Semicentralized greywater and blackwater treatment for fast growing cities: how uncertain influent characteristics might affect the treatment processes

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ABSTRACT

The SEMIZENTRAL infrastructure approach has been developed for fast growing cities, to meet their challenges regarding water supply as well as biowaste and wastewater (WW) treatment. The world’s first full-scale SEMIZENTRAL Resource Recovery reference plant has been implemented in Qingdao (PR China). Greywater (GW) and blackwater (BW) are collected and treated separately. Measurement of influent concentrations revealed significant differences, compared with the design values. Values from the literature for GW and BW characteristics vary more markedly than for municipal WW; recommended design values are still lacking. Moreover, cross-connections between GW and BW can influence the influent characteristics considerably. Consequences for the design of GW and BW treatment are evaluated for boundary conditions, which require high effluent quality for both treatment modules. Model calculations illustrate the significant influence of uncertain WW characteristics on the required aeration basin volume and oxygen demand for GW and BW treatment; however, uncertainties are considerably reduced for the combination of these modules. Thus, a flexible design of the treatment plant is required. A possible concept for such a design is presented.

Key words | implementation, integrated infrastructure system, source separation, wastewater characteristics

INTRODUCTION

Rapid urbanization, industrialization, and improved living standards lead to increasing water demand in urban areas; easily available water resources in many urban agglomerations have already been depleted and other additional resources are required (WWPA 2015). Seawater desalination and water transfer are possible solutions, but they considerably increase the energy demand for the water service. Water reuse is an alternative that can contribute significantly to making water available in the future. One approach is the separation of greywater (GW) (non-fecal contaminated wastewater (WW)) and blackwater (BW) (toilet WW). The reuse of treated GW usually finds greater acceptance by users (e.g., Domènech & Saurí 2010; Jiawkok et al. 2013).

The SEMIZENTRAL approach and its implementation

SEMIZENTRAL is an alternative infrastructure approach for fast growing urban areas. In a Resource Recovery Center (RRC), service water for non-potable purposes is produced from WW. Organic waste is integrated into the anaerobic sludge treatment. This increases the biogas output and, accordingly, heat and power production, which enables an energy self-sufficient operation of the RRC. In addition to its resource efficiency, SEMIZENTRAL is characterized by its system size, between central (entire city) and decentral (single building), and the district-wise realization. Whenever a new district is developed, an RRC can be built for this particular district. This enables co-growth of the infrastructure system with the city and reduces planning and investment risks stemming from uncertainties in long-term forecasts of the city’s development.

A SEMIZENTRAL RRC has been implemented in Qingdao (PR China) for 12,000 population equivalents (based on 100 gCOD/(C·d)) that treats, in total, 1,500 m³/d WW. GW light (from showers/bath, wash basins and washing machines) and BW (toilet WW and kitchen WW) are collected separately. The catchment area consists of two residential areas, two hotels, and the ShiYuan village, where a hotel, guest houses,
office buildings, and a canteen are located. The treated GW is used for toilet flushing. BW originates from conventional flush toilets and is used for intra-urban irrigation, following treatment (Tolksdorf et al. 2015). Excess service water/irrigation water is discharged to a water body; thus, not only Chinese reuse standards but also the effluent standard for WW treatment plants apply (cf. Figure 1) and the most stringent legal value is applicable. GW and BW are treated aerobically with a membrane bioreactor (MBR), because both effluents are reused, although for different purposes. Because of expected low total nitrogen (TN) influent concentration, the GW treatment was designed for carbon removal only. BW, in contrast, contains the major proportion of nutrients. Nitrification and denitrification are required, which were realized in a combination of pre- and post-denitrification. Because of the low C/N ratio in the influent, as well as the required high N-elimination rate (162 mg/L down to 15 mg/L), external carbon dosage is a calculative necessity. Acetic acid dosage into the post-denitrification step was planned (Tolksdorf et al. 2015).

