Designing sustainable sanitation in urban planning proposed for Changzhou, China
S. M. Kerstens, T. Z. D. de Mes and B. Lue

ABSTRACT

China is undergoing rapid urbanization and economic development. This requires a new approach on spatial planning and environmental infrastructure. In the presented project an example of this approach is given for the city of Changzhou (China) where a new residential area (Qinglong district) will be developed for 100.000 inhabitants. Key issue within the formulation of sustainable sanitation concepts is the integration and management of water, waste and energy in such a way that they will become beneficial to the establishment of the envisaged green city. Starting point was the closing of material cycles focusing on possibilities to recover and reuse valuable resources and energy from “waste” produced in an urban setting. Four different scenarios focusing on water, nutrient and energy recovery were compared with the baseline wastewater management practice. Besides environmental benefits, the economical benefits of sustainable sanitation concepts are attractive, the break even point with the baseline scenario, is already after 5 years, provided that recovered resources will be sold for a marketable price. We believe that presented concepts are applicable for a wide range of new urban development initiatives in China and similar rapidly developing densely populated regions worldwide.

Key words | CO2-emission reduction, economic analysis, energy production, resource recovery, sustainable sanitation

INTRODUCTION

With annual growth rates frequently in the low-double digit range during the previous 15 years, China’s economic development has been impressive. Various authors (Zhang et al. 2002; Van Dijk & Zhang 2005) have identified a negative impact of this economic progress on the environment. China’s already stressed environment is going through additional stress caused by the rapid industrialization and urbanization. Water scarcity and deteriorating water quality of rivers, lakes and groundwater are the result of industrial, municipal and agricultural sewage and drainage discharge (UNDP China 2005). Besides the low treatment rate, with a reported value of 34% in 2002, also a low efficiency in water utilization and a high universal wasting of water are identified. Solving this is considered as the major challenge for China (Zhang et al. 2002).

The in this paper described project is located in Jiangsu province (South East China). Jiangsu province, as a coastal province, is one of five provinces that contributed a total of more than one third of China’s GDP (Heilig 2006). Changzhou city is located in the South of Jiangsu. The nearby located Taihu lake suffered from severe eutrophication in May 2007. As a result of this event and the expected population increase from today’s 1.4 million to a planned 1.8 million people in 2020 and at the same time a planned increase of total GDP in the urban area of 138–150 billion RMB to 370–400 billion RMB in 2020, the Changzhou government will follow a sustainable economic development path. The Qinglong district is identified as a new area in which this sustainable development should be put into practice. Currently the area is used for some minor farming

activities, but should, in 5 years from now, develop into an urban area housing 100,000 people. Qinglong is regarded to start from a greenfield situation.

METHODS

Key issue for sanitation concepts is the integration and management of water, waste and energy. Applying this approach will help the government in achieving its sustainable economic ambition. In the presented concepts the focus is on closing material and energy cycles. Thus, “waste” is no longer perceived as a problem, but as a valuable resource that can be recovered. Optimizing the use of energy combined with the recovery of energy in waste streams contributes to China’s national ambition of reducing CO₂ emissions.

The possibilities and virtues for resource recovery from wastewater and organic waste have been extensively investigated (Otterpohl 2001; Lettinga 2006). With the different resource recovery possibilities a distinction has been made between three major opportunities:

1. Reuse of high quality effluent produced with Membrane Bioreactor (MBR) technology (Van Bentem et al. 2007).
2. Recovery of energy through application of anaerobic treatment (Kujawa-Roeleveld et al. 2005)
3. Recovery of nutrients through application of struvite precipitation (MAP process) focusing on P-recovery (Maurer et al. 2006).

In present study enhanced N-recovery processes like electrodialysis, reverse osmosis or ion exchange were not included, as these are not successfully proven yet (Van Voorthuizen et al. 2008).

Studied scenarios

Based on the identified potential usage of these recovered resources, four scenarios were developed employing source separation and were compared to a baseline scenario (Figure 1).

1. Combined collection and treatment of all wastewater streams (COM) in a (MBR).
2. Treatment of COM plus the organic kitchen waste (OW) fraction after which MBR was applied.
3. Combined collection and anaerobic treatment of toilet wastewater (blackwater BW) and OW, after which the effluent is combined with the remaining wastewater (“greywater GW”) and treated in an MBR.
4. Separate collection of urine (U), enables nutrient recovery as struvite via MAP precipitation; effluent is combined with the separately collected faeces (F) and OW and treated anaerobically. Finally, the effluent of the anaerobic treatment is combined with GW and treated in an MBR.

Baseline scenario: Combined collection and treatment of all wastewater streams (COM) in a conventional WWTP.

