Optimized plan of centralized and decentralized wastewater reuse systems for housing development in the urban area of Xi’an, China

X. C. Wang, R. Chen, Q. H. Zhang and K. Li

ABSTRACT

In an arid and water deficient urban area, such as Xi’an in the northwest region of China, gardening and forestation often use large amounts of tap water. Therefore, there is a need for treated wastewater reuse for such purpose to mitigate urban water shortage, especially in the newly developed housing area, where a high green coverage is often required for both commercial value and living condition improvement. Supply of the treated wastewater through a centralized system which has been planned and partially constructed is one measure to meet such need, but it may require an extension of the distribution system for a full coverage of the whole city area. A supplementary measure is to construct decentralized wastewater treatment and reuse (DESAR) systems in areas that are distant from the planned centralized system. In order to optimize the plan of wastewater reuse for housing development in the urban area, the authors analyzed the existing plan of centralized wastewater reuse and the envisaged plan of housing development in Xi’an urban area. A method was proposed for selection of a feasible way of reclaimed water reuse from two options, namely centralized and decentralized ones, by introducing a critical distance \( L_0 \) which depends on the relationship between the cost for DESAR system installation and that for water delivery pipeline construction. If the distance from the project site to the nearest access point of the centralized system \( L \) is shorter than \( L_0 \) then using reclaim water from the centralized system becomes more feasible, and otherwise DESAR system installation becomes more feasible. A distribution map was thus obtained to show an optimized plan of centralized and decentralized wastewater reuse systems for housing development in Xi’an city. An example was also given to show the advantage of a DESAR system installed.

Key words | centralization, decentralization, housing development, water reuse, water shortage

INTRODUCTION

Wastewater reuse has become very important in China for mitigation of water shortage especially in the northern regions where the available water resource cannot meet the needs of fast development (Zhang et al. 2007). Among various demands for water reuse, urban environmental use, such as for forestation, gardening, sprinkling and water replenishment of artificial ponds etc., is the biggest demand and should be given the first priority (Wang & Jin 2006).

Nowadays, wastewater treatment and reuse projects have been implemented in many cities. Using the effluent from a secondary wastewater treatment facility, tertiary treatment, often by a coagulation-sedimentation-filtration-disinfection process, is further conducted for an improvement of the reclaimed water quality to meet the reuse requirement. Because most of the users of the reclaimed water are in the city area, water transfer and distribution pipelines have to be
constructed for reclaimed water supply. This is called the “centralized” system for wastewater treatment and reuse (Wilderer 2001). Comparing with the construction cost for the tertiary treatment facility, the construction cost for the transfer and distribution pipelines often becomes more expensive, as well as the operation cost. Such a shortcoming of the centralized system has restricted its application in many cases, because both the government which is promoting wastewater reuse and the users who are willing to use the reclaimed water look forward to a price for the reclaimed water to be much cheaper than the tap water. In fact, in order to promote wastewater reuse, a number of cities have set the selling price of the reclaimed water at a very low level no matter how much is spent for its production, and the government is providing subsidies for the business. However, this may not be a sustainable way for wastewater reuse.

Under this circumstance, “decentralized” systems for wastewater treatment and reuse are drawing attention widely (Fane et al. 2002; Wang 2007). Such a system stresses onsite wastewater treatment and onsite reuse. Therefore, construction of a long distance transfer pipeline and a large scale distribution network for the reclaimed water may no longer be necessary.

In this paper, we consider a special case of wastewater reuse, i.e., wastewater reuse in housing development in urban area that is a growing business in many cities in China. With the fast development of the Chinese economy, all cities are expanding and this gives chances for housing development. Meanwhile, housing development also results in the fast growing of new urban area. On the other hand, with the request for better living environment, many newly developed housing areas are called “ecological friendly communities” or “green villages” which are constructed with large green coverage and water gardens. They need a large amount of water consumed for environmental purposes. In water deficient cities, this becomes an increasing burden for urban water supply. For this reason, some cities, such as Xi’an to be explained in the following sections, are restricting tap water consumption for such purposes, and call for wastewater reuse in the newly developed housing areas. Therefore, how to plan wastewater reuse systems in these areas becomes an issue of study, and “centralized” vs. “decentralized” becomes a hot topic.

