1444	1052	1.04	0.20	82	60	45
2011	1588	1303	1.13	0.24	84	70	53
2012	1670	1416	1.17	0.26	87	75	61
2013	1736	1504	1.25	0.27	89	78	66
2014	1808	1554	1.31	0.29	90	82	69

*Data sourced from MOEP (2014); MOHURC (2015).

**WWTP: wastewater treatment plant, a facility to treat and purify the wastewater that is collected through wastewater collection systems (GB18918-2002 by MOEP, 2002).

Nevertheless, at a national level, China's wastewater treatment development is uneven. Cities have experienced much greater development rates than counties, not to mention small-scale townships and villages (Liu and Persson, 2013; MOEP, 2014). At a global level, an indicator of wastewater treatment was introduced by the 2014 Environmental Performance Index (EPI) for comparison which measures the amount of collected wastewater that a country treats before releasing it back into the environment. As a result, China ranked 67th for its wastewater treatment, which lies behind other emerging economics, such as Mexico (49th), South Africa (56th) and Russia (62nd). Besides, the 2014 EPI indicates a low wastewater network connection rate of 47% in China, causing low utilization rates in some newly built wastewater treatment plants (WWTPs) (Hsu et al., 2014). Consequently, approaches to sustainable water management with an emphasis on advanced wastewater treatment, water reuse and resource recovery have received increasing attention.

As for wastewater management, there is always a wide discussion about optimized system models and their implications for innovative management (Padowski and Jawitz, 2013; McDonald et al., 2014). The provision of centralized water and wastewater services for urban areas has been common practice for over 100 years (Sapkota et al., 2015). The centralized wastewater systems involve the collection and transport of wastewater using an extensive network of pumps and piping, to a central location for subsequent treatment, discharge and/or reuse (Asano et al., 2007). However, some studies argue that centralized systems are expensive solutions that are normally associated with long-distance transport, large-scale distribution network, design complexity, high investment cost, high operational and maintenance requirements, lack of flexibility, and potential for catastrophic failure (Afferden et al., 2015; Chanan et al., 2009; Wang et al., 2008). Therefore, decentralized water treatment and reuse systems have been receiving much attention (Piratla and Goverdhanam, 2015; Sitzenfrei et al., 2013). The decentralized models address the collection, treatment, disposal and/or reclamation of wastewater at or near its point of generation (MOH, 2010). The decentralized systems have advantages in terms of flexibility, application in small, suburban and/or rural communities, viability in challenging topographical conditions, economies of scale, etc. Since decentralized systems can be managed as stand-alone facilities, clusters or semi-centralized or be integrated with centralized treatment systems, they complement rather than compete with centralized approaches (Wilderer, and Schreff, 2000; Afferden et al., 2015).

In China, centralized wastewater treatment and reuse systems have been the preferred models serving most cities and counties (Chu et al., 2004; MOHURC, 2015). The centralized systems have distinct advantages for densely settled population in terms of safety, reliability, stability, and economic feasibility (ISO, 2016). Particularly, for water reuse applications with high exposure risks (potential or direct contact with reclaimed water), safety and reliability of reclaimed water quality are paramount for public health protection (Hu et al., 2011). Therefore, centralized models are now

regarded as an effective component of urban water resources management in China (Cheng et al., 2009; MOHURC, 2015). The aim of this study is to provide an overview of water reuse and its development potentials in China, with an emphasis on centralized water reuse systems in urban areas. To facilitate the optimal design and management of centralized water reuse systems, a systematic framework with different reclaimed water usage patterns was proposed. A case study in Tianjin city was conducted afterwards to demonstrate the effectiveness of centralized water reuse systems for multiple applications with a hierarchical structure (each level of hierarchy is associated with specified water quality requirements of the application). The paper concludes with a highlight of the water reuse significance and a summary of sustainable water reuse via centralized management approaches.

