Separating grey- and blackwater in urban water cycles – sensible in the view of misconnections?
J. Tolksdorf and P. Cornel

ABSTRACT

The infrastructure approach SEMIZENTRAL has been developed for fast growing cities, to meet their challenges regarding water supply as well as biowaste and wastewater treatment. The world’s first full-scale SEMIZENTRAL Resource Recovery Center (RRC) has been implemented in Qingdao (PR China). Greywater (GW) and blackwater (BW) are collected and treated separately. Measurement of influent concentrations differ significantly from the design values. Thus, the operation strategy for the RRC had to be adapted. Amongst other reasons, the changed influent characteristic was caused by misconnections of GW and BW sewers. Already a misconnection rate of 6–8% requires an extension of the GW treatment process for nitrification/denitrification to fulfill effluent standards. Hence, measures should be taken to avoid or reduce misconnections. Nonetheless, in a semi-centralized scale (>10,000 inhabitants) a 100% avoidance might not be possible. Thus, consequences from misconnections should be considered during the design of source-oriented infrastructure systems.

Key words | implementation, integrated infrastructure system, misconnections, source separation

INTRODUCTION

Urbanization is one of the major trends of the 21st century. The rapidity with which urban growth occurs, usually hand in hand with regional water scarcity, represents a challenge for infrastructure planning. Urban water reuse can contribute significantly to making water available in the future. One approach is the separation of greywater (GW) and blackwater (BW) and, after treatment, reusing the GW that is only slightly or not at all contaminated with excreta.

SEMIZENTRAL is an infrastructure approach for fast growing urban areas. Through its integration of the water, wastewater (WW), and organic waste sectors, SEMIZENTRAL is more resource-efficient than conventional (centralized) systems; urban water reuse and energy recovery are key elements. Furthermore, SEMIZENTRAL is characterized by its system size – between central (entire city) and decentral (single building) – and its approach of district-wise realization of water infrastructure. Thus, the infrastructure system is able to grow with the city; planning and investment risks can be reduced (Bieker et al. 2010).

With the Resource Recovery Center (RRC) in Qingdao, PR China, the SEMIZENTRAL approach has been implemented for the first time in full-scale, treating the GW and BW of 12,000 population equivalents (based on 100 gCOD/(C·d)). The catchment area consists of two newly built housing areas and the so called ShiYuan Village, where three hotels, guest houses, office buildings and a canteen are located. According to the planning, GW includes WW from showers, washbasins and laundries; BW includes toilet WW and kitchen WW. Treated GW is reused for toilet flushing, treated BW for intra-urban irrigation. In addition, food waste from surrounding canteens, hotels, and restaurants is co-digested with the sewage sludge from GW and BW treatment, enabling an energy self-sufficient operation of the RRC (Tolksdorf et al. 2016a).

MATERIAL AND METHODS

Twenty-four-hour composite samples (sampling every 10 min) were taken from the effluent of the BW pre-storage tank and at the influent to the GW aeration basin (after the pre-storage tank and sieve). All samples were analysed for chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP) with cell tests from Merck KGaA.
The influence of potential cross-connections on the GW and BW treatment processes was evaluated by model calculations. Boundary conditions (e.g. effluent limits) and process technology were based on the RRC in Qingdao (cf. Table 1, Tolksdorf et al. 2016a). Two scenarios are investigated, which differ in the GW type (cf. Table 2). Scenario I was based on planning data of the RRC in Qingdao: GW excludes kitchen WW; kitchen WW is part of BW. In scenario II, GW includes all non-fecal household WW flows, BW is only toilet WW. The specific loads for GW in scenario II were chosen in accordance with data by Meinzinger & Oldenburg (2009); the BW loads are calculated as the difference between the loads in GW and total loads in scenario I.

For misconnections, it is assumed that pipes within the private drainage system were swapped. This means, for example, if 5% of GW were discharged to the BW sewer, at the same time 5% of BW would be discharged to the GW sewer. Systematic misconnections are possible as well, e.g. if in scenario I all kitchen WW were discharged to the GW instead of to the BW sewer. But these are not discussed here and should be avoided by measures during the implementation. Based on German standard DWA-A 131 (DWA 2016), oxygen demand and required activated sludge mass (as parameter for the aeration basin volume) are calculated for misconnection rates up to 25%. GW is expected to be warmer than municipal WW, because it contains a high percentage of the warm WW flow from showers. Nonetheless, in Qingdao nearly no differences between the GW and BW temperature were measured (cf. Tolksdorf et al. 2016b). Hence, for the model calculations two temperature levels were chosen. For the higher level the required activated sludge mass was calculated at a design temperature of 20 °C and the average O₂ demand with an average temperature of 25 °C. For the lower temperature level the design temperature was 15 °C and the average temperature 20 °C. Further assumptions are found in Table 1. The results as well as treatment requirements (i.e. carbon removal, nitrification, denitrification) are compared with the system without any misconnections.