**General condition of Xi’an City**

Figure 1 shows the location of Xi’an City in China. As the capital city of Shaanxi Province and with an urban population of about 3.4 million, it is the largest city in the northwest region of the country. In 2006, the GDP of Xi’an City increased by about 15% and reached 145 billion RMB or about 20.7 billion USD (Statistics Bureau of Xi’an City 2007). The fast economical growth has brought about a continuous development of housing development and real estate business. It is reported that from 2001 to 2005, the average annual increase of the real estate business was about 27.3%, much higher than the speed of economical growth. In the same period, the housing area increased by 25.49 million m², and the per capita housing area reached 24.42 m² at the end of 2005, indicating a great improvement of housing condition in the city area.

According to the “Eleventh Five Year Plan of Housing Development in Xi’an City” (Urban and Rural Construction Committee of Xi’an Municipality 2006), from 2006 to 2010, 50.65 million m² of new housing buildings will be constructed for a provision of about 500,000 households. Higher quality, better living condition and environmental friendly become the principle for housing development in this period. It requires that the green coverage of the newly developed housing area has to be no less than 35%. For these reasons, supply of sufficient water for environmental use in housing development becomes a topic to be considered in the urban planning.

![Figure 1](https://iwaponline.com/wst/article-pdf/58/5/969/436321/969.pdf)
In fact, Xi’an is within the arid and water deficient northwest region in China. The per capita available water resource in the Weihe River Basin where Xi’an is located is less than 350 m³ per year – far below the line of absolute water scarcity of 500 m³ per capita per year (Falkenmark & Widstrand 1992; Engelman & Leroy 1993; United Nations Population Fund 1997). Therefore, the municipal government calls for treated wastewater reuse for non-potable purposes as far as possible, and the environmental water use in housing development is considered to be a potential user.

ANALYSIS OF DEMAND AND SUPPLY FOR RECLAIMED WATER

Demand for reclaimed water in Xi’an

According to the “Master Plan of Domestic Wastewater Reclamation and Reuse in Xi’an City” (Xi’an Municipal Management Committee 2006), the usage of the treated wastewater in Xi’an City will mainly cover industrial reuse, replenishment of landscaping water bodies, municipal reuse and agricultural irrigation. The demand for each of these uses in 2010 has been estimated as 149,600 m³/d, 312,200 m³/d, 78,500 m³/d and 443,600 m³/d, respectively. Among them, the municipal reuse demand mainly covers public garden and green belt irrigation, road and square sprinkling, construction water use etc. Water demand for the environmental water use in housing development has not been taken into account in the master plan, and it can be estimated as below.

- Water for gardening. By 2010 the total area for housing development will be about 7 million m² or 700 ha. With an average green coverage of 35%, the green area using water for gardening will be about 2.45 million m² or 245 ha. Using the gardening water consumption standard of 30 m³ per ha per day, it is calculated that the demand for gardening in the housing area will be 6,750 m³/d.
- Water for sprinkling. The road and square area often takes about 10% in the housing area, so it can be estimated as 70,000 m². Using the sprinkling water consumption standard of 3 litres per m² per day, it is calculated that the demand for sprinkling in the housing area will be 2,100 m³/d.
- Water for replenishing landscaping ponds. Artificial pond is often constructed in the newly developed housing area and it also takes about 10% or 70,000 m² of the area. Considering an average water depth of 0.5 m, water replenishing twice per month and each time with 50% of the water volume, the demand for replenishing landscaping pond is calculated as 11,670 m³/d.

The total water demand will then be about 20,000 m³/d for environmental water use in housing development. This is additional to the total demand of 983,900 m³/d estimated in the abovementioned master plan.

