An independent water system with maximized wastewater reuse for non-potable purposes – Model case for future urban development


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Abstract

A study was conducted to formulate an optimized plan for upgrading an independent water system in a college campus where the available water source is from 5 groundwater wells with a maximum water supply capacity of 3000 m$^3$/d but the water demand is much beyond this value for both potable and non-potable consumption. By water balance analysis, it was estimated that with the available fresh water consumed only for potable and related miscellaneous uses for 30000 people, the quantity of the reclaimed water could be enough to cover all the non-potable consumption. By material balance analysis, the pollutant loadings of organics, nitrogen and phosphorus were calculated and the requirements for pollutant removal corresponding with reuse purposes were evaluated. Considering the quality criteria of water reuse for lake landscaping, toilet flushing and gardening, and the demand for each water usage in the campus, a dual-quality reclaimed water supply scheme was proposed as (1) supply of lower quality reclaimed water for gardening and road sprinkling by upgrading the existing wastewater treatment facility of 1500 m$^3$/d using conventional process, and (2) supply of higher quality reclaimed water for lake water replenishment and toilet flushing by implementing a new wastewater treatment facility of 2500 m$^3$/d using MBR process. The independent water system thus optimized could sustain a total water consumption of more than 6000 m$^3$/d using the 3000 m$^3$/d source water. This provided a model case for future urban development in the water deficient region.

Keywords: urban development; wastewater; reclamation; water balance; material balance; optimization

INTRODUCTION

China is a large country with numerous populations. Due to uneven distribution of water resources, northern China is suffering from the problem of chronic water shortage (Wang and Jin, 2006). Of the main watersheds in China, those that have very low per capita water resource are all in northern China, and the most serious conditions are found in the Hai River, Huai River, and Yellow River basins, with per capita water resource as only 164.1, 443.4 and 510 m$^3$/person, respectively (Ministry of Water Resources, 2008). The area of the model case to be studied in this paper is in Xi’an City within the Yellow River basin. Because of the high population density, the per capita water resource is less than 300m$^3$/yr. Therefore, water shortage is the main factor restricting the sustainable development of this city and wastewater reuse has to be taken as a counter measure to mitigate the problem.

The objectives of treated wastewater reuse are mainly for non-potable water supply such as toilet flushing, urban gardening and forestation. This can be conducted by two ways: one is to implement wastewater reuse facilities through the existing centralized urban wastewater systems, and another is to practice onsite wastewater treatment and reuse through decentralized systems (Wildender, 2001). The former often requires large investment for the construction of additional treatment facilities for water reclamation and large scale distribution networks for supplying the reclaimed water to various consumers and may not be always feasible due to economic constraints, while the later can often get rid of long distance transfer of both the collected wastewater and the reclaimed water and may be more feasible under different circumstances (Wang et al., 2008b). On the other hand, the basic requirement of the reclaimed water quality to meet the needs of various
reuse purposes is the prerequisite in practicing wastewater treatment and reuse. For a centralized system which supplies reclaimed water to a large service area, the quality requirement has to be set according to the most rigorous water use among all the reuse purposes, while for a decentralized system which supplies reclaimed water for onsite reuse, the quality requirement can be set according to the specific reuse purpose, or even practicing multiple-quality reclaimed water supply dealing with different reuse purposes.

In order to show the advantages of the decentralized systems to achieve maximized wastewater reuse, this study presents a model case in Xi’an, China where a limited available fresh water source can sustain the demand for various water uses and maintaining a sound local water environment through an independent water system.

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**CASE DESCRIPTION**

**Project location**

The project site is a college located in the southeast suburban area of Xi’an (Figure 1). The college campus is on a hill which is about 15 km from the central city. The average elevation is about 200m higher than the surrounding area. When the college was established in 2001 this area was still undeveloped. Therefore, it was not covered by the urban water supply and sewerage systems and independent water and wastewater system was implemented at the early stage of the campus construction.

**Needs for treated wastewater reuse**

Water supply in this college depends on 5 groundwater wells with a maximum capacity of 3000m$^3$/d. This could meet the demand for potable and non-potable uses only at the beginning period of the college when the number of students was small. However, the college developed very fast and the problem of water shortage appeared quickly with the increasing number of students enrolled and the enlargement of green belt area in the campus which needed large quantity water for irrigation. For this reason, the college became the first community in Xi’an city which began to use the treated wastewater for toilet flushing and gardening when the wastewater treatment and reclamation facility was put into operation in the campus. With its design capacity of 1500m$^3$/d for wastewater treatment, an equivalent quantity of reclaimed water was supplied to the campus for part of the non-potable uses. This successfully decreased the total demand for fresh water supply through groundwater withdrawal.