Following commissioning, measurements of the GW and BW influent concentrations in 24h-composite samples (24h-CS) showed values that differed significantly from the design values (cf. Figure 2). These design values were derived from inhabitant-specific loads given in the Chinese standard for the design of WW treatment plants (GB 50101-2005). The assumptions for their distribution to GW and BW, as well as the specific amount of water, are in accordance with the results of Bi (2004). Additionally, GW and BW samples from different points of the catchment areas indicated significant differences within the catchment area (cf. Figure 2). The chemical oxygen demand (COD) and TN concentration in combined WW, calculated from median values for GW and BW, correspond well with the values assumed during design (COD: 90%; TN: 102%, Tolksdorf et al. 2016). Thus, misconnections (Tolksdorf & Cornel 2016) and/or differing load distribution between GW and BW are probably responsible for the changes in the influent characteristics. Other reasons are:

- unexpected user behavior in residential areas: low proportion of shower WW in GW, in the winter, and a general tendency towards water saving;
- different types of GW: hotel 2 excludes kitchen WW (as planned); in the other parts of the catchment area, GW includes kitchen WW with a very high proportion of kitchen WW in GW from the ShiYuan Village (and from the canteen kitchen, where grease traps are partly lacking); and
- dilution of BW due to infiltration water (Tolksdorf et al. 2016).

The implementation of SEMIZENTRAL in Qingdao exemplifies the challenge of deriving design values from the literature. The possible influence of misconnections, as well as differing user behavior/ratio of different WW types and infiltration into the sewer, have to be considered. In order to meet the prescribed effluent limits, the treatment processes in the RRC in Qingdao had to be adapted. Although the GW module was designed for carbon removal only, nitrification and denitrification are required (Tolksdorf et al. 2016).
MATERIAL AND METHODS

The differences between design values and actually measured data are relatively extreme and might partially result from site-specific boundary conditions such as low occupancy of buildings within the catchment area and thus, alterations in the proportion of WW sources (hotels/restaurant kitchens/housing). Differences might be less extreme in other catchment areas. Nonetheless, compared with a conventional system, higher uncertainties of influent characteristics are to be expected because of potential misconnections and varying load distributions. Thus, the influence of additional uncertainties from varying load distributions between GW and BW on dimensioning was evaluated. A model for load distribution between GW and BW was defined on the basis of literature data. GW is defined as WW that includes all household WW except toilet WW (total GW). Design calculations were based on the German standard DWA-A 131 (DWA 2014) and the assumptions in Table 1. The influence of misconnections is discussed by Tolksdorf & Cornel (2016) and results are integrated into the development of recommendations for future planning.

RESULTS AND DISCUSSION

Inhabitant-specific pollutant loads from the literature as a basis for dimensioning?

Surveys are strongly recommended as a basis for dimensioning treatment systems (DWA 2014), but they may not always be possible. In the case at hand, inhabitant-specific loads were used to determine the influent characteristics at WW treatment plants. The WW characteristics are influenced by socio-economic boundary conditions and culture; factors such as user behavior, household appliances, and nutrition have to be taken into account (Meinzinger & Oldenburg 2009). Accordingly, the person load (pollutant load emitted by a person in a catchment area of a treatment plant) can vary strongly. In Germany, 120 gCOD/(C·d) is assumed (DWA 2000), but the specific load typically ranges from 110 to 130 gCOD/(C·d) (Henze & Comeau 2008, assuming COD = 2 · BOD). Additionally, for source separation systems, it is necessary to determine how the pollutant loads are distributed to the streams. Many studies have been conducted to characterize GW and BW and, from these,
suggestions for design values (for European conditions) were derived (Meinzinger & Oldenburg 2009; DWA 2014).