Municipal wastewater treatment and water reclamation in Xi’an by the centralized system

By 2010, in addition to the 3 existing wastewater treatment plants (WWTPs), another 2 WWTPs will be put into operation. Table 1 shows the general data of these WWTPs and Figure 2 shows their locations. The bold line in the figure is the boundary of the service area of the centralized wastewater system.

The breakdown of the reclaimed water from each WWTP for different reuse purposes are shown in Table 2.
Comparing with the total demand of about 1 million m³/d discussed above, the reclaimed water quantity can only meet 40% of the demand. However, between reclaimed water production and its efficient use, there are still many problems to solve. Among them, the construction of reclaimed water distribution network is the most important but needs much higher cost than that for water treatment.

Reclaimed water reuse in housing development

Reuse of the reclaimed water in housing development is considered to be promising and has been put into the category of municipal reuse by the government recently. In order to formulate a feasible plan for this purpose, a study was conducted regarding 165 housing development projects. The small dots in Figure 2 are the locations of these project sites.

In addition to the governmental policy to promote water reclamation, water tariff is another factor that stimulates water reuse in housing development. As discussed in the former section, for a housing area with large green coverage and/or artificial water surface, water consumption is one thing the developer has to consider. Nowadays, the tariff of tap water in Xi’an is 2.94 RMB per m³, while the tariff of reclaimed water supplied through the centralized system is 1.17 RMB per m³. As long as the reclaimed water can meet the quality requirement for environmental use, the developers may have a positive attitude toward water reuse. But, because the reclaimed water distribution pipelines in Xi’an are designed to supply water mainly to some potential users such as industries, water bodies and large municipal facilities, many housing developers are facing difficulties in getting easy access to the centralized reclaimed water supply. In many cases, rather long pipelines have to be constructed either by the developers themselves or by the government for the acquisition of the reclaimed water. Therefore, decentralized wastewater treatment and reuse (DESAR) systems may become good alternative measures. Which is more feasible will mainly depend on the total cost for construction, operation and maintenance. This is the topic to be discussed in this section.

System selection by introduction of a “critical distance”

Consider the distance from the housing development site to the access point of the centralized reclaimed water supply system and denote it as L. It is considered that the cost for the construction of a pipeline to the access point will

### Table 2 | Breakdown of the reclaimed water from each WWTP for different reuse purposes (unit: m³/d)

<table>
<thead>
<tr>
<th>WWTP</th>
<th>Reclaimed water quantity</th>
<th>Industrial reuse</th>
<th>Water body replenishment</th>
<th>Municipal reuse</th>
<th>Agricultural irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWTP No. 1</td>
<td>60,000</td>
<td>29,100</td>
<td>16,600</td>
<td>6,600</td>
<td>7,700</td>
</tr>
<tr>
<td>WWTP No. 2</td>
<td>100,000</td>
<td>49,700</td>
<td>37,400</td>
<td>10,300</td>
<td>2,600</td>
</tr>
<tr>
<td>WWTP No. 3</td>
<td>50,000</td>
<td>33,100</td>
<td>11,700</td>
<td>5,200</td>
<td>0</td>
</tr>
<tr>
<td>WWTP No. 4</td>
<td>100,000</td>
<td>10,700</td>
<td>500</td>
<td>1,700</td>
<td>87,100</td>
</tr>
<tr>
<td>WWTP No. 5</td>
<td>100,000</td>
<td>22,500</td>
<td>40,000</td>
<td>1,400</td>
<td>36,100</td>
</tr>
<tr>
<td>Total</td>
<td>410,000</td>
<td>145,100</td>
<td>106,200</td>
<td>25,200</td>
<td>133,500</td>
</tr>
</tbody>
</table>
depend on both \( L \) and the design flow rate \( Q \) which corresponds to the demand for reclaimed water. On the other hand, if a DESAR system is installed, the cost for its construction will only depend on \( Q \). Therefore, under a given \( Q \), there should be a distance \( L_0 \) at which the cost for pipeline construction equals to that for DESAR system installation. \( L_0 \) can be called the “critical distance”. If \( L < L_0 \) then using reclaimed water from the centralized system is economically more feasible, and if \( L > L_0 \) then DESAR system is economically more feasible. Of course, such a simple comparison is under an assumption that the tariff of the reclaimed water is about the same as the cost for water reclamation from the DESAR system.