2. Analysis of current status and development potentials of water reuse in China

Water reuse is among the fastest growing utility sectors in China and reclaimed water is being widely applied to satisfy a significant proportion of water demands (Chang et al., 2013). In 2013, there were 571 water reclamation plants (WRP) nationwide equipped to further treat secondary effluents for planned reuse and the reclaimed water pipeline length is 8300 km. In most cases, water reclamation facilities were added either within or adjacent to a conventional existing WWTP and then the upgraded plant was renamed as a WRP. In newly developed areas where WWTP do not yet exist, integrated planning, design, and construction of centralized wastewater treatment and reclamation facilities offer advantages in both water resource management and cost savings. The overall water reuse rate in urban cities of China was about 12% (MWR, 2013). The exploitation and development of water reuse can be driven by a variety of issues, including water shortage, technological and economic development, environmental protection, public awareness, effective regulation, interagency cooperation, water tariff, etc. These factors can interrelate and complement one another (GE Power & Water, 2011; Chen et al., 2014; Garcia-Cuerva

et al., 2016). However, there is presently a lack of research that identifies the most relevant factors in the evaluation of water reuse (Kandulu et al., 2014). It is widely recognized that water reuse is mainly driven by regional water scarcity concerns (Garcia and Pargament, 2015). Although the environmental, social and political influences are also important incentives, they are difficult to calculate and quantify directly (Miller, 2006). Hence, for simplicity, this study evaluates the impacts of two prominent quantitative factors, namely water resource availability and economic status, on local water reuse practices in China (SCC, 2012; NBSC, 2015a). As can be seen from Figure 1, at the provincial level, the promotion of water reuse activities was strongly correlated with provincial water resource availability and regional GDP levels. Generally, provinces with low available water resource and high GDP levels are associated with larger scale of reclaimed water construction and utilization. Geographically, due to serious water shortage situations in northern regions, the water reuse rate is much higher in north and northeast China, followed by east and south China, but lower in central regions. In western regions, although drought and water deficit issues occur frequently, a low level of economic development has hindered the local water reuse progress to some extent (Chang et al., 2013).

Figure 1 Correlations of the scale of reclaimed water facilities (m^3 per capita per year) in urban areas with water resource quantity and GDP level in 31 provinces of mainland China in 2015 (data sourced from SCC, 2012; NBSC, 2015a).

Notes: (1) the size of the circle indicates the scale of reclaimed water facilities at each province; (2) Statistical data of 31 provinces are included, except Hong Kong, Macao and Taiwan; (3) Data regarding the scale of reclaimed water facilities in Shanghai and Tibet is insufficient, thus these two provinces are marked with empty circles; (4) the 31 provinces of China were divided into 7 regions based on geographical locations, North China: Beijing, Tianjin, Hebei, Shanxi, Neimenggu; Northeast China: Liaoning, Jilin and Heilongjiang; East China: Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong; Central China: Henan, Hubei and Hunan; South China: Guangdong, Guangxi, Hainan; Southwest China: Chongqing, Sichuan, Guizhou, Yunnan, Tibet; Northwest China: Shannxi, Gansu, Qinghai, Ningxia, Xinjiang.

Furthermore, as megacities are ideal models for assessing the urban eco-environment management and proposing recommendations for improvement (Zeng et al., 2016), water reuse figures in seven megacities of China are also analyzed. In megacities, the GDP levels and population density are significantly higher than in other cities, but the available water resource per capita is remarkably low (Figures 2 and 3). It is worth noting that the water availability in six of these megacities is below the world recognized scarcity threshold of 1700 m^3 per capita per year (Jiménez-Cisneros, 2014). Specifically, in northern megacities such as Beijing and Tianjin, severe water shortage is one of the biggest obstacles for sustainable development of the regional economy and reclaimed water has become an important alternative water resource. For instance, in Beijing, the water reuse rate reached 63% in 2014, which is significantly higher than the national average level. Besides, the annual reclaimed water consumption was highest among all megacities, which was $8.6 \times 10^8 \text{ m}^3$, accounting for 23% of the city's total water consumption (BMEPU, 2015).

Figure 2 Correlations of the scale of reclaimed water facilities (m^3 per capita per year) with available water resource and GDP level in megacities and national scale of mainland China in 2015 (data sourced from NBSC, 2015b; SBGP, 2015).

Notes: (1) the size of the circle indicates the scale of reclaimed water facilities at each megacity. (2) Data regarding the scale of reclaimed water facilities in Shanghai is insufficient, thus the city is marked with a small circle.

Comparatively, in southern regions, despite relatively abundant natural water resource, the high level of economy and population density, together with surface water contamination and water quality deterioration, contribute to the rapid development of water reuse projects in megacities. For example, the city of Shenzhen has the least land area among other megacities. Due to growing limitations on local freshwater exploitation and external water diversion, the current water reuse rate in Shenzhen has surged to 35% in 2013 and reclaimed water consumption is expected to reach up to $37 \times 10^5 \text{ m}^3$ per day by 2020 (Ding et al., 2014). In the future, there is still a great amount of space for further water reuse development in megacities.

Figure 3 Water reuse quantity and population density in megacities of mainland China in 2015 (data sourced from NBSC, 2015b; SBGP, 2015).