To evaluate the effect of differing load distributions between GW and BW on the design of the treatment processes, model assumptions for the load distribution were defined, based on literature data containing values for both flows. Literature values for COD and TN loads in GW and BW vary considerably. The comprehensive literature review by Meinzinger & Oldenburg (2009) resulted in a similar range and median for the COD loads (cf. Figure 3 [1] compared with [3]). Apart from disparities in analyses and data quality, variations in literature values may originate from different definitions and site specifics (Meinzinger & Oldenburg 2009). For GW, a marked variation of the loads may derive from the various types of GW, e.g., including/excluding kitchen WW or laundry, although, in this study’s literature review, only data for total GW were included. Very low inhabitant-specific loads were excluded from the model assumptions, because they are probably caused by the absence of inhabitants (e.g., time at workplaces) during sampling times (e.g., Wendland 2009).

For the total load, three scenarios (‘min’, ‘median’, ‘max’); cf. Table 2) were calculated, and the COD and TN loads or their distribution were varied independently of each other, from minimum to maximum. The oxygen demand and required activated sludge mass (MMLSS) for GW and BW treatment and combined WW were calculated, including nitrification and denitrification, if required (cf. Figure 4). COD and TN are related to each other. Hence, the COD/TN ratios were additionally taken into account when defining the value range (cf. Figure 4(d)), to ensure that unrealistic WW compositions were not assumed.

**BW treatment**

With the model assumptions, the average oxygen demand for BW treatment is 59 g/(C·d) ±32% and the required sludge mass 437 g/C ±17%. The high uncertainty is mainly related to differing total loads (greater distance between planes for ‘min’ and ‘max’ in Figure 4(b)). The proportion of total COD has almost no influence on the oxygen demand. Regardless of the assumed influent load, an external carbon dosage is required for denitrification. Thus, higher COD influent loads only reduce the methanol dosage. The dosed methanol load is thus 19 g/(C·d) ±99%. An increase in the nitrogen load increases the load of nitrified ammonia and, consequently, the oxygen demand. If the total load could be evaluated beforehand, the difference due to varying distributions for BW would be considerably lower: with the ‘median’ total loads, the oxygen demand is 61 g/(C·d) ±9% and the required sludge mass 441 g/C ±7%.

**GW treatment**

Compared with the BW treatment, uncertainties regarding the dimensioning of the GW treatment are even more pronounced: for unknown total loads (either ‘min’, ‘median’, or ‘max’ scenarios), the oxygen demand is 26 g/(C·d) ±45%, and the required biomass is 116 g/C ±36%. In contrast to the BW treatment, these uncertainties are more strongly related to the differing load distribution between GW and BW (cf. greater distance between minimum and maximum value within a plane in Figure 4(c)). Treatment requirements can change as a function of the proportion of the total COD and TN influent load. At low influent loads, carbon removal is sufficient. Here, an increase of the COD load results in an equivalent increase of the oxygen demand, whilst an increasing nitrogen load only leads to an increase in the effluent concentration. When the effluent ammonia concentration exceeds 5 mg/L, nitrification is required. At this point, the oxygen demand and required biomass increase abruptly, the latter because of the higher required sludge age. At very high nitrogen influent loads, denitrification may be necessary to meet the nitrogen effluent limit. Accordingly, the oxygen demand decreases, as oxygen is recovered by denitrification, whereas the additional anoxic volume increases the required sludge mass in the system. If the total load can be determined, the uncertainties regarding the oxygen demand and required sludge mass decrease only slightly. For example,
24 gO₂/(C·d) ± 34% and 106 gMLSS/C ± 24% are required in the 'median' load scenario.

The influence of the assumed GW and BW influent flows on the above results were evaluated. With the same influent loads and required effluent concentrations, varying influent flows alter the required removal rates. Although the absolute values for the required activated sludge mass change, the percentage deviation from the mean value is the same (cf. Table 3).
The influence on the oxygen demand is negligible. For GW treatment, the influence of the GW flow is stronger. With high water consumption (cf. ‘Qmax’ in Table 3), denitrification is not required, and nitrification only at high total TN load percentages. Thus, the uncertainties regarding the required sludge mass are smaller. Nonetheless, relatively pronounced uncertainties remain when dimensioning the GW treatment.