**Current water and wastewater system in the campus**

Figure 2 shows the water and wastewater system currently used in the campus. This includes (1) fresh water supply facility to distribute groundwater for potable use in the whole campus and non-potable use in some administrative buildings, (2) wastewater collection facility to collect discharged wastewater from all the buildings and to send it to the wastewater treatment facilities, (3) reclaimed water supply facilities to distribute the treated wastewater for toilet flushing, gardening and road sprinkling through a series of pumping stations. In front of the main teaching building, the artificial lake receives part of the reclaimed water as well as some rain water from the campus. It also plays the function of a regulating reservoir where the stored water can be pumped for gardening and road washing in the surrounding area.
Requirement of system upgrading

After several years’ operation, the system gradually showed its limitation to meet the increasing needs for wastewater treatment and reuse. Firstly, the design capacity of the wastewater treatment facilities was 1500 m$^3$/d which was originally calculated as 50% of the maximum daily water consumption excluding the water consumed for gardening, road sprinkling etc. which would not be collectable by the wastewater system. However, the real flow rate of the influent to the treatment system could be over 3000 m$^3$/d in the peak season partially because of the increase of fresh water supply and partially because of the increase of return flow from toilet flushing that used the reclaimed water. Secondly, as the existing treatment facilities were operated under overloading condition, the treated water quality was deteriorating. Because a great portion of the reclaimed water used for toilet flushing in fact formed a closed cycle in the system shown in Figure 2, the pollutants carried by the flushing water after each time of use would accumulate in the closed cycle if they could not be effectively removed in the treatment process. For these reasons, a plan has to be formulated for upgrading the current water and wastewater system in the campus.

Basic considerations

The objectives of system upgrading are to increase the capacity of the existing system for wastewater treatment and production of reclaimed water, and to improve the ability of the whole water and wastewater system for water quality safeguarding to meet both the current and future needs. Toward these objectives, the plan for the system upgrading should follow the principles as below:

1. Quantitatively, the available amount of fresh water will still be limited to 3000 m$^3$/d, which will support a population of 30000 (most are students living in the campus). On the other hand, the green belt coverage in the campus is about 60%. Its water consumption has also to be taken into account. Therefore, fresh water has to be mainly used for potable purposes and most of the non-potable water uses have to be covered by the reclaimed water, including the treated
wastewater and harvestable rain water. A water balance calculation thus has to be carefully conducted.

(2) Qualitatively, the reclaimed water should meet the quality criteria for reuse purposes. However, in this case there are principally two categories of reclaimed water use: an open cycle use such as gardening and road washing where the used water will not flow back to the wastewater system, and a closed cycle use such as toilet flushing etc. where the used water will flow back to the wastewater system. From a viewpoint of safety for water use, hygienic safety would be the main thing to consider for the first category and hygienic safety plus prevention of hazardous substances accumulation in the closed cycle would be important for the second category.

(3) As an independent water system in the campus, wastewater collection and treatment become the processes of reclaimed water production, and an important component of the whole water cycle. In this case, system optimization has to be done under a consideration of high efficiency water use.

![Water system diagram](https://iwaponline.com/wpt/article-pdf/6/1/wpt2011012/382755/12.pdf)

**Figure 2 | Current water and wastewater system at the project site**

**Water balance for the system upgrading**

The available fresh water of 3000 m$^3$/d from the groundwater wells will be the original source of water supply in the campus. With the total population of 30000, the per capita water allocation will be merely 100 L/d which is apparently insufficient to cover all water consumptions and will principally be used only for potable purposes. All non-potable water consumptions have to depend on water reclamation. As the prerequisite for rational planning of the system, an analysis was conducted for estimating the demand for non-potable water demand as shown in Table 1.
In order to make clear whether or not the calculated non-potable water demand can be covered by water reclamation, water balance analysis was conducted as shown in Figure 3 under a consideration of maximum water consumption (full use of the 3000 m$^3$/d fresh water supply). Rainwater harvesting can also be a measure for increasing water supply capacity. In the past 20 years, the average annual rainfall in Xi’an is 536 mm, of which more than 70% is concentrated in the period of June to October. Considering its uneven distribution, the availability of rainwater harvest is estimated as 10% – 20% from the rainwater collectable surface in the study area depending on the collection and storage condition. Considering the rainwater collectable area of about 200000 m$^2$ (including roof area), annual rainfall as 0.536 m and availability of rainwater harvest as 20%, the total quantity of rainwater harvest can be calculated as 21440 m$^3$/yr or about 60 m$^3$/d.

