Water reuse system in Xi'an Municipality of China

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ABSTRACT

A water reuse system was formulated for the Xi'an International Metropolitan Urban Planning Project, with the aim of mitigating water stress in the central city of Xi'an, China in 2020. The main reuse purposes of the reclaimed water were agriculture, industry, municipal, ecological, and indoor uses. A wastewater reuse potential capacity of 427.2×10^6 m^3/yr was deduced by analyzing the water demand for the different reuse purposes. This reuse capacity makes significant contribution to increasing the total urban water supply capacity and mitigating the water shortage problems imposed by the process of urbanization. A supply scheme for the reclaimed water was configured, which comprised the reclaimed water sources, water supply service areas, and the main reuse purposes. As a result, a wastewater treatment plants (WWTPs)-centered reclaimed water supply system was formed, and the main reuse purposes of the 15 WWTPs and their service districts were defined. Through an economic analysis, the feasibility and benefits of the water reuse system were ascertained. Overall, this study provided the theoretical basis and implementation strategies for a system configuration of water reuse in Xi'an City and also contributed to solving the water-deficiency problems associated with the rapidly developing urban areas in China.

Key words | cost benefit, potential demand, supply scheme, water reuse, Xi'an

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INTRODUCTION

The distribution of water resources is severely uneven in China; whereas the south is rich in water resources, the North faces problem of water shortage, as Figure 1 shows (Tian 2012). The per capita water resource of the Haihe River, Yellow River, and Huaihe River basins, in the north of China, amounts to less than 500 m^3/yr (Wang & Jin 2006). Xi'an, the largest city in the northwest region of China, is located in the Yellow River basin and its per capita water resource totals only 234 m^3/yr. With rapid urbanization in China, Xi'an is planning to develop into a Grand International Metropolis, which will have an area of 850 km^2 and a population of 8,800,000 in the central city in 2020 (Xi'an Government 2009). As shown in Table 1, the total water demand in the year 2010 was 787.7×10^6 m^3/yr and is projected to increase to $1,200.9 \times 10^6$ and $1,368.0 \times 10^6$ m^3/yr in 2020 and 2030, respectively. By contrast, the available conventional water resources including surface water and groundwater tend to remain stable over the long term. Nonetheless, the water supply capacity increases slowly mainly because of the planned increasing use of reclaimed water and rainwater. The total capacities of water supply were 766.4×10^6 m^3/yr in 2010, and are 825.1×10^6 and 894.3×10^6 m^3/yr in 2020 and 2030, respectively (Water Supply Bureau of Xi'an 2010). Table 1 indicates that the present water shortage is 21.3×10^6 m^3/yr, which will amount to 375.8×10^6 and 473.7×10^6 m^3/yr in the years 2020 and 2030, respectively, accounting for 46 and 53% of total water supply.

On the condition that the available conventional water resource is shrinking, the demand for unconventional water resources including wastewater and rainwater is increasing. Table 1 shows that the planned reclaimed water supply capacity is 215.0×10^6 and 272.0×10^6 m^3/yr, which covers 26 and 30% of the total water supply in the years 2020 and 2030. However compared with the urban wastewater production, the rate of wastewater reuse is

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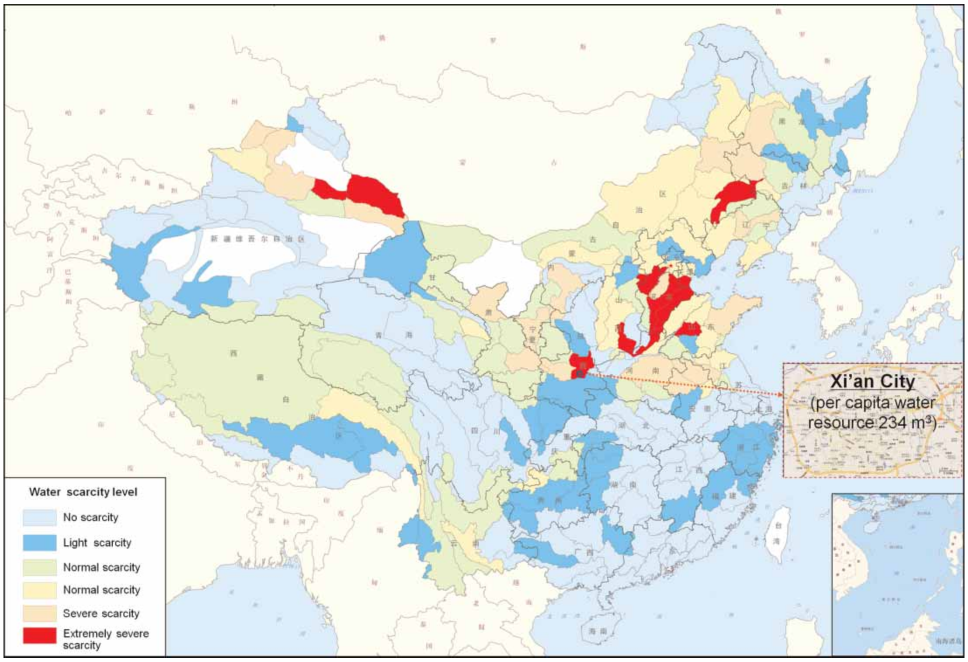

Figure 1 | Location of Xi'an city and water scarcity situation in China.