Regarding the Xi’an case, we did a calculation as shown in Table 3 where \( Q \) is the capacity of wastewater treatment and reuse by a DESAR system, \( C_1 \) is the estimated cost for the system construction, and \( L_0 \) is critical distance, i.e., the equivalent length of the pipeline that needs the same cost for construction. The results indicated that the critical distance \( L_0 \) depends on the scale of wastewater treatment and reuse.

A survey of the housing developers indicated that for most of the housing areas to be developed, the average scale of wastewater reuse would be between 500 and 800 \( \text{m}^3/\text{d} \). Following the calculation results of Table 3, the critical distance can be evaluated as 4 to 6 km. Taking 5 km as an average distance, we can plot a map as shown in Figure 3 according to the current condition of centralized wastewater treatment and reuse systems in Xi’an City.

### Table 3 | Calculation of the critical distance \( L_0 \) based on the wastewater treatment and reuse capacity of a DESAR system

<table>
<thead>
<tr>
<th>( Q ) (( \text{m}^3/\text{d} ))</th>
<th>( C_1 ) (DESAR cost, RMB) (^{a})</th>
<th>( L_0 ) (Equivalent length for pipeline construction, ( \text{km} )) (^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>476,000</td>
<td>1.90</td>
</tr>
<tr>
<td>300</td>
<td>674,000</td>
<td>2.70</td>
</tr>
<tr>
<td>400</td>
<td>863,000</td>
<td>3.45</td>
</tr>
<tr>
<td>500</td>
<td>1,046,000</td>
<td>4.18</td>
</tr>
<tr>
<td>600</td>
<td>1,223,000</td>
<td>4.90</td>
</tr>
<tr>
<td>700</td>
<td>1,397,000</td>
<td>5.59</td>
</tr>
<tr>
<td>800</td>
<td>1,567,000</td>
<td>6.27</td>
</tr>
</tbody>
</table>

\(^{a}\)Formula for \( C_1 \) calculation: \( C_1 = 4993.2Q^{0.86} \) according to experience of wastewater treatment system construction in the study area.

\(^{b}\)For outdoor pipeline construction, the minimum pipe diameter is 100 mm which is sufficient for water supply within the range of \( Q = 200 \text{ m}^3/\text{d} - 800 \text{ m}^3/\text{d} \). The average cost for pipeline construction (pipe material: steel) in the study area is 250,000 RMB/km.

The housing development project sites within the circled areas belong to the category of \( L < L_0 \) and using reclaimed water from the centralized system is considered to be more feasible, while those outside the circled areas belong to the category of \( L > L_0 \) and DESAR system installation is considered to be more feasible.

### Case study

In this section, a case study will be introduced to show the advantage of installation of a DESAR system for a housing development project which locates at a place belonging to \( L > L_0 \).

### Project description

The case study site is at south of the Xi’an City as shown in Figure 3. It is outside the circled area with \( L < L_0 \) so the developer decided to install a DESAR system for onsite reuse of the treated water for environmental purposes including replenishment of an artificial pond, green belt gardening and car washing etc. Figure 4 shows the composition of the system. In the 6 residential buildings, dual pipe collection system is installed for separate collection of black water and grey water. The black water is treated by a septic tank system while the grey water is treated for...
environmental reuse. The treated grey water is led to the artificial pond for water replenishment. It also performs the function of a regulation tank for other reuse purposes. In order to control the pond water quality, part of the stored water is circulated. The total households in the 6 residential buildings are 400 and the total population is about 1,600 people. The green belt covers an area of 6,400 m² and the artificial pond is with a water surface of 6,500 m² and an average water depth of 0.5 m. The average retention time of the pond water is designed as about 15 days.