Of the maximum fresh water supply of 3000 m$^3$/d for potable and miscellaneous uses, 80% will be discharged into the wastewater collection system and then sent to the wastewater treatment facilities. On the other hand, in the process of reclaimed water reuse the water for lake replenishment, gardening and road sprinkling is non-collectable after use while that for toilet flushing will discharged into the wastewater collection system again and thus be added to the influent to the wastewater treatment facilities. Therefore, the total influent flow will become $Q_1 + Q_2 = 3600$ m$^3$/d. 90% of this quantity is supposed to be the product of water reclamation, so the reclaimable quantity is estimated to be $Q_R = 3240$ m$^3$/d which is larger than the total non-potable water demand of 3125 m$^3$/d as estimated in Table 1. It can thus be concluded that the scheme of non-potable water supply by wastewater treatment and reclamation in this case is quantitatively feasible.

Table 1: Analysis of non-potable water demand

<table>
<thead>
<tr>
<th>Water usage</th>
<th>Unit</th>
<th>Quantity</th>
<th>Water demand</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilet flushing</td>
<td>40 L/d/person a</td>
<td>30000 persons</td>
<td>1200 m$^3$/d</td>
<td>Timer controlled flushing in most buildings</td>
</tr>
<tr>
<td>Gardening &amp; road sprinkling</td>
<td>3 L/m$^2$/d b</td>
<td>60000 m$^2$</td>
<td>1800 m$^3$/d</td>
<td>–</td>
</tr>
<tr>
<td>Lake replenishment c</td>
<td>20% daily replacement</td>
<td>Volume 3120 m$^3$</td>
<td>(624 m$^3$/d)</td>
<td>Replacement by pumping for gardening</td>
</tr>
<tr>
<td>Lake water loss d</td>
<td>20% of replacement</td>
<td>624 m$^3$/d</td>
<td>125 m$^3$/d</td>
<td>Including evaporation and other losses</td>
</tr>
<tr>
<td>Total</td>
<td>–</td>
<td>–</td>
<td>3125 m$^3$/d</td>
<td>Excluding lake replenishment</td>
</tr>
</tbody>
</table>

a: According to Chinese specification of 20 – 40 L/d/person for toilet flushing, high value for timer controlled flushing in community buildings (Li, 2002).
b: According to Chinese specification of 2.5 – 3.5 L/m$^3$/d for gardening and road sprinkling (Li, 2002).
c: According to Chinese specification of water replacement per time in 4 – 5 days interval (Li, 2002). In this case the lakes will also be reservoirs for water storage and the water replacement will be done by pumping for gardening.
d: According to local practical experience.

Material balance for the system upgrading

Material balance calculation is important for estimating the daily pollutant loading that enters the influent of the wastewater treatment facilities. In order to ensure the reclaimed water quality and prevent the pollutants from accumulating in the water cycle, the pollutant reduction plan has to be formulated based on the material balance calculation results.
Figure 3 | Water balance for the system upgrading

Table 2 summarized the calculation of the pollutant loading regarding organics, nitrogen and phosphorus which relate to the main water quality parameters. Considering the relationship of water balance discussed in the former section, pollutant loadings in the flow from toilet flushing and that in the flow from other miscellaneous usage was calculated separately.

Table 2 | Pollutant loading calculation regarding organics, nitrogen and phosphorus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit loading ( \text{(g/d/person)} )</th>
<th>Population ( \text{(persons)} )</th>
<th>Calculated loading ( \text{(kg/d)} )</th>
<th>Total</th>
<th>Fecal</th>
<th>Miscellaneous</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>42</td>
<td>1260</td>
<td>1620</td>
<td>478.8</td>
<td>781.2</td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>14</td>
<td>30000</td>
<td>420</td>
<td>344.4</td>
<td>75.6</td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>0.8</td>
<td>24</td>
<td>24</td>
<td>16.32</td>
<td>7.68</td>
<td></td>
</tr>
</tbody>
</table>

\( a \): Unit loadings were estimated according to experiences in China (Wang et al., 2008a; Feng et al., 2009).