### RESULTS AND DISCUSSION

#### Experiences from the implementation of the full-scale RRC

The design of the RRC in Qingdao was based on inhabitant-specific loads according to the Chinese standard GB50101-2005. Their distribution to GW and BW, as well as the specific water amounts, was chosen in accordance with results of Bi (2004). The measured influent concentrations differ considerably from the design values (cf. Figure 1); GW is much more concentrated while BW is more diluted than expected. An additional survey of the GW and BW composition at various points in the catchment areas suggests the following reasons for the differences (Tolksdorf et al. 2016b):

- unexpected user behavior in residential areas: low proportion of shower WW in GW and general tendency towards watersaving,
- high proportion of kitchen WW from canteens and restaurants (partly without grease traps),
- inclusion of kitchen WW into GW although, according to the planning, it is part of BW,
- dilution of BW due to infiltration water,
- cross-connections between GW and BW.

### Table 1 | Basis for model calculations

#### Assumptions for model calculations

- Nutrient elimination required for GW and BW (effluent standard as required in the RRC: TN 15 mg/L, NH₄-N 5 mg/L, TP 0.5 mg/L)
- BW treatment: primary clarifier (removal efficiency: COD 30%, suspended solids (SS) 50%, TN 10%, TP 10% (DWA 2016)), biological treatment with nutrient removal
- GW treatment: sieve (removal efficiency: COD 10%, SS 20% as assumed during design of the RRC), biological treatment with nutrient removal, when required
- Anaerobic sludge stabilization, N-return load (50% of sludge-bound nitrogen) to BW treatment (as in RRC in Qingdao)
- COD fractions: 85% biodegradable, rest according to recommendations for municipal WW in Germany (DWA 2016); same assumptions for GW and BW.

### Table 2 | Influent flow and loads for the scenarios

<table>
<thead>
<tr>
<th>Scenario: BW GW</th>
<th>Scenario: total GW</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scenario I:</strong></td>
<td></td>
</tr>
<tr>
<td>Q&lt;sup&gt;a&lt;/sup&gt;, L/(C·d&lt;sup&gt;b&lt;/sup&gt;)</td>
<td>68</td>
</tr>
<tr>
<td>COD, g/(C·d)</td>
<td>88</td>
</tr>
<tr>
<td>TN, g/(C·d)</td>
<td>11</td>
</tr>
<tr>
<td>TP, g/(C·d)</td>
<td>1.4</td>
</tr>
<tr>
<td>SS&lt;sup&gt;c&lt;/sup&gt;, g/(C·d)</td>
<td>55</td>
</tr>
</tbody>
</table>

<sup>a</sup> Q – flow.
<sup>b</sup> SS – suspended solids.
GW and BW characteristics are influenced by socio-economic boundary conditions and culture. Factors such as user behavior, household appliances and nutrition have an effect (Meinzinger & Oldenburg 2009), leading to a high variance in literature values for separated WW streams. Although some of the differences between the actual and assumed WW characteristics can be explained by such factors, a significant influence from misconnections is likely. This assumption is supported by the results for the concentration levels of COD and TN in combined WW (GW + BW), which are relatively close to the design values (cf. Figure 1), as well as a microbiological survey, which showed no significant difference between GW and BW for Escherichia coli (Tolksdorf et al. 2016b). In addition, the relatively high NH₄⁺N/TN ratio of 0.6 in GW indicates the discharge of urea to the GW sewer, which hydrolyzes fast to ammonia. In comparison, literature values for NH₄⁺N/TN in GW lie typically between 0.10 and 0.25 (Elmitwalli et al. 2005; Hernández Leal et al. 2011; Hocaoglu et al. 2013; Sievers et al. 2014).