Table 1 | Water supply capacity and consumption demand in the central city of Xi'an (10^6 m^3/yr)

Available water resource	2010	2020	2030
Surface water	344.8	317.8	327.8
Underground water	243.8	236.5	236.5
Reclaimed water (planned)	52.6	215.0	272.0
Rainwater	0.2	5.8	8.0
Guest water	95.0	0	0
Inter-basin water transfer	30.0	50.0	50.0
Total water supply capacity	766.4	825.1	894.3
Water consumption demand	**2010**	**2020**	**2030**
Domestic use	172.1	280.6	346.5
Primary industry use	126.8	90.8	64.5
Secondary industry use	343.1	534.7	576.3
Tertiary industry use	104.2	199.7	262.1
Ecological use	41.5	95.1	118.6
Total use	787.7	1,200.9	1,368.0

quite low. The total amount of wastewater can be predicted as 812.0×10^6 and 948.4×10^6 m^3/yr in 2020 and 2030, assuming that the water use from domestic, secondary industry, and tertiary industry can be collected, 80% of which is discharged into the sewage system. As a result, the planned rate of wastewater reuse can only reach 26.5 and 28.7% in 2020 and 2030, respectively, which indicates that wastewater reuse can be promoted. Compared with the amount of water shortage of 375.8×10^6 m^3/yr in 2020, it tends to be feasible that the water deficiency will be largely alleviated in the event that the wastewater reuse rate reaches 72.8% and the reclaimed water supply amounts to 590.8×10^6 m^3/yr. Increasing the rate and the amount of wastewater reuse could not only solve the problem of urban water deficiency, but also reduce the dependence on long distance water transfers, and guarantee the urban water supply.

In this paper, a scheme for the utilization of unconventional water resources is developed, whereby reclaimed wastewater is used to mitigate the water deficit accompanying the development of the Grand Xi'an International Metropolitan Project in year 2020. Wastewater reuse potential is obtained from an analysis of the reuse purposes for the reclaimed water. The supply scheme of the reclaimed water is also formed on the base of distribution of the planned wastewater treatment plants (WWTPs) and their service areas, and the wastewater reclamation capacity.

METHODS

Basic consideration

As mentioned above, sustaining the development of the Grand Xi'an International Metropolis in 2020 requires maximizing the exploitation of all the available and reasonable water sources. The conventional water source is shrinking (Liu & Liu 2002), and rainwater use is constrained by the limited rainfall and seasonal variations in the northwest regions of China (Pei *et al.* 2010). Wastewater becomes a potentially important water source, which should be emphasized and the use of the reclaimed water must be maximized. Agriculture, industry, municipal, ecological, and indoor uses are the five main reuse purposes of reclaimed water worldwide (Asano *et al.* 2007), and which can be adopted for the Grand Xi'an International Metropolis in 2020. In this study, we assume that because of the low exposure to human beings the reclaimed water can reasonably supply most of the agriculture, industry, municipal, and ecological water demands. Indoor use of the reclaimed water is limited to toilet flushing, particularly in public buildings. Therefore, analysis of the wastewater reuse potential for every reuse purpose is very important and is implemented in the sections below.

Apart from wastewater reuse purposes and their reuse potential, the supply scheme for the reclaimed water is another important factor of the water reuse system. This should include the reclaimed water source, water supply service area, and main reuse purposes. In this study, we assume that the reclaimed water can reach the quantity demand for different reuse purposes, and can meet the related water quality standard for reuse requirements. In the supply scheme, the reclaimed water source will be covered from the centralized WWTPs, which are able to implement wastewater reuse in 2020. Water supply service areas will be arranged based on the governmental district divisions and their surrounding WWTPs. The main reuse purposes should be listed according to the function or developmental feature of the service area. Therefore, the supply scheme of the reclaimed water is configured below. An economic analysis will be employed to verify the feasibility and benefits of the newly formed supply scheme.

Data collection

To analyze the wastewater reuse potential capacity, we collected data from public city plan documents for different reuse purposes. For the agriculture use potential, the irrigation areas of various primary crops were investigated. To determine the industry use potential, data on the water use characteristics of the leading industrial enterprises were collected. For the municipal use, the total gardening and road washing areas were calculated. For the ecological uses, all the main water bodies in the central city were enumerated and the total surface area and volume were determined. Regarding indoor use, we used the per capita toilet flushing water use plus the population to estimate the indoor toilet flushing water consumption.

To configure the reclaimed water supply scheme, we collected data related to WWTPs, pipeline systems of the reclaimed water and districts distribution of the central city. For WWTPs, the capacities of wastewater collection, treatment, and reclamation were obtained. For pipeline systems, the main service areas, delivery capacities, and major users were identified. For distribution by district within the central city, the industry characteristics and developing orientation were investigated, which determined the specific reuse purpose of reclaimed water.