Wastewater characteristics

Calculations of greywater and blackwater and urine parameters were based on Kujawa (2005). Table 1 shows the applied values of the in-house water consumption.
In China separate discharge of rainwater from wastewater is common practice. For the irrigation of city parks a value as presented by the city council of 0.75 m³/m²/y is applied.

Efficiency of treatment units and conversion factors

An anaerobic COD removal efficiency of 70% is applied for blackwater treatment (Elmitwalli et al. 2006; De Mes 2007). Effluent characteristics and energy data for an MBR were obtained from the full-scale practical MBR in Varsseveld (Van Bentem et al. 2007). Nitrification and denitrification are assumed to proceed via conventional processes. Calculations of CO₂ emission were based on oxidation of organic matter with an average TOC/COD ratio of 0.33 (STOWA 1998). For the calculation of CO₂ emission as a result of electricity production a CEF/MWh of 0.7822 is applied (http://cdm.ccchina.gov.cn).

Economic costs and benefits

In 2008 10 RMB equaled ± 1 euro. Costs for the sewer system are obtained via DHVs’ local design institute and are 650 RMB/m for pipes inside the city (total 30 km) and 3,000 RMB/m for main pipes (additional 5 km in baseline scenario). For separate collection of blackwater and greywater, costs are 1.5 times higher and 1.7 times higher in case of additional separate urine collection (communication with the DHV sewage department).

Presented capital costs (CAPEX) are based on DHV’s estimates of realized projects and converted to the local Chinese situation by the DHV China office and are calculated by annuities in which the depreciation period for civil works and the sewer system is 30 years, whereas for mechanical and electromechanical equipment 20 years is applied. Operational (OPEX) costs (sludge treatment, labour, maintenance) as well as Consumer Price Index (8.3%), energy price increase (9.8%) and interest (7.8%) were obtained via Chinese local sources. Membranes need to be replaced every 5 years and are considered part of OPEX. Determination of the running costs over time are based on the sum of indexed OPEX and CAPEX. All assumed values in this paper, e.g. sewer price, price for the products, energy price etc., are predicted based on historical market development but can be subject to change. A sensitivity analyses can help to identify the influence of a change of each individual value on the total costs. However, at this stage we consider this outside the scope of this paper.

RESULTS AND DISCUSSION

Wastewater production

The characteristics of produced wastewater streams in different scenarios are presented in Table 2.

Energy data

Figure 2 shows the energy data for the operation of the four different scenarios. In the baseline scenario surface aeration is applied, as this is currently widely applied in China due to its robustness and low maintenance. In the presented scenarios bubble aeration is applied, as this is generally more energy efficient.

Compared to the baseline scenario, application of an MBR (scenario 1) consumes more energy. Based on the loading only scenario 2-4 can be compared, as here organic fraction of the kitchen waste is included. From that perspective, it becomes clear that scenario 2 is worst in terms of energy consumption, due to a high energy input requirement for aeration as well as for membrane filtration. Both scenario 3 and 4 result in an energy producing system, despite the application of an MBR. Scenario 4 is most

Table 1 | Applied values for in-house water consumption

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greywater l/cap/d</td>
<td></td>
<td>90</td>
</tr>
<tr>
<td>Frequency female WC faeces + urine</td>
<td>1/d</td>
<td>1.5</td>
</tr>
<tr>
<td>Frequency male WC faeces + urine</td>
<td>1/d</td>
<td>2</td>
</tr>
<tr>
<td>Frequency male WC urine</td>
<td>1/d</td>
<td>2</td>
</tr>
<tr>
<td>Frequency male urinoir</td>
<td>1/d</td>
<td>4</td>
</tr>
<tr>
<td>Water use WC male/female to blackwater</td>
<td>1/flush</td>
<td>6</td>
</tr>
<tr>
<td>Water use WC male/female to urine</td>
<td>1/flush</td>
<td>3</td>
</tr>
<tr>
<td>Water use urinoir</td>
<td>1/flush</td>
<td>0.1</td>
</tr>
</tbody>
</table>
favorable as part of the nitrogen has been removed during MAP precipitation process and therefore less nitrification and thus aeration is required.

**CO2 emission**

In a WWTP the total CO2 emission is the sum of direct and indirect processes. Direct CO2 emission is the result of oxidation of organic pollutants. Indirect CO2 emission is due to the production of consumed electricity. Figure 3 shows CO2 emission from both processes for the four scenarios and baseline scenario. CO2 emissions related to the electricity requirements are in line with the energy data. However, scenarios 3 and 4, in which part of the organic pollutants is converted anaerobically, thereby producing a far smaller amount of CO2 show a CO2 emission reduction as well. The yearly CO2 emission reduction between scenario 3&4 and scenario 2 is about 5,000 tons. Compared to the baseline scenario a 2,500 tons reduction is achieved. However, part of the produced methane, which is considered to be a 21 fold stronger greenhouse gas than CO2, will dissolve in the effluent of the anaerobic step in scenarios 3 and 4 and be emitted to the atmosphere in the MBR after all. According to Van Haandel & Lettinga (1994) the dissolved methane represents under equilibrium conditions 64 mg/l as COD. Thus, in scenario 3 and 4 will emit, as a worst case scenario, an additional CO2 of 280 ton CO2/y, which equals about 10% of the achieved reduction. Today’s Clean Development Mechanism in which a price for each ton of CO2 of €5 is applicable, provides an additional driver for implementation of sustainable sanitation concepts in which anaerobic treatment is included. In the remaining cost benefit analysis this additional income is not included.