After commissioning of the RRC, the treatment processes had to be adapted to meet the effluent standard despite the changed effluent characteristic. The GW module was designed for carbon removal only, because the TN effluent concentration was expected to be 3 mg/L, and thus lower than the TN effluent limit of 15 mg/L. Now, with median TN effluent concentration of 55 mg/L, nitrification and denitrification are required. The GW treatment occurs in an MBR. The chosen design sludge age was 25 d, with the aim of reducing fouling processes at the membrane modules. Thus, nitrification is possible and NH₄⁺N effluent concentrations were usually <1 mg/L. The aeration basin consists of two consecutive chambers, each with independent aeration grits and mixers. The latter were installed because the mixing energy due to aeration would not have been sufficient. Pre-denitrification was intended by switching off the aeration in the first chamber. Nonetheless, the oxygen concentration in the second chamber was low as well (<0.5 mg/L). Compared to the expected nitrate effluent concentration, based on the theoretically possible removal rate with the given nitrate recirculation by the return sludge, the actual nitrate effluent concentration was lower. Nitrification and denitrification occur apparently simultaneously and the TN effluent standard was met. The total influent flow and COD load (GW + BW) in 2015/2016 were only 38% and 32%, respectively, of the design values, because many buildings in the catchment area were still unoccupied. With increasing influent flow and load due to increasing occupancy of the buildings it can be expected that the aeration capacity in the GW module will not be sufficient. In this case, a part of the GW flow can be bypassed to the BW module, as long as its hydraulic capacity is sufficient.

The example of SEMIZENTRAL in Qingdao shows the operational challenges from unexpected effluent characteristic, amongst others, because of misconnections between the separated streams. Thus, the possibility of misconnections should be considered during planning and implementation of similar systems.

**Risks of misconnections**

To date, the occurrence and consequences of cross-connections within reuse systems have mainly been discussed in terms of the water distribution system, meaning misconnections between tap water and reuse water (e.g. Oesterholt et al. 2007; Hambly et al. 2012; Friedler et al. 2015). When
separating WW streams, misconceptions between these streams are also possible; cross-connections can occur on different levels: in households, in sewer systems and within the treatment plant. In conventional systems, misconceptions in separated drainage systems (storm water/sewage) are also known and are mostly discussed with regard to receiving water quality (e.g. Ellis & Butler 2015; Panasiuk et al. 2015). The effects on WW treatment are usually limited to rain events and mainly involve the hydraulic capacity. In contrast, with GW and BW separating systems, the influence is expected to be not temporally limited and to involve more than the hydraulic conditions, as misconceptions result in considerable changes of the influent characteristic, such as concentration level and nutrient ratio (cf. Figure 2).

The example of the RRC in Qingdao shows the importance of measures to avoid misconceptions. Integrated, non-conventional systems require higher interlinking of the various planning disciplines. Apart from linking the planning of different sectors (water supply, WW treatment and waste disposal), it is crucial to also include actors involved in planning and construction of the buildings within the catchment area. Investors, architects, building technology planners, but also installation technicians and workers on the construction site, should be informed about the requirements of the integrated water and WW system. Especially in countries where untrained migrant workers are often employed, control systems for the correct separation of WW streams should be implemented. In the SEMIZENTRAL project in Qingdao, different pipe colors were recommended for tap water and service water supply to increase awareness on the construction site and to reduce the risk of cross-connections. The same is recommendable for the WW drains; different profiles might also be a possible measure against cross-connections. For small systems (single building up to a few hundred population equivalents), it might be possible to implement an effective control system to identify misconceptions at an early stage. However, this is increasingly difficult with increasing system size, with the higher number of connections and actors involved. Misconceptions might not be completely avoidable. Therefore, as recommended by DWA (2014), the effect of possible misconceptions should be considered during the planning of the WW treatment; the treatment processes should be adaptable, at least to a certain degree.

Influence of misconceptions on treatment processes

Treatment requirements for GW can change due to misconceptions. With the example of the higher temperature level: already a 2% cross-connection rate leads to the requirement of nitrification for GW treatment in scenario I. For scenario II, with total GW, above a 3% misconnection rate, nitrification is necessary (cf. Figure 3 and Table 3). If the misconnection rate exceeds 6% in the system with GW light or 8% with total GW, additional denitrification would be required. For lower temperature level, the excess sludge production and thus N incorporation into the

Figure 2 | Influent characteristic and flow depending on misconnection rate in scenarios (Sc.) I and II.
Biomass is higher. Therefore, nitrification and denitrification are required at a slightly higher misconnection rate compared to the higher temperature level (cf. Figure 3).