Based on the above-mentioned analyses, costs and benefits were evaluated to verify the feasibility of the planned reuse system from an economic perspective. The costs included the investments in WWTPs construction and operation, and supplying pipelines' construction. For the benefits, on the other hand, we compared the price of the reclaimed water with that of urban water, which was charged differently for agriculture, industry, municipal, ecological, and indoor uses, respectively. Therefore, the benefits were calculated based on the price difference and reclaimed water use quantity.

Analytical methods

Potential demands' calculation

Wastewater reuse potential capacity (P) was obtained by the summation of the agriculture reuse potential capacity (P_1), industry reuse potential capacity (P_2), municipal reuse potential capacity (P_3), ecological reuse potential capacity (P_4), and indoor reuse potential capacity (P_5).

For the calculation of P_1, irrigation area, crops species, and gross irrigation quota (GIQ) were considered, and the calculation model is shown in Equation (1)

$$P_1 = \sum_{i=1}^{n} q_i a_i \tag{1}$$

where i is a certain crop, q_i is the GIQ of crop i, and a_i is the irrigation area of crop i.

For P_2, the products output, water quota based on products, and the ratio of reclaimed water use were considered. The calculation model is shown in Equation (2):

$$P_2 = \sum_{i=1}^{n} p_i o_i r_i \tag{2}$$

where i is a certain industrial product, p_i is the water quota of product i, o_i is the output of product i, and r_i is the ratio of reclaimed water use for producing product i.

For P_3, public green areas, roads and squares, as well as the water quota for irrigation were considered, and calculated using Equation (3)

$$P_3 = sG \tag{3}$$

where s is the water quota of irrigation for greening and road washing, G is the scale of public green area and roads and squares.

The calculation of P_4 considered the surface areas and volumes of water bodies, evaporation and leakage rates, and the refresh period for closed water bodies. The calculation model is shown in Equation (4)

$$P_4 = \frac{365}{c} W + eV \tag{4}$$

where c is the decided refresh period for closed water bodies, W is the total volume of closed water bodies, e is the evaporation and leakage rate, and V is the total surface area of water bodies including rivers and lakes.

Finally, for P_5, the population size, toilet flushing water consumption, and the ratio of reclaimed water use for indoor toilet flushing were considered. The calculation model is shown in Equation (5)

$$P_5 = 365tNf \tag{5}$$

where t is the average water consumption of toilet flushing per person per day, N is the population, f is the predicted ratio of reclaimed water use for indoor toilet flushing.

Supply scheme configuration

On the basis of the wastewater reuse potential analysis, we proposed a WWTPs-centered method for the configuration of the reclaimed water supply scheme. According to the location and reclamation capacity of every WWTP as well as the industry characteristics of the different districts, we could arrange the service area of every WWTP and specify the main reuse purposes inside the service area. As a result, a table list for every WWTP and a map for reclaimed water supply in the central city of Xi'an in 2020 can be formed.

Cost–benefit calculation

The total costs (C) of the planned water reuse system were comprised investment on WWTPs construction, WWTPs operation and maintenance costs, and investment on reclaimed water distribution pipelines (Chen & Wang 2009), which can be calculated from Equation (6)

$$C = \varepsilon c_1 P + 365 c_2 P + \delta c_3 T \tag{6}$$

where c_1 is the average construction investment of wastewater reclamation treatment per m^3, c_2 is the average operation cost of wastewater reclamation treatment per m^3 per day, c_3 is the average construction investment of supplying pipeline of reclaimed water per km, ε is the yearly depreciation of construction investment of wastewater reclamation treatment, δ is the yearly depreciation of construction investment of supplying pipeline, P is the wastewater reuse potential capacity, and T is the total length of supplying pipelines.

The total benefits (B) of the planned water reuse system were calculated as the costs reduction, which was compared with the previous habits of water use due to reclaimed water employment in agriculture, industry, municipal, ecological, and indoor uses. This can be calculated from Equation (7)

$$B = \sum_{i=1}^{5} (h_i - h_0) P_i \tag{7}$$

where i is the reuse purpose, h_i is the unit water cost of reuse purpose i before using reclaimed water, h_0 is the price of reclaimed water, P_i is the potential capacity of reuse purpose i.

RESULTS

Potential demands of reclaimed water

Wastewater reuse potential is analyzed on the basis of the calculation that categorizes agriculture use, industry use, municipal use, ecological use, and indoor use as the main reuse purposes of the reclaimed water in Xi'an in 2020. By means of Equations (1)–(5), the demand for reclaimed water for every reuse purpose is calculated.

Agriculture use, P_1

The total agricultural irrigation area is planned to be 16,151.3 ha, which will be located mainly in the rural-urban fringe zone in 2020. Wheat, vegetables, and fruits are the three main crops (Xi'an Agriculture Bureau 2009). GIQ of the three crops are 1,350, 3,450, and 2,850 m^3/yr·ha, respectively (Office of Water Conservation of Shaanxi Province 2011), and the total potential demand for agriculture irrigation is 32.2×10^6 m^3/yr. Table 2 shows the overall results based on Equation (1).