Overall system compared with conventional WW treatment

Due to variations in specific loads, the oxygen demand for total WW treatment is 66 g/(C·d) ± 18%, whilst, for the sum of GW and BW, 82 gO₂/(C·d) ± 32% is required. Thus, due to uncertainties regarding the distribution of total loads to the separated streams, the dimensioning results become significantly less certain. The higher oxygen demand, compared with the conventional system, results mainly from the additional oxygen demand for COD oxidation in GW treatment, because oxygen is either not recovered by denitrification, or only in smaller amounts. For total WW treatment, 477 g/C ± 27% biomass is required, and the total for GW and BW treatment amounts to 534 g/C ± 15%. The greater uncertainties for total WW treatment result from differing COD/TN ratios between the minimum/median/maximum scenarios, and, thus, differing proportions of the anoxic volume in the total aeration basin volume (V_D/V_tot) and, respectively, the required sludge ages. For BW treatment, by contrast, the V_D/V_tot and, consequently, the sludge age, are constant; any additional required denitrification capacity is compensated by methanol dosing. The uncertainties for the sum of GW
and BW treatment are considerably reduced if the total loads can be estimated by measurement campaigns: for the ‘median’ scenario, the oxygen demand is 85 g/(C·d) ±10% and the required biomass 543 g/(C·d) ±2%.

In addition to COD and TN influent loads, TP and total suspended solids (TSS) loads as well as other parameters can differ. TP and TSS mainly affect the required aeration basin volume. In Qingdao, GW was assumed to be considerably warmer than BW, due to water from showers. However, measurement campaigns in the winter yielded a low temperature level, probably due to the small proportion of shower water (Tolksdorf et al. 2016). Water consumption can also vary, leading to different concentration levels and, therefore, for identical effluent limits, to changes in the required removal efficiency (see above). Hence, uncertainties regarding the dimensioning of the treatment system may be even greater than discussed above.

**Influence of misconnections**

In conventional systems, misconnections in separated drainage systems (storm water/sewage) are known and usually discussed with regard to receiving water quality (e.g., Ellis & Butler 2015; Panasiuk et al. 2015). With respect to WW treatment plants, they mainly affect the hydraulic conditions during rain events. In GW and BW separating systems, additional misconnections between GW and BW can potentially occur on different levels: in households, in sewer systems, and within the treatment plant. These misconnections can lead to considerable alterations of the influent characteristics to the treatment lines, and this not only to a temporally limited extent. Using the example of median values for GW and BW composition according to Meinzinger & Oldenburg (2009), nitrification for GW treatment will be required with 4% misconnections between GW and BW sewers, denitrification with 10%. With a 25% misconnection rate between GW and BW, the oxygen demand for GW treatment increases moderately by 20% and the required aeration basin volume by 50%. For systems with GW light (assumptions for Qingdao, without kitchen WW), the effects are considerably stronger: for a 25% misconnection rate, the oxygen demand increases by 230% and the aeration basin volume by 125% (Tolksdorf & Cornel 2016).

**Consequences for the planning of GW and BW treatment**

Compared with conventional systems, literature-based design values and possible misconnections can result in higher uncertainties regarding the influent characteristics and, thus, in risks for the planning of GW and BW treatment. Hence, measures are required to reduce these uncertainties.

**Reduction of uncertainties**

With regard to the design basis, comprehensive measurement campaigns for total WW, at least, are strongly recommended to determine the influent characteristics. However, this might not always be possible, especially
when the infrastructure is planned and built simultaneously with the city district. In this case, the use of literature-based, inhabitant-specific loads should be complemented by values of best-practices examples of similar applications and, of course, by measured values whenever available. The risk of misconnections can be reduced by:

- the supply of information regarding requirements of the WW system to all relevant players within the planning and construction process of buildings in the catchment area (e.g., architects, building service engineers, plumbers);
- usage of differently colored sewer pipes (a common practice for service water supply); and
- implementing a control system during the construction phase.