Notes: (1) the bars represent the water reuse quantity in megacities; (2) the blue dots indicate the population density in megacities.

With respect to water reuse applications, reclaimed water is mostly considered for non-potable purposes in urban areas at present, including scenic environment uses (ornamental and recreational purposes), industrial uses, agricultural irrigation, municipal miscellaneous uses and groundwater recharge (Figure 4). Among these end uses, scenic environment and industrial applications are the two largest applications for reclaimed water, which represent over 80% of the total reclaimed water consumption (Yi et al., 2011; Qu, 2013). Particularly, scenic environment uses of reclaimed water are mainly associated with urban river or lake flow supplementation, ecological restoration and recreational purposes. Taking Beijing as an example, the total water consumption for environmental and recreational uses was $5.7 \times 10^8 \text{ m}^3$ in 2012, of which the reclaimed water usage was as high as $3.7 \times 10^8 \text{ m}^3$. It was reported that over 70% of lakes and rivers in Beijing are supplemented with high quality reclaimed water (Chang and Ma, 2012; Fan et al., 2013). In addition, industrial uses of reclaimed water come in different ways, such as cooling water, process water and boiler feed water. On the one hand, the government has undertaken a series of

measures to encourage industries to use reclaimed water sourced from surrounding municipal WWTPs. On the other hand, internal water reuse within the industrial parks has been greatly improved (Zhou, 2015). Besides, for municipal miscellaneous uses, the applications such as toilet and urinal flushing, firefighting, car washing and landscape irrigation are often observed. Nevertheless, too little water is actually reclaimed compared to the design capacity of WRPs. In the planning stage, a WRP is normally designed for a high capacity of treatment, which leaves room for future possible expansion and upgrade. The low productivity of WRPs in China results mainly from the lack of reclaimed water sources, low reclaimed water consumption, low connection rates of distribution networks, relatively high treatment costs but low prices of reclaimed water, etc. (Tian and Qu, 2015). As shown in Figure 4 (the blue curve with dots), despite that the facility's capacity utilization rate (the ratio of actual output to the potential output) has been improved from 33% in 2009 to 56% in 2013, there is still significant room for development.

Figure 4 Water reuse quantity by different applications in urban areas of China (data adapted from Qu, 2013; MOHURC, 2015; Tian and Qu, 2015).

Notes: (1) the bars represent the water reuse quantity annually; (2) the bars in 2013 and 2020 represent the total and estimated water reuse quantity respectively; (3) the blue dots indicate

the reclaimed water production capacity.

To further expand the wastewater treatment and reuse, the Chinese Twelfth Five-Year Plan has clearly stated the national development targets by the end of 2015. The main targets for urban cities of China include: (1) to improve the overall water reuse rate to 15% nationwide; (2) to increase the quantity of reclaimed water production to 3.9×10^8 m³/d; (3) to increase an overall investment on water reuse planning and facility construction by 430 billion Yuan (\$64.5 billion US dollars) (SCC, 2012). Potentials of water reuse in China were also delineated. By 2020, the amount of reclaimed water used in China is predicted to increase to 2.2×10^{10} m³/year with the development and exploitation of existing and new applications, formulation of targeted and detailed water reuse guidelines, construction of supporting facilities (e.g. water transmission and distribution systems), implementation of incentives and policies on water reuse, etc. (Chu et al., 2015; Tian and Qu, 2015).

Figure 5 Proportion of centralized and decentralized wastewater treatment systems in urban areas of China in 2014 (data sourced from MOHURC, 2015).

Notably, as for wastewater treatment and reuse models, the proportion of centralized

wastewater treatment systems in both cities and counties of China is significantly higher than decentralized systems (Figure 5). Particularly, in megacities and large cities, the centralized treatment facility coverage is even higher. In Beijing, wastewater treatment by centralized systems in the downtown area reached 94% in 2010 (Chang and Ma, 2012). Due to the popularity of centralized wastewater treatment systems in urban areas of China, centralized reuse systems are widely implemented in urban areas (MOHURC, 2015). In comparison, there are only a few decentralized water reuse cases in Chinese cities. Some decentralized greywater reuse projects are observed in university campuses and institutes (e.g. Beijing Normal University and Chongqing University), however, most of Chinese decentralized cases are still in research and experimental stages (Chen et al., 2013; Liang et al., 2010).

3. Methods

A systematic framework for the design and evaluation of a centralized water reuse system was established. The framework with three specific utilization patterns is of great potential to be applied in urban areas of China and other high population density areas.