Table 2 | Potential demands of reclaimed water for crop irrigation in the central city of Xi'an

Crops	Irrigation area a_i (ha)	GIQ (m^3/ha)	Reclaimed water (10^6 m^3)
Wheat	10,093.2	1,350	13.6
Vegetables	2,163.6	3,450	7.5
Fruits	3,894.5	2,850	11.1
Total	16,151.3		32.2

In general, the crop area is shrinking, mainly due to the rapid urbanization in most of the cities in China. As well, crop species tend to be simplified and centralized, which leads to the development of an agriculture base characterized by large-scale and centralized crop planting. Like most of the cities in China, Xi'an is planned to develop several modern agricultural zones with central management and intensive farming in its eastern suburb by the year 2020. This will provide favorable conditions for centralized use of reclaimed water from nearby WWTPs through constructing not too long distribution pipelines.

Industry use, P_2

Water is mainly used for production processes, boiler feed and recycled cooling in industry. Of these, water consumption for boiler feed and recycled cooling in many industries including petrochemical, power, steel, and metallurgy industries account for 50–90% of the total consumption, and can be supplied with reclaimed water (Zhang & Su 2007). Different water usage for production processes may vary considerably because of various industries, which have been separated into three categories. First, in some industries such as cement and concrete production, which do not require high-level water quality, water use was encouraged to be supplied by reclaimed water. Second, in some industries such as papermaking and auto manufacture, part of the water use is suitable to be supplied by reclaimed water (Chao *et al.* 2013). Furthermore, in other industries such as electronic elements manufacture and food production, it is unsuitable to use reclaimed water. Table 3 lists the main industrial products and their water quota (Office of Water Conservation of Shaanxi Province 2011) in Xi'an City as well as their calculated potential demands for reclaimed water based on Equation (2). The total potential demands for industry use of reclaimed water were 89.5×10^6 m^3/yr.

In Xi'an, the major industrial enterprises are mainly located in the eastern, western, and northern suburbs. Owing to the local topographic feature of higher altitude in the south than the north, most of the WWTPs are located in the northern, northeastern, and northwestern suburbs, which facilitate the industrial water supply. According to the development plan for Xi'an City, major industrial

Table 3 | Main industrial water use and their potential demands of reclaimed water in the central city of Xi'an

Product	Output	Water quota	Ratio of reclaimed water use (%)	Reclaimed water (10^6 m^3/yr)
Power generation	18.4×10^9 kwh	0.5 m^3/gws	90	29.8
Cement	391×10^4 t	2 m^3/t	90	7.0
Commercial concrete	$2,606 \times 10^4$ m^3	0.7 m^3/t	90	16.4
Petroleum refining	213×10^4 t	1.5 m^3/t	60	1.9
Papermaking	16×10^4 t	40 m^3/t	60	3.8
Motor	575×10^4 kw	0.1 m^3/kw	60	3.5
Automobile	42×10^4	60 m^3/auto	60	15.1
Compressor	416×10^4	4.8 m^3/compressor	60	12.0
Dairy product	133×10^4 t	10 m^3/t	0	0
Liquid milk	121×10^4 t	3 m^3/t	0	0
Feed	103×10^4 t	0.15 m^3/t	0	0
Detergent	12×10^4 t	8 m^3/t	0	0
Blower	0.15×10^4	20 m^3/blower	0	0
Transformer	1.2×10^8 kw	80 m^3/10^4 kw	0	0
Cable	1.0×10^4 km	0.15 m^3/km	0	0
Electronic component	3.78×10^8	1,120 m^3/10^4 components	0	0
Total				89.5

enterprises are going to be moved to the suburban areas. Consequently, the distance between industrial enterprises and WWTPs will be shortened, which can significantly reduce the costs of reclaimed water delivery.

Municipal use, P_3

Municipal water use mainly includes gardening and road washing, which is reasonably covered by reclaimed water. In 2020, the gardening and road washing area is predicted to be 10,243 km^2 and the reclaimed water consumption will reach 112.2×10^6 m^3/yr, assuming unit consumption of 3 L/m^2·d (Li *et al.* 2002) based on Equation (4).

Currently, municipal use has become the major purpose for reclaimed water, surpassing industrial use. This is realized in two ways, one of which is taking reclaimed water from the built-up pipelines for gardening and road washing in the surrounding areas. The other is transporting reclaimed water from WWTPs by watering carts to the city areas for greening and road washing. Owing to continuous construction of reclaimed water pipelines, the coverage area of pipeline networks will be gradually enlarged. Hence, municipal use is believed to be the most important use of reclaimed water under the encouragement of governmental policies for promoting reclaimed water reuse in public facilities.