Nonetheless, the high number of connections in a semi-centralized system with more than 10,000 inhabitants still bears a risk of misconnections. The remaining uncertainties related to the influent loads, due either to unknown load distribution or to misconnections, mainly influence the dimensioning of the GW treatment. Thus, a flexible design of the treatment processes is required.

Flexible process design

In Qingdao, MBRs were built for GW and BW treatment. MBRs have not only the advantage of high effluent quality, but also a greater flexibility of the activated sludge mass in the system, due to a wider possible range of the sludge concentration. By choosing a middle range for the design MLSS, an adaptation that depends on the influent conditions is possible. The GW module should be designed to enable nitrification and denitrification, if required. In the case of the RRC in Qingdao, the design sludge age was 25 d (Tolksdorf et al. 2016). The activated sludge basin consists of two consecutive chambers, each with a mixer and an aeration grid (Tolksdorf et al. 2016). Because of the aim of pre-denitrification, the aeration in the first chamber was switched off. Intermittent denitrification would be an alternative. The treatment capacity (or reserve capacity) of the GW module has to be limited, for economic reasons. The adaptability to varying influent conditions can be further increased with a partial bypass of GW to the BW module, in case the treatment capacity of the GW module is not sufficient.

The influence of an uncertain load distribution on the design of BW modules is smaller (see above). With increasing misconnections, the oxygen demand and required aeration basin volume decrease because of decreasing influent loads (cf. Tolksdorf & Cornel 2016). However, the option of co-treating BW with a proportion of GW has to be considered during the design of the BW module. For example, if the BW is treated in an MBR (as in the RRC in Qingdao), at least some of the membrane modules should be usable for both GW or BW filtration, to avoid hydraulic limitations. Such a modular approach, where units provide only one basic function and can be connected or disconnected non-destructively from a system, was suggested by Spiller et al. (2015), as part of a flexible urban water infrastructure. The modular design should be considered for other parts of the treatment as well, e.g., mechanical pretreatment.

The sum of the required oxygen demand for GW and BW treatment is less variable with changing load distribution (cf. Figure 4) or misconnections (cf. Tolksdorf & Cornel 2016). Thus, by designing blowers that could be used for the aeration of BW or GW, safety margins or overcapacities could be reduced. A coordinated planning of the GW and BW module is required, e.g., for choosing the blower grading. Pipes should be laid within pipe channels, so that they are easily accessible and changes are relatively easy to make.

It is recommended that the GW and BW modules consist of at least two or more lines that can be operated independently. In addition to higher flexibility in general, this might also enable the production of effluents with differing water qualities. For example, in the summer, irrigation water with higher nutrient content could be produced from BW, and only BW that will be discharged is treated, including advanced nutrient elimination. The bypass from the GW to the BW module can also be used for optimization: if less service water that is produced from GW is needed, the ‘excess’ GW can be co-treated with BW, so that the external carbon dosage would be reduced.

Such a design increases the flexibility of the GW and BW treatment; an adaptation to the actual influent conditions or changing treatment requirements is possible within reasonable limits. Nonetheless, there are some drawbacks. Although standardization might decrease costs, due to the smaller size and higher number of units, investment costs might be higher. The design can result in high complexity, which might result in faulty operation. Thus, well-qualified staff are important.

Planning process

Based on the results from measurement campaigns, scenario analyses should be conducted to evaluate the possible
effects of misconnections and (in case only combined WW is analyzed) of varying load distributions.

To achieve flexibility in sanitation in urban areas, Spiller et al. (2013) suggested, amongst other approaches, phased design. SEMIZENTRAL is a phased design approach: the implementation of RRCs occurs stepwise, according to the district development of a city. In this way, it is possible to learn from experience with one implementation for the next. If the catchment areas remain similar between two implementations, uncertainties regarding the influential characteristic are reduced. If processes and equipment in one RRC are similar between treatment modules and to those used in other plants in a city, maintenance can be simplified.