3.1 Development of a centralized water reuse framework

In a typical centralized water reuse system, water reclamation facilities are added either within or adjacent to a WWTP. According to Figure 6, a generic centralized water reuse framework consists of five components, namely reclaimed water sources, treatment, transmission and storage, distribution and monitoring. The storage system is either located before and/or after the distribution system based on specific hydraulic designs. Remarkably, water quality safety (e.g. minimum water quality requirements by multiple barrier approach) should be guaranteed through all system components (ISO, 2016). Depending on different water quantity needs and water quality requirements by end users, the framework of a centralized water reuse system ranges from simple to more complicated patterns which are discussed as follows.

Figure 6 Generic framework of a centralized water reuse system (modified from Hu et al., 2011).

3.1.1 Pattern I: Reclaimed water for single application

In a simple pattern, a centralized water reuse system serves only one type of water quality application (e.g. Intended use A in Figure 6). This is probably more likely on a smaller scale. This pattern is employed when 1) reclaimed water is being provided to a singer user, such as one industrial plant or an individual building, or 2) reclaimed water is being provided for a standard user or similar users, such as a community-based residential area where the quality of the reclaimed water needs to meet all of the requirements specified for water reuse applications.

3.1.2 Pattern II: Reclaimed water for multiple applications

Pattern II is being widely applied in large-scale centralized water reuse systems where the reclaimed water is for multiple users with different water quality requirements, such as in an industrial park with several industries (e.g. Beijing Yizhuang Industrial Development Zone, 30,000 m³/d of reclaimed water with 46 different users), or a region with miscellaneous industrial and domestic uses (e.g. Tianjin Economic-Technological Development Area). Compared to Pattern I, a reuse project with

multiple user agglomeration can effectively reduce the carbon footprint of land use, improve use efficiency and reduce pollution and waste (Shi et al., 2010). However, because of different user requirements, Pattern II is complex in system design and operation. One of the key issues in system design is to select an appropriate treatment technology or technology combinations. For safety considerations, minimum water quality requirements should be ensured for all applications. Basically, the main treatment unit needs to satisfy the water quantity and quality requirements of large and high priority users (e.g. Intended use A in Figure 6). Small users with higher quality requirements can connect to the main treatment unit, and either provide an additional treatment unit before distribution or at the point-of-use (e.g. Intended use B-D in Figure 6). Alternatively, small users with lower quality requirements can connect directly to the main treatment unit without further treatment (ISO, 2016). In addition, a cascading use of reclaimed water for different reuse applications (e.g. Intended uses D to E in Figure 6) is also a common practice. For instance, industrial uses are large consumers of reclaimed water in China (Figure 4), a cascading use can be broadly introduced to industrial parks where wastewater from an industrial process can be applied to subsequent reuse applications such as cleaning or ornamental landscape irrigation with/without additional specific water quality improvement (Song et al., 2014).

3.1.3 Pattern III: Combination of treatment, environmental storage and use

As environment uses represent a large user of reclaimed water in China (Figure 4), Pattern III gives emphasis on the environmental functions of reclaimed water (Figure 7). This pattern is mainly considered when water bodies such as natural/artificial wetlands, ponds, lakes, rivers and streams are located in close proximity to the treatment system and can be used as storage reservoirs and/or treatment units in which reclaimed water can undergo further purification (Hu et al., 2015). For instance, in Beijing, some water bodies such as wetlands and lakes in Olympic Forest Park and Summer Palace receive reclaimed water for scenic environmental uses, and are also used as storage reservoirs and treatment units. Specifically, for the Beijing Olympic

Park project, reclaimed water from the Qinghe WRP (60,000 m³/d) is processed by ultrafiltration, ozone oxidation and chlorine disinfection. Of the total water supply capacity, 3200 m³/d of reclaimed water is further treated by an eco-biological system including a constructed wetland and an indoor ecosystem (e.g. Environmental storage in Figure 7). A proportion of the water is subsequently polished by an aquatic plant pond and a hydraulic circulation system (e.g. Treatment unit 2 in Figure 7). The remaining water is supplied for road cleaning landscape irrigation, toilet flushing and other purposes where additional treatment might be needed (e.g. Treatment unit 3 in Figure 7). A detailed example is described by Sun et al. (2013). This project provides a good example for the establishment of modern environmental purification and maintenance system by urban water bodies.

Figure 7 Typical example of Pattern III for combined treatment, environmental storage and reuse (modified from Hu et al., 2011).