**Water saving**

In the governments’ planning it is indicated that one person consumes between 140–160 l/cap/d. In this project the starting point was that the daily water consumption should not be limited, but the quality does not necessarily need to be the same as of municipal tapwater. It must be noted that the provided amount is based on water used for in-house application (drinking, toilet, showering, etc) as well as external community oriented water use (e.g. road cleaning

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**Table 2** | Wastewater characteristics in the scenarios; COM: all wastewater streams OW: organic kitchen waste, BW: blackwater, GW: greywater, F: faeces, U: urine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3/4</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>m³/d</td>
<td>11,260</td>
<td>11,315</td>
<td>9,000</td>
<td>2,315</td>
<td>1,100</td>
</tr>
<tr>
<td>COD</td>
<td>mg/l</td>
<td>1,000</td>
<td>1,520</td>
<td>445</td>
<td>5,700</td>
<td>11,070</td>
</tr>
<tr>
<td>TN</td>
<td>mg/l</td>
<td>85</td>
<td>105</td>
<td>11</td>
<td>470</td>
<td>500</td>
</tr>
<tr>
<td>TP</td>
<td>mg/l</td>
<td>17</td>
<td>25</td>
<td>4</td>
<td>106</td>
<td>152</td>
</tr>
</tbody>
</table>

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**Figure 2** | Energy produced and consumed in the treatment process.

**Figure 3** | CO2 emissions in the different scenarios.
and gardening). In the present project the daily (in-house) water consumption is determined as 113 l/cap/d of which 90 l is greywater (Table 2). In contrast to the baseline WWTP, an MBR (Derksen et al. 2006; Van Bentem et al. 2007) will comply with the Chinese standards for different uses such as toilet flushing or gardening. A conventional WWTP can in general comply with effluent quality class IB and IA, and irrigation for some non-food agricultural purposes. Table 3 shows the standards, which are referred to.

Therefore in all four scenarios the effluent of the MBR can be reused for all aesthetic related applications as well as for toilet flushing. All other in-house water applications will still be fed by municipal tapwater. Applying the aforementioned, the daily total water consumption is 157 l/cap/day of which only 90.5 l/cap/d is required of municipal tapwater, which equals over a 40% reduction.

**Struvite production**

Scenario 4 includes the struvite production from urine of which an amount of 220 ton/year of struvite is expected. In order to realize a source-separate urine collection system, a more complex and elaborated sewer system is required. It is acknowledged that alternative methods for urine collection are available as well (Mels et al. 2005). Additionally a reactor aimed for struvite precipitation is required. Based on Shu et al. (2006) struvite can be sold at a value of 460 Euro/ton (~4,600 RMB/ton). This price level might not be realistic at this moment (local information), but increasing scarcity of phosphate ore (www.fullermoney.com, 2008) will ultimately have its effect on struvite selling prices.

**Yearly operation costs**

Figure 4 shows the CAPEX based on annuities for the establishment of the presented WWTP and the required sewer system. Specific yearly CAPEX for sewer system ranges from 17 RMB/cap in scenario 1 and 2 up to 25, 29 and 30 RMB/cap for, respectively, scenarios 3 and 4 and the baseline scenario. For the WWTP the specific yearly CAPEX values are 58, 66, 81, 85 and 29 RMB/cap for, respectively, scenarios 1 - 4 and the baseline scenario. It is found that establishment of scenarios 3 and 4 involve almost double the costs of the establishment of the baseline scenario.