\( b \): Percents of fecal and miscellaneous were estimated as 38% and 62% for COD, 82% and 18% for TN, 68% and 32% for TP.

Based on the calculation results and considering the water balance relationship shown in Figure 3, a material balance relationship can be established as shown in Figure 4.

The total pollutant loading entering the wastewater treatment facilities will be the sum of the miscellaneous pollutant loading, faecal pollutant loading, and the pollutant loading \( Q_{R1}C_1 \) carried by the reclaimed water to be used for toilet flushing. According to the requirement of water reuse, wastewater treatment and reclamation can be done by different options as will be discussed in the following section. However, if the pollutant concentrations in the reclaimed water for toilet flushing, lake replenishment, and gardening are set as \( C_1 \), \( C_2 \), and \( C_3 \) as shown in Figure 4, the pollutant loading to be reduced by the wastewater treatment facilities can be calculated as

\[
\Delta M = M_T - \sum_{i=1}^{3} Q_{R_i}C_i = M_1 + M_2 - Q_{R2}C_2 - Q_{R3}C_3
\]

and the required removal will be

\[
\frac{\Delta M}{M_T} = \frac{M_1 + M_2 - Q_{R2}C_2 - Q_{R3}C_3}{M_1 + M_2 + Q_{R1}C_1}
\]
The above equations can be applied to each of the pollutants listed in Table 2.

**IMPLEMENTATION PLAN**

Requirements for pollutants removal

Referring to Chinese standard for treated wastewater reuse, the required quality for the 3 kinds reuse purposes should follow the criteria showing in Table 3 (Standardization Administration of China, 2002a, 2002b). Generally speaking, the replenishment of landscaping lakes needs the most rigorous reclaimed water quality, and then that for toilet flushing. The criteria for gardening are less rigorous.

**Table 3** | Quality criteria for different reuse purposes (unit: mg/L)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reuse purpose</th>
<th>Landscaping lake</th>
<th>Gardening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toilet flushing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD₅</td>
<td>10</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>TN</td>
<td>-</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>NH₃-N</td>
<td>10</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>TP</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>SS</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Colour</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Taking the most rigorous case, i.e. water reclamation for the replenishment of landscaping lake, for estimating the requirement for pollutants removal, it can be calculated using Eq. 2 that the required removals for BOD₅, NH₃-N and TP will be 97.0%, 93.7% and 93.4%, respectively. In the calculation, \( Q_R = 3240 \text{ m}^3/d \), \( Q_{R1} = 1200 \text{ m}^3/d \), BOD₅ loading is taken as 50% of the COD loading, and NH₃-N loading is taken as 60% of the TN loading according to the experience in the study area. In this case, not only high organic removal, but also high nitrogen and phosphorus removals will be required. However, if the less rigorous case, i.e. water reclamation for gardening is considered, the required removals for BOD₅ and NH₃-N will become 90.0% and 83.8%,
respectively. To achieve a high removal of pollutants to meet the higher quality, advanced treatment processes may have to be employed while for a moderate removal to meet the lower quality, conventional treatment may still be an option.

**Upgrading of the existing treatment facility**

The existing wastewater treatment and reclamation facility which employed an A-O process (anaerobic+oxic) followed by sedimentation and sand filtration has a treatment capacity of 1500 m$^3$/d. To solve its overloading problem, it is planned that the influent flow to the existing facility should be controlled at the design level. In order to facilitate process operation and management, the operation mode is changed from A-O to A-A-O (anaerobic+anoxic+oxic), the same system as the biological treatment stage of the additional treatment facility to be explained later. Reclaimed water from the upgraded facility can well cover $Q_{R3}$ shown in Figure 3, i.e. water directly supplied for gardening and road sprinkling.

**Construction of additional treatment facility**

As estimated in Table 1, the total demand for non-potable water consumption is much larger than the existing water reclamation capacity. Therefore, construction of additional treatment facilities has to be planned. From the water balance result shown in Figure 3, the total capacity of wastewater treatment should be no less than 3600 m$^3$/d, so the capacity of the newly constructed treatment capacity should be no less than 2100 m$^3$/d. It is thus decided that the design capacity of the new facility should be 2500 m$^3$/d so that the total capacity of wastewater treatment will become 4000 m$^3$/d, 10% higher than the calculated value.