3.2 Potential applications of the framework in China

In many cities and counties, centralized water reuse systems have been developed to a degree that they are considered as an effective component of urban water management. They achieve safety, reliability, stability and economy in system design, construction and management, and also tend to be managed more easily and effectively with uniform regulations and control methods.

Particularly, municipal wastewater in China normally includes a mixture of domestic, industrial, commercial and institutional (e.g. hospital) discharges, which contains a variety of toxic and harmful chemicals or pathogens. Reclaimed water sources are mainly secondary effluents from municipal WWTPs. In many case, water reclamation facilities were added either within or adjacent to a conventional existing WWTP and then the upgraded plant was renamed as a WRP. In cases of land space limitations and/or hydraulic and geographical restrictions, independent WRPs are also reportedly built. The refractory contaminants in source water quality may negatively impact the subsequent reclaimed water treatment and reuse. Particularly, many conventional WWTPs are shown to be ineffective in removing a broad range of micropollutants (e.g., pharmaceuticals, personal care products, steroid hormones, industrial chemicals, pesticides and many other emerging compounds) (Luo et al., 2014). Although most of these are typically present at low concentrations, their potential for additive and synergistic adverse mixture effects to the aquatic environment raises considerable toxicological concerns (Knopp et al., 2016). Moreover, due to quality and quantity fluctuations in wastewater inflows, the reclaimed water quantity source is subject to hourly and seasonal variations. This brings difficulties in stable reclaimed water supply for downstream users (Hu et al., 2015).

Faced with these challenges, centralized water reuse systems are more likely to achieve safe and reliable performance than onsite decentralized systems owing to high consistency, robustness and resilience of system components. For instance, large-scale centralized treatment systems are mainly maintained by skillful process operators and managed by systematic approaches including risk assessment, multiple barrier treatment and continuous online water quality monitoring. To prevent water quality degradation during reclaimed water storage and/or distribution, adequate strategies such as periodic water sampling and analysis, cross-connection control, rechlorination and additional treatment (e.g. filtration) are also implemented. Moreover, preventative actions are taken for emergency issues, such as backup water resources, standby or

alternative equipment, emergency storage, and emergency response plan. In regard to economic feasibility, the cost-effectiveness of the reuse system is often assessed taking into account of capital and operational and maintenance costs. Specific tariffs and policies (e.g. government subsidies and price superiority) are set up to further promote water reuse (Chang et al., 2013; ISO, 2016).

Besides, in urban areas, on account of high population density, many water reuse applications are associated with high likelihood of human exposure to reclaimed water (potential or direct contact), such as toilet flushing, car washing, road cleaning, landscape irrigation, ornamental and recreational environment uses. Thus, at the end user site, acceptable variability in reclaimed water quality for multiple reuse purposes is much more restricted than direct discharge of treated wastewater to receiving waters (Esposito et al., 2005). Centralized water reuse systems are capable of satisfying users' multiple water quality requirements by a systematic framework together with different utilization patterns, which provide effective and efficient support for the various design and management of a system.

Comparatively, the reported decentralized water reuse cases in urban areas of China could not operate in good condition over a long period of time due to poor treatment performances, lack of professional training and maintenance, financial problems, etc. (Liang et al., 2010). There are over 300 and 475 decentralized facilities in Beijing and Kunming city, with a total capacity of $5 \times 10^5 \text{ m}^3/\text{d}$ and $1 \times 10^6 \text{ m}^3/\text{d}$ respectively (MWR, 2015). Based on a survey conducted in Beijing of over 30 decentralized systems by Wang et al. (2006), operational costs in commercial buildings were relatively high, followed by residential buildings and university campuses. Moreover, less than half of operational workers understood treatment facilities and kept daily logs, resulting in low operating efficiencies and potential failures of reclaimed water quality. There are also difficulties with respect to onsite sludge treatment and facility maintenance due to lack of sufficient management and surveillance (Wang et al., 2013). Nevertheless, both centralized and decentralized systems are indispensable water reuse models in

urban areas of China. Decentralized or cluster cases can complement centralized models by meeting water reuse needs in specific areas which face practical constraints (e.g. geographical conditions and long-distance transport).

4. The case study

To illustrate the effectiveness of the proposed centralized water reuse framework for multiple user applications, a case study in Tianjin City of China was conducted. This is an attempt to extend the research framework in urban areas, and provide a reference for development in megacities.