The oxygen demand for the treatment of GW light increases considerably with increasing misconnection rate; with 12% cross-connections ($T_{\text{average}}$ 25°C), the oxygen

### Assumptions for nitrogen balance:
- nitrification required, if $\text{NH}_4^-\text{N} > 5 \text{ mg/L}$; denitrification, if $\text{NO}_3^-\text{N} > 12 \text{ mg/L}$
- with nitrification: $\text{NH}_4^-\text{N} = 0 \text{ mg/L}$
- with denitrification: minimum proportion of denitrification volume on total aeration basin ($V_D/V_{\text{total}}$): 0.2

**Figure 3** | Influence of misconnection rate on average oxygen demand and required activated sludge mass ($M_{\text{SL,SS}}$).

**Table 3** | Influence of pre-treatment elimination rates on the result at higher temperature level

<table>
<thead>
<tr>
<th>COD, TN</th>
<th>Nitrification</th>
<th>Denitrification</th>
<th>Oxygen Demand</th>
<th>Biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD 0%, TN 0%</td>
<td>&gt;3%</td>
<td>&gt;5%</td>
<td>&gt;6%</td>
<td>&gt;10%</td>
</tr>
<tr>
<td>COD 10%, TN 0%</td>
<td>&gt;2%</td>
<td>&gt;3%</td>
<td>&gt;6%</td>
<td>&gt;8%</td>
</tr>
<tr>
<td>COD 30%, TN 10%</td>
<td>&gt;2%</td>
<td>&gt;2%</td>
<td>&gt;6%</td>
<td>&gt;8%</td>
</tr>
</tbody>
</table>
demand is already double the demand without any incorrect connections. Hence, when dimensioning the aeration system, the effects of misconnection rates have to be considered. The required aeration basin volume (or required activated sludge mass) is also influenced by the degree of incorrect connections. The effect is higher with low design temperature (cf. Figure 3), because of the higher required increase of the (aerobic) sludge age for nitrification; at 20 °C a sludge age of 5 days would be sufficient for nitrification.

The influence of misconnections is higher for systems with the collection of GW light (cf. Figure 3), as GW and BW differ more strongly in their characteristic, compared to a system with total GW. Because of the higher COD in total GW, proportionally more nitrate is denitrified, leading not only to low effluent concentrations (Figure 3) but also to relatively higher oxygen recovery by denitrification. Moreover, at a misconnection rate of 25%, the percentage of BW on used water in the GW module is 38% in scenario I, but only 19% in scenario II with total GW.

The influent concentration to the GW module depends on the elimination rate of the sieve. The elimination rate, in turn, is dependent on the particle characteristics. These may differ between GW light, total GW and their mixtures with BW. Hence, the calculation is verified for different elimination rates (no elimination and elimination rate as for pre-clarifier (cf. Table 1)). There is no significant influence on the overall result (cf. Table 3). Nonetheless, for a system with GW light, the elimination rate probably changes with misconnections and cannot be assumed to be constant. Comparing GW light without any misconnections and 0% TN, 10% COD removal by sieve to GW light with 25% misconnections and 10% TN, 30% COD removal by sieve, the difference is 198% for oxygen demand and 100% for the required activated sludge mass. These values are lower, compared to the calculation with a constant removal rate of the sieve (cf. Table 3), because more of the additional COD and TN loads from the misconnections are removed by the sieve. However, the overall tendency remains.

For BW treatment, the oxygen demand as well as the required activated sludge mass (aeration tank volume) is reduced with increasing cross-connection rates, because the influent loads decrease. For complete denitrification, external carbon has to be dosed. With increasing misconnections, the C/N ratio increases and the influent concentration decreases (cf. Figure 2). As the required TN effluent concentration remains the same, the required N-elimination rate decreases. Thus, less COD dosage is needed with increasing misconnection rate. In scenario II (total GW) 22% and in scenario I (GW light) 38% less COD can be dosed for BW denitrification.

In summary, the model calculation shows that the possibility of misconnection requires flexible solutions for the process technology. GW light systems are more highly affected than total GW systems. Moreover, the influence of misconnections increases with decreasing temperature level.

How can systems adapt to uncertainties resulting from possible misconnections?

If faulty connections cannot be completely avoided, systems with total GW should be preferred for systems with GW light, because they are more robust against cross-connections. Nonetheless, total GW is more polluted; thus greater effort to produce service water is required, compared to systems with GW light.