Ecological use, P_4

According to the urban plan, the total volume of water for the central areas in Xi'an City will amount to 73.9×10^6 m^3 by the year 2020, and the reclaimed water will be used mainly for urban water replenishment. As mentioned earlier, the water bodies were categorized into two in Equation (4), one of which is the slow-flow or closed water body represented by urban landscape lakes. By calculation, this part of the water volume will reach 5.4×10^6 m^3. Owing to the shortage of replenishment by natural water sources, reclaimed water has been applied for lake water replenishment in some areas, and possibly this will become the only way for lake water replenishment in the future. Since this part of the water body is mainly in the central areas of the city landscape, the refresh duration of changing water was chosen as 20 days for the purpose of calculation (Wang *et al.* 2008). Hence, the potential demand of reclaimed water for landscape amounted to 98.6×10^6 m^3/yr.

Urban rivers represented the other category of water body. These kinds of water bodies are mainly located in the surrounding areas of the city, some of which are near the centralized WWTPs. Others are the receiving water bodies of the WWTPs. These have been the main reclaimed water users and the total scale of this kind of water body amounted to 23.6 km^2. Furthermore, the reclaimed water was mainly used for river base flow maintenance along with natural replenishment. By calculation, the potential demand of reclaimed water could amount to 47.2×10^6 m^3/yr, based on the calculation of water loss as 2 m/m^2 per year, and considering the water loss of evaporation and leakage (Wang *et al.* 2011). Hence, the potential capacity of reclaimed water for urban water replenishment could reach 145.8×10^6 m^3/yr.

The potential of reclaimed water for ecological use was high. Nonetheless, compared with the other reuse purposes, it is difficult to define the specific ecological users. Similar to the closed water body for landscaping, the administrative units of the parks may pay the water fee. However, for the other water bodies such as rivers for urban landscaping, it is possible that nobody will be willing to pay the fee of water replenishment. With the expectation for a rise in the public perception of urban water environment quality, the government should make efforts to promote the utilization of reclaimed water for water replenishment.

Indoor use, P_5

Toilet flushing is the key component of the indoor use of reclaimed water. Research has shown that the amount of toilet flushing accounted for about 30% of the total water consumption per capita (Matulova *et al.* 2010). The utilization of reclaimed water for indoor toilet flushing depends on the construction of a dual water supply system. The larger the coverage area of the dual water supply system is, the higher the usage rate of reclaimed water for toilet flushing. By calculation of the indoor reclaimed water reuse potential based on Equation (5), the total population size was 8.8×10^6 and the unit water use for toilet flushing amounted to 40 L/d per person (Chu *et al.* 2007). Similar to the utilization ratio of reclaimed water for toilet flushing, since the popularity degree of reclaimed water was much higher in public buildings than residential buildings, the ratio of public building areas including commercial buildings, cultural and recreational buildings, sports buildings, medical buildings, and education and research buildings to the total urban land area was assumed as the utilization ratio of reclaimed water for toilet flushing, which was 37% in this study. By calculation, the potential demand of reclaimed water for indoor reuse was 47.5×10^6 m^3/yr.

The popularity of reclaimed water for toilet flushing was not only related to the construction of a dual water supply system inside the building, but also related to the public acceptability of the reclaimed water for toilet flushing. Hence, in order to promote the indoor utilization of reclaimed water, it is important to reinforce the construction of a reclaimed water delivery system and a dual water supply system. It is also important to encourage the public to use the reclaimed water in place of tap water for toilet flushing. Certainly, other factors including the rise of water quality standards, the reduction of usage risks, and price increases for tap water will also promote the popularity of reclaimed water use for toilet flushing.

Supply scheme of reclaimed water

Based on the urban planning of Xi'an City, the 15 centralized WWTPs including WWTP1–7, WWTP9–11, WWTP13–16, and WWTP-Chanba being put into operation before 2020 realizes 100% of municipal water collection. All the 15 WWTPs are located in the fringe fields of the urban area surrounding the city. We propose a WWTPs-centered reclaimed water supply scheme, which synthesizes WWTPs locations, district divisions and main reuse purposes.

As is shown in Table 4 and Figure 2, the main reuse purposes and service areas of every WWTP vary. Since the northern and western suburbs are featured as the combination of old and new industry bases, the WWTPs located in the western, northern, northwest, and southwest suburbs are mainly for the supply of industry use. On the other hand, the eastern and southern suburbs are featured as newly developed ecological and tourist areas, so that the plants in these regions are mainly for the supply of municipal use including gardening and road washing. In addition, the reclaimed water is also one important source for river replenishment in Xi'an City, including the Zaohe River, Weihe River, Fenghe River, Juehe River, Chanhe River,

Table 4 | Reuse purposes and service areas of WWTPs in the central city of Xi'an in 2020