4.1 Description of study area

Tianjin is a rapidly growing megacity in both population and economy that is facing intensified water scarcity (Figures 1 and 2). In recent years, Tianjin has taken great efforts in promoting water reuse but the scale of WRP is lower than that of the other two megacities, Beijing and Shenzhen which encounter similar economic status and water shortage issues (NBSC, 2015a). Hence, water reuse has a great deal of potential in Tianjin and is expected to increase rapidly in the coming years. Its development progress can be taken as a typical case for other cities.

Figure 8 Water reclamation plants (WRP) in central areas of Tianjin and their service regions (modified from Li, 2012).

Tianjin initiated its first water reuse project, the Jizhuangzi WRP in 2002 with a design capacity of 70,000 m³/d, which was one of the earliest large-scale centralized water reuse projects in China. Due to the municipal plans of the city, Jizhuangzi WRP was moved and replaced by a new plant named Jingu WRP at the end of 2014. Currently, there are five centralized WRPs in central areas of Tianjin (Figure 8 and Table 3), three of them are in operation while the other two plants are under commissioning (Li et al., 2011; Li, 2012).

Table 2 Water reclamation plants (WRP) in central areas of Tianjin*

Plant name	Design capacity ($\times 10^4$ m ³ /d)	Actual reclaimed water supply ($\times 10^4$ m ³ /d)	Service area (km ²)	User types	Serviced population
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Jingu WRP	7	3.6	200	Industrial, residential and environmental users	60,000 households
Xianyang Road WRP	5	1.9	73	Industrial and residential users	—
East Suburb WRP	5	0.9	99	Industrial users	—
Beichen WRP	2	—	83	—	—
Zhangguizhuang WRP	6	—	—	Industrial users	—

*Data sourced from TWRC (2016).

4.2 Multiple-application centralized water reuse pattern

As Jingu WRP is the largest centralized water reuse system in Tianjin for multiple use applications (Table 2), it was selected as a representative case for discussion. As can be seen from Table 3, the secondary effluent (meeting Class I-A treated wastewater discharge standard, GB18918-2002) processed by the nearby Jingu WWTP is used as reclaimed water sources (Designed influent amount: 89,000 m³/d). Instead of directly sending the reclaimed water sources to membrane processes, a regulation tank was employed. This pre-treatment process was found to be effective to reduce shock-loading of the Ultrafiltration (UF) membrane modules and adjust the source water in case of water quantity and quality variations. Chlorine (5 mg/L) was also dosed in this step in order to control the excess growth of microorganisms and reduce membrane fouling.

Table 3 National wastewater discharge and water reuse standards in China

Parameter	Secondary treated effluent from Jingu WWTP directed to Jingu WRP	Urban miscellaneous use (Chinese GB/T 18920-2002)					Industrial use (Chinese GB/T 19923-2005)			Reclaimed water produced at Jingu WRP*
		Toilet flushing	Road cleaning	Municipal landscape	Car washing	Building	Cooling water		Boiler water	
							Once-through	Circulating		
pH	6-9	6-9	6-9	6-9	6-9	6-9	6-9	6.5-8.5	6.5-8.5	6-9
Color	≤ 30	30	30	30	30	30	30	–	30	≤ 30
Turbidity (NTU)	–	5	10	10	5	20	–	3	3	≤ 5
SS (mg/L)	≤ 10	–	–	–	–	–	30	–	–	≤ 10
TDS (mg/L)	≤ 1500	1500	1500	1000	1000	–	1000	1000	1000	≤ 1000
BOD ₅ (mg/L)	≤ 10	10	15	20	10	15	30	10	10	≤ 10
COD _{Cr} (mg/L)	≤ 50	–	–	–	–	–	–	50	60	≤ 60
NH ₃ -N (mg/L)	≤ 5 (8)	10	10	20	10	20	–	10	10	≤ 5 (8)
Anionic surfactant (mg/L)	≤ 0.5	1	1	1	0.5	1	–	0.5	0.5	≤ 0.5
Iron (mg/L)	≤ 0.3	0.3	–	–	0.3	–	–	0.3	0.3	≤ 0.3
Manganese (mg/L)	≤ 0.15	0.1	–	–	0.1	–	–	0.1	0.1	≤ 0.1
DO (mg/L)	–	≥ 1	≥ 1	≥ 1	≥ 1	≥ 1	–	–	–	≥ 1.5
TN (mg/L)	≤ 15	–	–	–	–	–	–	–	–	≤ 15
TP (mg/L)	≤ 0.5	–	–	–	–	–	–	1	1	≤ 0.5
Total coliform (cfu/L)	–	3	3	3	3	3	–	–	–	≤ 3
Faecal coliform (cfu/L)	≤ 10 ³	–	–	–	–	–	2000	2000	2000	–
Chlorine residual (mg/L)	–	≥ 1.0 after 30 min contact time, ≥ 0.2 at point of use					0.05	0.05	0.05	≥ 1.0 after 30 min contact time, ≥ 0.2 at point of use

Note: 1) values in parentheses indicate standard values for winter season; 2) GB/T 18920-2002: The reuse of urban recycling water – Water quality standard for urban miscellaneous water consumption; 3) GB/T 19923-2005: Water quality standard for industrial uses; 4) *Data sourced from TWRC (2016).