Although full capacity is expected to be reached faster at the semicentralized scale, compared with centralized plants, underload can be expected during commissioning. This enables a kind of phased design of the RRC itself. Thus, a two-step planning/construction approach is suggested. In the first step, the general outline of treatment modules is planned and built, whereby high adaptability is taken into account for the process design. For commissioning (under underload conditions), only part of the mechanical equipment is installed, e.g., for one line. In a second step, after commissioning and data collection, the relevant modules can be adapted and optimized to the actual requirements.

Economic aspects

Compared with a conventional system, the investment costs for the treatment plant/RRC will increase, due to the separation of GW and BW. The main reason is a higher number of machines and sensors/measurement devices. Moreover, more nutrients are eliminated in a GW and BW separating system, because of the higher concentration level (and the same effluent limits) in BW (cf. Tolksdorf et al. 2013). However, in terms of operational cost, this increases the costs for chemicals (external carbon for denitrification and precipitant). Nonetheless, the main advantage of semicentralized RRC derives from the production of service water for non-potable purposes as well as the integration of organic waste (electricity production reduces energy costs; reduction of transport costs). Thus, the economic evaluation strongly depends on local boundary conditions such as alternative water sources (e.g., groundwater availability or seawater desalination), alternative waste disposal (e.g., landfill or composting) and energy prices. Model calculations have shown that, under specific boundary conditions, semicentralized RRC have an economic advantage (Cornel et al. 2013; Liesegang 2016). Moreover, the district-wise, subsequent implementation, in parallel with the city’s growth, reduces the planning and investment risks related to uncertainties regarding the future city development. In addition, the system is less vulnerable to external factors such as natural disasters; even if one RRC and its infrastructure fail completely, only a part and not the entire city is affected (Bieker et al. 2010).

However, the pricing system is another important aspect for the economic feasibility. In many countries, prices do not follow the cost-recovery principle. Water production and WW treatment are often heavily subsidized. The costs for the RRC in Qingdao were higher than for a typical Chinese WW treatment plant. The price for service water is regulated by the government (1 RMB/m³ or approx. 0.15 USD) and does not correlate with the costs for service water production. Thus, when deciding on prices or subsidies, the overall system (water supply, WW and waste treatment) has to be considered. This is still uncommon, because different companies and government authorities are usually involved in or responsible for the different infrastructure sectors. Thus, in order to use the available water as well as financial resources more efficiently, a higher linkage between the sectors is required.

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. Because such concepts are mainly developed for new housing areas and, to date, only a few systems implemented on a larger scale exist, it might be difficult to carry out representative surveys to determine GW and BW characteristics. In such cases, it is common practice to use inhabitant-specific loads based on the experiences of the designers. Literature data on GW and BW characteristic vary markedly, making it hard to derive basic planning data for dimensioning. Model calculations have shown that, compared with a conventional system without source separation, uncertainties for the design are considerably higher, due to the additional possible variation of load distribution between GW and BW. Moreover, misconnections can strongly affect the influent characteristic and, thus, the treatment processes. To reduce possible variation of influent data, data for combined WW should be collected through surveys, at least. In addition, measures against misconnections have to be taken. Remaining uncertainties due to varying load distribution and/or misconnections mainly involve the dimensioning of the GW module, whilst the uncertainties
for the entire system (sum of GW and BW treatment) are considerably fewer. For urban areas, where high effluent standards apply, a flexible design for a semicentralized RRC, in combination with planning and construction in two steps, was suggested. GW and BW treatment should be planned as an overall system and not independently.

Nonetheless, for each individual project, the necessity for GW and BW separation should be considered critically. Compared with a system that reuses treated combined WW, the efforts for collection and the complexity of treatment are much greater. The requirement for advanced nutrient removal for BW treatment results in significant treatment efforts (external carbon dosage, possibly insufficient acid capacity, or required decolorization, etc., cf. Tolksdorf et al. 2015). These challenges should be weighed against the advantage of an (expected) greater acceptance of reuse water, produced from GW, for toilet flushing. From a technical point of view, the reuse of treated combined WW is possible, and successful projects already exist.

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