No.	WWTP	Agriculture use	Industry use	Municipal use	Ecological use
1	WWTP1	–	Northwestern suburb	Lianhu District	Hancheng, Labor, Lianhu, and Revolution Lake
2	WWTP2	–	Southwestern suburb	Lianhu District	City Moat, Taoyuan Lake, Zaohe River, and Kunming Lake
3	WWTP3	Baqiao District	Eastern suburb	Xincheng and Baqiao District	Chanhe and Bahe River
4	WWTP4	–	Northern and northwestern suburb	Weiyang District	Sports Lake, Caoyunming Trench, and Weiyang Lake
5	WWTP5	–	Northern suburb	Xincheng, Baqiao, and Weiyang District	Chanhe and Bahe River, Xingqing and Taiye Lake
6	WWTP6	–	Northwestern suburb	Weiyang District	Zaohe River
7	WWTP7	Yanta District	Southwestern suburb	Beilin and Yanta District	Fengwei Trench, Zaohe, and Taiping River
8	WWTP9	–		Beilin and Yanta District	Landscape replenishment, Zaohe and Juehe River, Tang Paradise and South Lake
9	WWTP10	Weiyang District	Northern suburb	Weiyang District	Weihe River
10	WWTP11	–		Baqiao District	Bahe River
11	WWTP13	–		Baqiao District	
12	WWTP14	–		Beilin and Yanta District	Tang Paradise and South Lake
13	WWTP15	–		Road washing and gardening	Landscape replenishment and Juehe River
14	WWTP16	–		Gardening	Fenghe and Taiping River
15	WWTP-Chanba	Baqiao District	Eastern suburb	Xincheng and Baqiao District	Guangyun Lake and Bahe River

and Bahe River surrounding the central city; Xingfu Trench, Caoyunming Trench, and Taiping River inside the city; the lakes of Weiyang, Hancheng, Guangyun, Xingqing, Kunming, Tang Paradise, South Lake, and Taiye. Moreover, the WWTPs located in the Baqiao District, Weiyang District, and Yanta District could also serve for the supply of crop irrigation. Indoor use of reclaimed water for toilet flushing depends on the buildings' distribution and indoor pipeline construction, which is not specified in Table 4 and Figure 2.

Cost–benefit analysis

Equations (5) and (6) processed the economic analysis of the reclaimed water reuse system. For the cost calculation, empirical data of existing WWTPs in Xi'an City were chosen as the construction unit price and operation price per m^3. The potential amount of reclaimed water for reuse was assumed as the scale of wastewater reuse, which was 427.2×10^6 m^3/yr or 1.2×10^6 m^3/d. As well, the construction cost per km of water supply pipelines employed the empirical data of tap water construction. To present the effect of maximum wastewater reclamation, the length of the tap water supply pipeline was assumed as the ideal goal of reclaimed water pipeline construction. The total costs are shown in Table 5.

The results of the benefits are shown in Table 6. For the calculation of benefits (Equation (6)), the reclaimed water price was assumed at the current price of 1.7 RMB/m^3. The price difference between the water for various reuse purposes and the reclaimed water could be influenced by several factors. First, for agriculture use, the agricultural areas are mainly located in the eastern suburbs and its development was mostly restricted by water deficiency, as mentioned before. Exploiting the groundwater was the main way to supplement urban water in those areas. Currently, the average cost of groundwater exploitation is

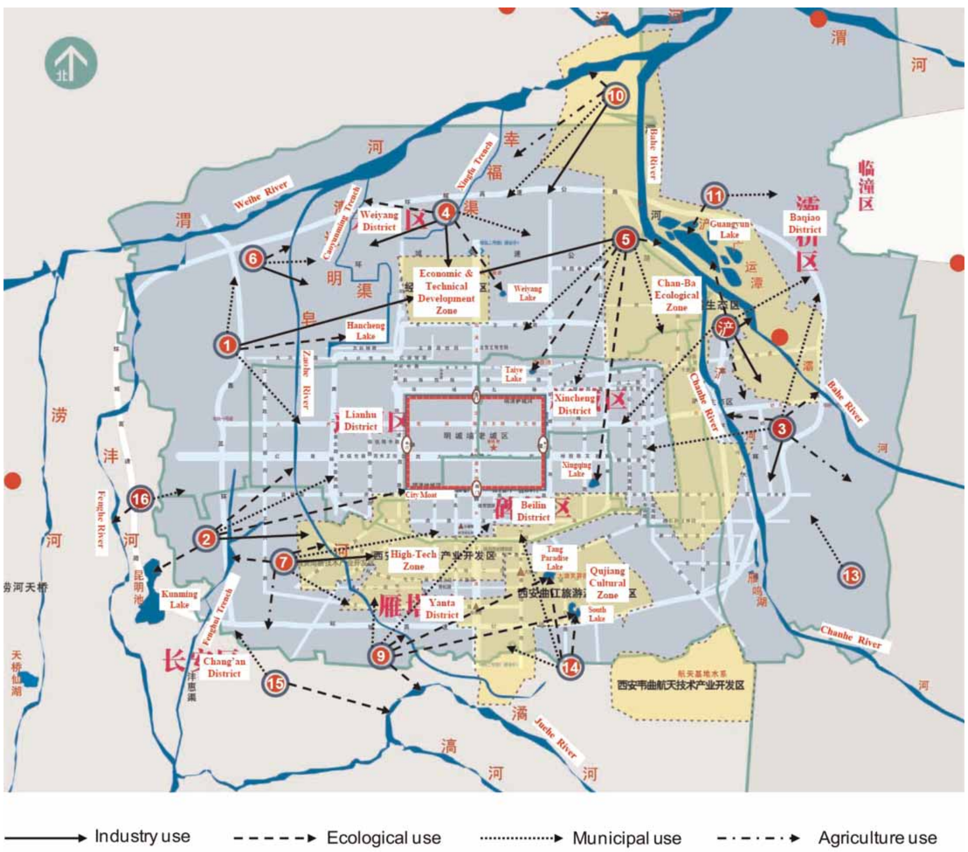

Figure 2 | WWTPs-centered reclaimed water supply scheme in the central city of Xi'an in 2020.