The major users of the reclaimed water include thermal power plants and residents in the surrounding Meijiang Residential Zone. The whole service area is over 200 km². Because of different water reuse quality requirements by residential and industrial applications, the plant adopts varied treatment processes and separate distribution pipelines for hierarchical water reuse. The utilization pattern is depicted in Figure 9. Specifically, after being processed by UF, the reclaimed water falls into two parts. One part of reclaimed water is subject to ozonation for decoloration followed by chlorination for disinfection, and then distributed for residential uses at over 60,000 households. The residential uses include toilet flushing, landscape irrigation, road cleaning, car washing and ornamental fountain and lakes. In some cases, additional treatment for specific water quality requirements might be needed at user sites. The other part of reclaimed water (Designed treatment amount: 42,000 m³/d) is sent to reverse osmosis (RO) process to further remove total dissolved solids (TDS), chloride, sulfate and other key water quality parameters due to high salinity issues of the reclaimed water source in Tianjin (Li, 2012). For cost savings, the RO permeate is blended with the treated effluent from the UF-Ozonation process with a mixture ratio of 2:3. The blended water is of high quality that is suitable for most industrial applications. Under the circumstances of poor water quality or high variations of reclaimed water inflows, the mixture ratio is adjusted and the blended water is also provided for residential uses occasionally. The produced reclaimed waters from two different treatment process chains comply with the Chinese water reuse standard GB/T 18920-2002 for urban miscellaneous water uses and GB/T 19923-2005 for industrial uses (Table 3). In 2015, the Jingu WRP has supplied 13×10⁶ m³ of reclaimed water for multiple users, of which industrial applications accounted for 45% of the total supply (TWRC, 2016).

Figure 9 Utilization pattern of the Jingu centralized water reuse system in Tianjin

The Jingu WRP achieves its positive development especially in the following aspects:

- 1) Semi-underground structure of the WRP and equipment. With optimized design and planning, the surface green space is increased largely and the facilities are operated in high efficiency.
- 2) Safety and reliability of centralized water reuse system. The plant employs multiple barrier treatment approach (i.e. UF-Ozonation-Chlorination and/or UF-RO) and emergency response plans (e.g., back-up sources and facilities and an adjustable mixture ratio of reclaimed water with different quality) for reclaimed water treatment. The optimized treatment technology combinations are stable in performance despite of high TDS concentrations (sometimes as high as 2,000 mg/L) in reclaimed water sources.
- 3) Hierarchical use of reclaimed water with multiple use applications. The comprehensive utilization model makes the maximum use of limited space and benefits different types of consumers in densely populated areas. The efficiency and economy are also enhanced under central management and surveillance systems.
- 4) Continuing increase of the reclaimed water production and supply. The increased reclaimed water consumption in urban areas can result in reduced drinking water demand for various applications (e.g., residential and industrial purposes). The

water tariff of reclaimed water for residential and industrial uses in Tianjin are presently charged at reasonable prices (Table 4). Although the use of reclaimed water in Tianjin is optional, the lower price of reclaimed water in contrast with drinking water price increases the willingness of reclaimed water consumption to a large extent. Furthermore, strong government support, well-established reclaimed water distribution networks, and wide public recognitions in Meijiang Residential Zone also contribute to a steady growth of reclaimed water consumption. The Jingu WRP not only maintains the functions of previous Jizhuangzi WRP but is also planned to serve a larger area of 273 km² with an expanded treatment capacity of 150,000 m³/d as well as the addition of extra pump stations and pipeline networks for more users.

Table 4 Water and reclaimed water price for different uses in Tianjin*

Category	Residential uses (Yuan RMB ^{**} /m ³)	Industrial uses (Yuan RMB/m ³)	Other uses (Yuan RMB/m ³)
Drinking water	4.9	7.9	22
Reclaimed water	2.2	2.5	4

*Data sourced from TWRC (2016).