As the reclaimed water from the new facility will be supplied for lake replenishment and toilet flushing, the target water quality is set as that for landscaping lake shown in Table 3. It is thus decided that a hybrid process of A-A-O combined with membrane bioreactor (MBR) will be employed. With the high concentration biomass and long solid detention time in such a treatment system, its performance for organic, nitrogen and phosphorus removal can be much better than the conventional A-A-O process. Combined biological and chemical phosphorus removal is also considered in the process for better nutrient content control in the reclaimed water. The treated water will be supplied for lake water replenishment and toilet flushing as shown in Figure 3. From the lakes water will be pumped for gardening and road sprinkling in the surrounding area.

The planned scheme for existing treatment facility upgrading and additional facility construction is shown in Figure 5.

![Wastewater treatment and reclamation process scheme](https://iwaponline.com/wpt/article-pdf/6/1/wpt2011012/382755/12.pdf)
Reclaimed water distribution and reuse system in the college campus

Figure 6 is the general scheme of the reclaimed water distribution and reuse system in the college campus. The 6 existing pumping stations (PS) will continue to be employed for distributing the reclaimed water to all the campus. Of them, PS 1 and PS 6 will be used for distributing the lower quality reclaimed water for gardening and road sprinkling, and the other 4 will be used for distributing the higher quality reclaimed water for lake (pond) water replenishment and toilet flushing in all the administrative, teaching and dormitory buildings. 4 artificial lakes and ponds are important components in the water reuse system. They play both the functions of landscaping and reclaimed water storage for local gardening and road sprinkling by movable pumps.

DISCUSSIONS

The task of this project was to ensure water supply in the college using the limited available fresh water source. As the per capita water source is only about 100 L/d, which is much lower than the average per capita domestic water consumption of 180~200 L/d in this region, this amount of water source can only cover the basic potable water demand. Because the college also possesses a large campus area (about 0.8 km$^2$) and large green coverage (about 60%), gardening water consumption takes a large percentage in the total water consumption. For these reasons, water reclamation through wastewater treatment and rain water harvesting become the main measure for solving the water shortage problem.

By water balance analysis (Figure 3 and Table 1), we estimated that the demand for non-potable water consumption totaled as 3125 m$^3$/d, a value higher than the fresh water supply capacity of 3000 m$^3$/d. If all the non-potable water consumption would be covered by wastewater treatment and reclamation in order to save the limited fresh water only for potable and related miscellaneous purposes, the recovery rate of water reclamation should be larger than 100%. Such a difficult problem was solved in the analysis by taking into account the recirculation of toilet flushing water in the water utilization loop. The total reclaimable quantity was thus calculated as 3240 m$^3$/d, indicating that water reclamation was quantitatively possible to meet the non-potable water demand. In the analysis we also tried to decrease the water demand by combining the consumption for lake water replacement with water supply for gardening and road washing (Table 1). This would be an effective way to increase the efficiency of water use.

From Figure 3, we also understand that the water system in this college can be seen as an open cycle with continuous inflow (fresh water supply) and continuous outflow (consumed by gardening, road washing, surface evaporation, sludging and other losses) plus a closed circulating flow (toilet flushing water). The closed circulating flow receives most of the pollutants, i.e. the fecal pollutants that take 38% of COD, 82% of TN, and 68% of TP loadings (Table 2). These pollutants may accumulate in the circulating flow if they cannot be effectively removed by wastewater treatment in each cycle of reclamation and reuse. The requirement for pollutant loading reduction was assessed in this study by using the material balance analysis results (Figure 4) and taking into account the water quality criteria corresponding to water reuse purposes (Table 3). Supplying reclaimed water of varied qualities corresponding to varied reuse purposes may be a wise method from the economic viewpoint. A dual quality water reclamation plan was thus formulated in this study that by upgrading the existing wastewater treatment facilities of conventional treatment, part of the collected wastewater could be treated to acquire the lower quality reclaimed water for gardening and road washing, while another part could be treated by newly constructed facilities employing advanced MBR process to acquire the higher quality reclaimed water for lake water replenishment and toilet flushing.
CONCLUDING REMARKS

This study provided an example of maximization of wastewater reuse in an independent local water system where a limited water source could be effectively used to meet a water demand of more than doubled the original water supply capacity. An optimized plan for the existing system upgrading and enlargement was formulated based on the water balance and material balance analyses results. In the water deficient region, urban development and environmental improvement are often hindered by limited available water sources. Therefore, the project discussed in this paper could provide a model case to show the direction of future urban development under similar conditions.
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