Table 5 | Costs calculation of wastewater reuse in Xi'an in 2020

Item	Value	Unit price	Depreciation (%)	Cost (10^6 RMB [b])
Construction	1.2×10^6 m^3/d	2,500–3,000 RMB/m^3	4.0	120–144
Operation	427.2×10^6 m^3/yr	1.0–1.5 RMB/m^3 d		427–641
Pipelines	1,071 km[a]	10–15 × 10^6 RMB /km	3.3	357–536
	857 km (80%)			286–429
	534 km (50%)			179–268
	321 km (30%)			107–161
Total	(100%)			904–1,321
	(80%)			833–1,214
	(50%)			726–1,053
	(30%)			654–946

[a]Length of urban water supply pipeline, which was the optimum length of reclaimed water supply pipeline.
[b]Chinese currency unit.

5 RMB/m^3, which gives a price difference with reclaimed water as 3.3 RMB/m^3. Second, for industrial use, the industrial water price is 5.8 RMB/m^3, which gives a price difference with reclaimed water of 4.1 RMB/m^3. For municipal use, the water price of greening and road washing was assumed as the residents' water price, 2.9 RMB/m^3, which gives a price difference with reclaimed water of 1.2 RMB/m^3. For ecological use, the economic benefits

were mainly from the slow-flow water body replenished by reclaimed water. Since the economic benefit from urban rivers' replenishment was difficult to calculate, its benefit was neglected in this calculation. The slow-flow water body was mostly replenished by extra water from water plants, and its price was assumed as the residents' water price, 2.9 RMB/m^3. The price difference with the reclaimed water was 1.2 RMB/m^3. Lastly, for indoor use, the price difference between tap water for toilet flushing and reclaimed water was 1.2 RMB/m^3.

Through the comparison of Tables 5 and 6, it is demonstrated that if the reclaimed water use was maximized, the construction and operation costs of the production facilities of reclaimed water were stable. However, the coverage area of the reclaimed water network had a great impact on the balance of costs and benefits. When the construction length of reclaimed water pipelines reached 50–80% of the total length of tap water supply pipeline, the costs and benefits of the constructed wastewater reuse system could achieve a good balance.

DISCUSSION

Different reuse purposes in reclaimed water use

From the analysis of the potential demands for reclaimed water we can find that agriculture use makes only a small contribution to the total reclaimed water consumption, which is 32.2×10^6 m^3/yr and accounts for 7.5%. This is because only a small agricultural area in the central city is irrigated. Industry use is an increasing demand for reclaimed water along with the water price rising and the reclaimed water quality improving. The demand in 2020 is predicted to be 89.5×10^6 m^3/yr and account for 21% of the total consumption. Municipal use forms an important reuse purpose for the reclaimed water, which is 112.2×10^6 m^3/yr and accounts for 26.3% of the total consumption. The high municipal use is a result of the construction of large green belts and squares in the city. Ecological use should be another important reuse purpose for the reclaimed water because the demand for water bodies' replenishment will increase rapidly with the expansion in construction of the livable city area in Xi'an in the near future. The reclaimed water consumption in 2020 is 145.8×10^6 m^3/yr and accounts for 34.1% of total consumption. Indoor use is the most flexible reuse purpose for reclaimed water because it depends on investment in indoor dual pipe systems. It can make a more notable contribution if more attention is paid to it.

Table 6 | Benefits calculation of wastewater reuse in Xi'an in 2020

Item	Potential demands (10^6 m^3)	Price difference (RMB/m^3)	Benefit (10^6 RMB)
Agriculture use	32.2	3.3	106
Industry use	89.6	4.1	367
Municipal use	112.2	1.2	135
Ecological use	98.6[a]	1.2	118
Indoor use	47.5	1.2	57
Total			783

[a]Economic benefits of rivers replenishment were neglected in this study.

New balance of water supply and consumption

Based on the analyses above, the potential demands for reclaimed water were predicted to be 427.2×10^6 m^3/yr in the central city of Xi'an in 2020, and the corresponding wastewater reuse rate is 52.6%. By fully exercising the potential for reclaimed water reuse, the whole configuration of urban water supply will change and form a new balance, as shown in Figure 3.

In the new balance, the available water resource will increase substantially owing to the maximized use of reclaimed water. The water supply scheme will be altered as follows: (1) the surface water, groundwater, and inter-basin water are mainly supplied for domestic use as well as part of the secondary and tertiary industry which have higher requirements for water quality; (2) the rainwater is mainly used for ecological water replenishment; and (3) the reclaimed water could not only be supplied for the primary industry dominated by agriculture and ecological replenishment, the required quality of which is not high, but also could be supplied for part of the secondary and tertiary industry.