The grey water is treated by a process combining enhanced primary treatment with ozone enhanced flotation. The enhanced primary treatment is performed by a fluidized pellet bed bioreactor which is a specially designed wastewater treatment device for onsite wastewater treatment and can perform chemical coagulation, biological degradation, particle pelletization and separation in one unit (Wang et al. 2007). The ozone enhanced flotation is performed by a dispersed-ozone flotation separator which is a compact device combining coagulation, ozonation and flotation in an integrated unit (Jin et al. 2006). As for the circulated pond water, it only enters the ozone enhanced flotation unit for treatment.

Table 4 | Estimation of the operation and maintenance (O&M) cost of the DESAR system (unit: RMB per year)

<table>
<thead>
<tr>
<th>Item</th>
<th>Estimated cost</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Electricity</td>
<td>77,800</td>
<td></td>
</tr>
<tr>
<td>(2) Chemicals</td>
<td>4,300</td>
<td></td>
</tr>
<tr>
<td>(3) Labour salary</td>
<td>20,000</td>
<td>Two labourers for system operation</td>
</tr>
<tr>
<td>(4) Daily maintenance fee</td>
<td>7,200</td>
<td></td>
</tr>
<tr>
<td>(5) Major repair fee</td>
<td>11,000</td>
<td>4% of the equipment cost</td>
</tr>
<tr>
<td>(6) Annual depression cost</td>
<td>120,300</td>
<td>25 years depression</td>
</tr>
<tr>
<td>Total for O&amp;M without depression</td>
<td>34,000</td>
<td>Sum of (1) to (5)</td>
</tr>
<tr>
<td>Total for O&amp;M with depression</td>
<td>154,300</td>
<td>Sum of (1) to (6)</td>
</tr>
<tr>
<td>Unit production cost without depression</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Unit production cost with depression</td>
<td>1.06</td>
<td></td>
</tr>
</tbody>
</table>
Cost analysis

Construction cost

The wastewater treatment system was installed in the basement of one building next to the underground parking. The total construction cost was about 850,000 RMB which includes 220,000 RMB for civil work and 630,000 RMB for equipments and installation work. The cost is equivalent to that for constructing 3.4 km pipeline of 100 mm diameter but the real distance from the project site to the nearest access point of the centralized reclaimed water system is about 8 km.

Operation & maintenance (O&M) cost

Table 4 shows the estimated O&M cost for the DESAR system in this case. If the depression cost is ignored, then the unit O&M cost is calculated as 0.82 RMB per m$^3$ water production, and if the depression cost is included, then the unit O&M cost becomes 1.06 RMB per m$^3$ which is lower than the current tariff of 1.17 RMB for reclaimed water from the centralized system.

SUMMARY AND CONCLUSIONS

In order to optimize the plan of wastewater reuse for housing development in the urban area of Xi’an City, the authors analyzed the existing plan of centralized wastewater reuse and the envisaged plan of housing development. A method was proposed for selection of a feasible way of reclaimed water reuse from two options, namely centralized and decentralized ones, by introducing a critical distance $L_0$ which depends on the relationship between the cost for DESAR system installation and that for water delivery pipeline construction. If the distance from the project site to the nearest access point of the centralized system $L$ is shorter than $L_0$ then using reclaim water from the centralized system becomes more feasible, and otherwise DESAR system installation becomes more feasible. A distribution map was thus obtained to show an optimized plan of centralized and decentralized wastewater reuse systems for housing development in Xi’an city. An example was also given to show the advantage of a DESAR system installed.

ACKNOWLEDGEMENTS

The study is supported by the National Natural Science Foundation of China (Grant No. 50621140001).

REFERENCES


Urban and Rural Construction Committee of Xi’an Municipality 2006 Eleventh Five Year Plan of Housing Development in Xi’an City (in Chinese).


Xi’an Municipal Management Committee 2006 Master Plan of Domestic Wastewater Reclamation and Reuse in Xi’an City (in Chinese).