Whenever separated treatment of GW and BW has to be designed, it should be based on scenario analysis for different influent characteristics due to misconnections. Misconnections result mainly in capacity problems of the GW module. Although carbon removal would be sufficient for GW treatment, it is advisable to dimension the GW treatment (the sludge age) for nitrification, because nitrification is already required at relatively low misconnection rates. If higher nitrogen influent concentrations are possible, even the possibility of adaptation measures for denitrification should be kept in mind. Regarding the variation in the required activated sludge mass (aeration basin volume), an MBR enables higher flexibility for the sludge concentration. When dimensioning the GW module, the sludge concentration should be set in a middle range so that, in case more sludge mass is needed, the sludge concentration can be increased.

Even though the oxygen demand for GW treatment is highly dependent on the degree of misconnections, the sum for GW and BW is less variable (cf. Figure 3). It decreases slightly with increasing misconnections, because less ammonia is nitrified in BW treatment, and in GW treatment, additional oxygen is recovered by denitrification. Therefore, it would be advisable to plan the installed blowers so that they could be used optionally for BW as well as for GW. This requires coordinated planning of the GW and BW treatment (e.g. same water depth in the aeration basin to ensure similar pressure head for the blowers) and a respective grading of the blowers. Through this, subsequent upgrading of the aeration system or extensive (uneconomic) backup capacities might be avoidable.
In addition, bypasses between GW and BW treatment are recommendable to achieve more flexibility and to reduce required safety margins of the GW module. While the BW modules’ aeration capacity and aeration basin volume might be sufficient, the hydraulic capacity of the BW module must be considered (cf. Figure 4). Moreover, the production of service water should be ensured. With the example of scenario I: the aeration basin of the GW module is calculated with a design sludge concentration (mixed liquor suspended solids (MLSS)) of 7 g/L. In case of misconnections, MLSS can be increased up to 10 g/L, meaning 30% backup capacity for the required sludge mass in the system. Hence, the aeration basin volume of the GW module would be sufficient up to 5% misconnection rate. If the entire system were aimed to work up to 25% misconnection rate, the additional required hydraulic capacity of the BW module to treat the bypass from the GW module would be 26% (cf. Figure 4). The calculation is based on average influent flows, assuming pre-storage tanks for equalization, as built in the RRC in Qingdao. It might be recommendable to treat BW in an MBR system as well. By building external membrane chambers, this gives the opportunity to connect membrane modules either to the BW or to the GW module and thus to reduce the overcapacity. Appropriate flexible pipe connections between activated sludge tanks and membrane chambers must be provided. In general, modularization of treatment units increases flexibility (Spiller et al. 2015) and should be considered where possible.

Is GW and BW separation in semi-centralized systems recommendable?

Measures to avoid misconnections should be taken. However, implementation of GW and BW separation on a semi-centralized scale (>10,000 population equivalents) still includes the risk of misconnections. Additionally, unexpected user behavior can influence the influent characteristic; e.g. for the implemented RRC in Qingdao, low warm water consumption led to a low temperature level of GW (Tolksdorf et al. 2016b). Uncertainties regarding basic data for dimensioning should be considered as well (Tolksdorf & Cornel 2017). Thus, relatively high safety margins might be required, possibly leading to less efficient designs regarding space or energy, the latter because of machines not running at the optimal operating point. Moreover, the design is more complex; this may also apply to the operation. In cities, not all treated BW can be used for irrigation; hence, advanced nutrient removal is probably required, which means greater effort for treating BW (external carbon dosage, possibility of insufficient acid capacity, requirement of decolorization, etc., cf. Tolksdorf et al. (2015)). Considering all these aspects, the advantage of higher acceptance of treated GW reuse should be weighed against the challenges resulting from the separation. The reuse of treated total WW is, from a technical point of view, possible. Successful examples, such as NEWater in Singapore, show that, with extensive public relations work, acceptance can be gained.

CONCLUSIONS

In fast growing urban areas, freshwater resources are often limited and not sufficient. Thus, intra-urban water reuse is becoming increasingly important. Separation of GW and BW is a promising solution in terms of public acceptance for water reuse in households and for reduced efforts for service water production. Pure GW requires typically just carbon removal and disinfection to reach intra-urban reuse standards for non-potable service water. However, model
calculations showed that already low misconnection rates, e.g. less than 10% BW in the GW system, lead to the additional requirement of nitrification and even denitrification. Experienced operational challenges in the RRC in Qingdao, due to changed influent characteristic, might not be an exception, but could happen in other similar implementations. Thus, measures to avoid or reduce misconnections are important at an early stage of the planning and implementation of such systems. Especially for GW treatment possible misconnections should be taken into consideration, when planning the process technology. The necessity of GW and BW separation should be critically, site-specifically questioned.

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