As a result, the total water supply capacity can reach $1,037.3 \times 10^6$ m^3/yr including surface water, groundwater, inter-basin water, reclaimed water, and rainwater, which

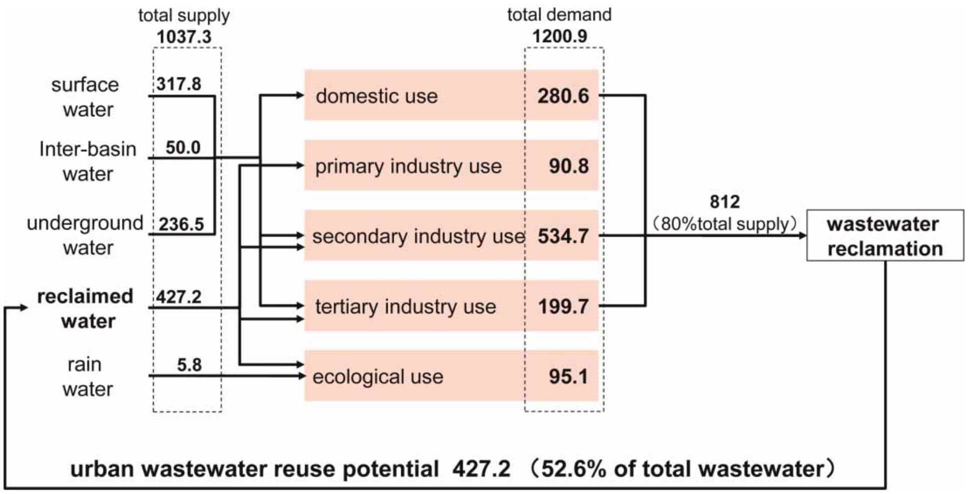

Figure 3 | New balance of water supply and demand in the central city of Xi'an in 2020 (10^6 m^3/yr).

could reduce the water shortage from 31.3 to 13.6% of the total demands.

Implications for policy

Although the Xi'an Urban Planning (2009–2020) stated that reclaimed water could replenish urban water and introduced the total amount of utilization, the main approach and total demand for wastewater reuse have not been confirmed. This study analyzed the main approach of urban wastewater reuse and its potential capacity. It also confirmed the main reuse purposes for the reclaimed water and its optimal distribution for various purposes. Furthermore, the goals for the construction of new WWTPs have been mentioned in the plan, but the reuse scheme of the reclaimed water has not been confirmed. This study presented a WWTP-centered reuse scheme for reclaimed water based on the layout of administrative districts and industrial structure. It also confirmed the service areas of different WWTPs and the main reuse purposes for reclaimed water. Therefore, this study effectively supplemented the Xi'an Urban Planning and enhanced its operability. It also accomplished the specific goals of the plan, while providing guidance for policy-making and operation of the plan.

The operation of a wastewater reuse system in this study will involve a number of urban administrative departments. As to water supply, the Water Supply Bureau is in charge of the production of reclaimed water, and the Construction Bureau the reclaimed water pipeline, respectively. As to water demand, the agriculture use, industrial use, municipal use, and ecological use falls under the Agriculture Bureau, the Industry and Information Bureau, the Municipal Public Utilities Association, and the Bureau of Park and Woods as well as the Water Ssupply Bureau, respectively. Although these departments will all participate in the promotion of urban wastewater reuse under the guidance of Xi'an Urban Planning, they still lack systemic operation and effective communication. This study will help to establish close relationships among different departments, and build a rounded system incorporating production, distribution, and utilization, thus forming an ideal working mechanism characterized by multi-disciplinary cooperation to promote the reclaimed water reuse.

CONCLUSIONS

With the prospect of severe water shortage in 2020, maximized wastewater reuse should be implemented to mitigate water stress. A water reuse system formulated for the Xi'an municipality in this study included an evaluation of reclaimed water reuse purposes, reuse potential demands, and a supply scheme for the reclaimed water. Agriculture use, industry use, municipal use, ecological use, and indoor use should be the five main reuse purposes of reclaimed water. The reuse potential capacity was deduced to be 427.2×10^6 m^3/yr, which makes a significant contribution to increasing the total urban water supply capacity and mitigating water shortages. A supply scheme for the reclaimed water composed of reclaimed water sources, water supply service areas, and the main reuse purposes was configured. A WWTPs-centered reclaimed water supply system was proposed, which defined the main reuse purposes of the 15 WWTPs to be put into use in 2020 and their service districts. Based on the results of an economic analysis, the costs of the water reuse system could be covered by the benefits when the total length of reclaimed water supply pipelines accounts for 50–80% of that of the tap water pipelines, a perfect coverage condition of a distribution network for reclaimed water. This study provided theoretical basis and implementation strategies for a system configuration of water reuse in Xi'an City and also contributed to mitigating the water-deficiency problems related to rapid development in China.

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