**1 Yuan (RMB) roughly equals to 0.15 US dollar or 0.13 Euro.

4.3 Possible future improvements on centralized water reuse

Overall, the multiple-application pattern of reclaimed water in Tianjin is shown to be a viable strategy for urban water management. Based on actual municipal situations in Tianjin, centralized water reuse is taken as the main form for development, together with sporadic small-scale decentralized systems. Notably, the water reuse market can be further expanded when the following issues are addressed:

- 1) Low connection rates of reclaimed water distribution networks. By the end of 2015, the completed reclaimed water distribution pipeline length in central areas of Tianjin was 755 km. However, due to connection difficulties in real practice (e.g. bridges, intersections and dead ends during construction), the actual pipeline length with connected reclaimed water in use is only 295 km in early 2016. More efforts should be made to improve the pipeline connection rate, such as careful planning and

investigation, frequent communication with municipal, road, bridge and railway construction authorities, design adaptability and flexibility, etc.

2) Currently, most reclaimed water in Tianjin is supplied for residential and industrial uses. As an old industrialized city in north China, the water reuse market in Tianjin will likely to be expanded greatly if reclaimed water is accepted by more potential users in industrial parks. Besides, compared to Beijing where scenic environment uses reach 43% of total reclaimed water consumption, environment uses of reclaimed water in Tianjin only take a small amount (less than 2%). In addition to environmental flow augmentation, the purified reclaimed water through environmental storage can also be applied for agricultural and landscape irrigation, road cleaning, etc. (Pattern III). The relevant policies and incentives on these two types of applications should be put forward and water reuse still has tremendous room for expansion.

5. Future prospects of water reuse in urban areas

Water-related issue is one of the most serious threats to the sustainable development of society. Years of experience in water reuse in Chinese urban areas has shown that centralized systems are promising for sustainable water management, especially in densely populated cities. Meanwhile, decentralized or cluster facilities can raise flexibility and convenience in special circumstances. Particularly, for multiple users with different water quality requirements, centralized systems with hierarchical use structures can achieve high performance in reclaimed water treatment and supply (Pattern II). In regard to water reuse applications, industrial and environmental uses are potential large consumers and more large-scale schemes can be established in these fields. For environmental uses, apart from environmental flow augmentation, the combination of treatment, environmental storage and use can be addressed in centralized systems (Pattern III). Moreover, for industrial parks, multiple-application pattern and/or cascading water reuse pattern can be considered in centralized system design and management so as to maximize the reclaimed water utilization value and

efficiency. Besides, municipal miscellaneous uses of reclaimed water are also likely to be expanded significantly in urban areas. As most of municipal and residential uses are associated with high exposure of reclaimed water to humans, reclaimed water quality control and assurance are vital to ensure the safe and reliable operation of centralized water reuse systems.

With the identified significance and strengths of centralized water reuse systems, the tendency and prospect for long-term sustainable development in urban areas may include: improved water reclamation facility efficiency and productivity; advanced treatment technologies for enhanced pollutant removal; energy exploration, resource recovery and new reuse applications. The ultimate goal of the sustainable water management is to establish a safe and smart system for water reuse that maximizes water recycling and produces minimum discharge of treated wastewater in urban areas (Qu et al., 2014; Hu et al., 2015).

6. Conclusions

Continuous population growth, rapid urbanization, climate change, water scarcity and contamination have been occurring in most cities around the globe, bringing tremendous challenges to sustainability in urban planning and development. As a major emerging economy and the most populous country in the world, China has gained experiences in applying reclaimed water as an alternative water resources for various non-potable applications. In urban areas, the higher the GDP levels and the more intense the water scarcity, the larger the scale on which WRP is developed. Particularly, centralized water reuse systems have demonstrated their overwhelming advantages in densely populated areas (e.g. megacities) in terms of three different utilization patterns. In each pattern, concepts of safety, reliability, stability and economy are applied in system design, construction and management. To prove this, a case study in a Chinese megacity, Tianjin, was conducted where a multiple-application model has shown its effectiveness in a hierarchical treatment and

distribution design for meeting different user requirements. Therefore, in a sustainable urban water management, centralized models can play the leading role while decentralized facilities can raise flexibility and convenience in special circumstances. In the future, more research can be conducted in centralized water reuse systems towards advanced treatment, system productivity improvement, energy exploration, resource recovery and new reuse applications. The discussion in this study may facilitate urban planners and managers in identifying optimal ways to initiate water reuse projects and improve urban water sustainability in other rapidly developing cities and regions.

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