Analysis of the OPEX (Figure 5) shows that scenario 3 and 4 (both energy producing) are most cost effective, followed by scenario 1. Scenario 2 comes out less favorable than the baseline scenario. In this estimation it is assumed that 40% of the water that is saved (which equals the amount of water required for toilet flushing and gardening)

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**Table 3** | Discharge limits primary pollutants Class IA and B GB18918-2002 and Control Indexes of Reclaimed Water for Miscellaneous Use (GB/T18920-2002)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>IA</th>
<th>IB</th>
<th>Toilet flushing</th>
<th>Road cleaning &amp; fire fighting</th>
<th>Gardening</th>
<th>Vehicle wash</th>
<th>Civil constr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD</td>
<td>mg/l</td>
<td>50</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOD5</td>
<td>mg/l</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>SS</td>
<td>mg/l</td>
<td>10</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄⁺-N</td>
<td>mg/l</td>
<td>5 (8)</td>
<td>8 (15)</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>TN</td>
<td>mg/l</td>
<td>15</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>mg/l</td>
<td>0.5</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td></td>
<td>5</td>
<td>10</td>
<td></td>
<td>10</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/l</td>
<td>1,500</td>
<td>1,500</td>
<td>1,000</td>
<td>1,000</td>
<td>1,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>mg/l</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.0 – 9.0</td>
<td>6.0 – 9.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fecal coliform</td>
<td>Units/l</td>
<td>10³</td>
<td>10⁴</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figures out of brackets are for water temperature > 12°C, whereas the figures in brackets are requirement for water temperature ≤ 12°C.*
is sold at the price of 2.4 RMB/m$^3$, whereas an additional (assumed) 30% is sold for agricultural purposes at 0.5 RMB/m$^3$. This additional 30% is also sold at the same price in the baseline scenario.

When looking at the development of total yearly running costs in time (Figure 6), it appears that scenario 2 is least favorable, followed by scenario 1 and the baseline scenario. Only scenario 3 and 4 show a distinct pattern, as they, despite high initial investments, result in decreasing running costs. Break-even point with the baseline scenario is after 5 years. Because of the additional struvite production scenario 4 is the most favorable. Again it is emphasized that the treated organic load in scenario 1 and baseline scenario are smaller than in scenario 2–4. Therefore, the former would require an additional infrastructure for the collection, transfer and treatment of organic kitchen waste.

Risk and Sensitivity

- In the presented scenario the starting point is that all water for the toilet flushing and park irrigation is obtained from treated effluent. Figures 7 and 8 show the results when no effluent is sold for higher quality effluent purposes (still 30% used for low-quality purposes) and all effluent from MBR is sold as higher quality effluent (and 100% of the baseline scenario as low quality). Thus, it becomes clear that the application of an MBR only becomes economically attractive if a considerable amount of effluent can be sold for higher quality effluent purposes.

- The effect of small footprint, which greatly increases the economic attractiveness of MBR application, was not included. In a fast urbanizing country like China, this effect will increase.

- It must be taken into consideration that source separated systems bring in a risk of misconnection of the different sewer lines, as was shown in the case of Leidsche Rijn (www.waterforum.net, 20-06-2002) Experiences (personal communication with A. During) reveal that about 1% is falsely connected immediately after finalizing the infrastructure, whereas this number can increase to 15% over time due to private/illegal interventions.
Different scenarios and transport means are available to convey/collect blackwater to a treatment location. In case of a decentralized treatment step, application of vacuum toilet has been successfully demonstrated (Kujawa-Roeleveld et al. 2005; Meulman et al. 2008). In present scenarios it is assumed that for the 100,000 people only one central treatment plant is constructed for which a sewer system based on vacuum toilet is not found feasible due to the long transportation distances and problems with clogging. When a water saving toilet is applied without the mixing of greywater such problems are still a possibility, which can be overcome when transportation is realized via a pressurized system. The required pump energy for this transport was excluded.

Studies have been performed in which the acceptation of source separated systems has been identified as a potential problem for successful introduction (Lienert & Larsen 2006). This issue has not been extensively incorporated in present study.

By offering the possibility for extensive effluent reuse for non-agricultural purposes (park greening), as proposed in the four scenarios, the aesthetics of the environment will be improved. Previous projects in which an increase of green in the living environment was achieved resulted in an increased “willingness to pay” for users of such areas. In this study this price increase has not been included.

CONCLUSIONS

The outcomes of the study that were performed for the Changzhou project show the following.

- By introducing an alternative sanitation several environmental benefits can be realized, resulting in a 40% water saving (by closing part of the water cycle), production of energy (by application of anaerobic technology), reduction of CO₂ emission, and struvite recovery (by treating separate collected urine).

- Economic analysis shows that application of a source separated sewer system followed by treatment in an anaerobic and struvite precipitation and post treatment in an MBR becomes already attractive after a period of 5 years, provided the recovered resources (water,
energy and nutrients) can be sold at mentioned prices. The presence of long term and reliable buyers are essential for the successful economic applicability of presented scenarios.

- Besides the realization of the two basic goals for sanitation (assuring the public health and preventing the environmental pollution), this paper shows that by introducing sustainable sanitation concepts an enhanced resource recovery is possible which stimulates the economic development of rapidly emerging urban areas in China and similar regions.

REFERENCES


STOWA 1998-02 Replacement of COD by TOC, Utrecht (in Dutch).


