Characterization of domestic graywater and graywater solids

Jan Christian Sievers and Jörg Londong

ABSTRACT

The knowledge of loads and concentrations is fundamental for the design of graywater treatment units, but the data on the characteristics of graywater and in particular graywater solids are weak. As general design values regarding graywater treatment facilities are not available for Germany, the objective of this article is to elaborate the characteristics of graywater and graywater solids. This paper describes the results of six sampling campaigns carried out on graywater systems in the German cities Berlin, Lübeck and Kiel. All graywater samples were collected proportional to the flow and the graywater solids were gathered separately. The collected data include graywater volumes and characteristics regarding the organic pollution (chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD₅)) and nutrients (total nitrogen (TN), total phosphorus (TP)). The graywater volume fluctuated depending on the location. The specific average flow was 68 litre per inhabitant per day (L/inh.d). Inhabitant-specific loads of 49.3 gCODt/inh·d, 28 gBOD₅/inh.d, 1 gTNt/inh.d and 0.38 gTPt/inh.d (subscript ‘t’ = total) were found. Information about the composition of graywater solids in terms of quantity and quality is seriously lacking. Therefore, graywater solids were examined with respect to organic matter (COD) and nutrients (TN, TP). The contribution of graywater solids with particle sizes over 200 microns in relation to the total inhabitant-specific load was approximately 3–8% depending on the parameter. The qualitative and quantitative characteristics of the investigated graywater fractions may serve as a base for the estimation of design values.

Key words | design values, graywater characterization, graywater solids, graywater, NASS, new alternative sanitation systems

INTRODUCTION

Graywater is defined as wastewater from baths, showers, and washing machines as well as dishwashers and kitchen sinks, excluding wastewater from toilets (DIN EN 12056-1 2001; DIN 4045 2003; Jefferson et al. 2004; Birks & Hills 2007). Because of different system boundaries, e.g. the inclusion or exclusion of graywater from kitchen wastewater, the graywater definition varies in international studies. Graywater that includes wastewater from washing machines, dishwashers or kitchen sinks only is usually referred to as dark graywater (DWA 2014). Wastewater from bathrooms, showers and baths is named light graywater (Friedler & Hadari 2006; Birks & Hills 2007; Chaillou et al. 2011; DWA 2014). Graywater varies widely in quantity and composition depending on user’s behavior, the equipment of the households (e.g. dishwasher), the used cleaning agents (e.g. detergents, soaps, softeners, toothpaste), the quality of the water used (e.g. drinking water) and the type of water distribution as well as household occupancy, gender, age, country, and character and climate of the area (Eriksson et al. 2002; Oldenburg et al. 2008; Donner et al. 2010; Boyjoo et al. 2013). Graywater is the largest domestic wastewater flow accounting for 50–75% of the household wastewater (Eriksson et al. 2002; Lazarova et al. 2003; Friedler 2004). The graywater volume in Germany is about 60–90 litres per capita per day (LPCD) (Otterpohl et al. 1999; Rosenwinkel et al. 2004; fbr 2005; DWA 2014). The information available in the literature shows a wide variability regarding the parameters total suspended solids (TSS), biochemical oxygen demand (BOD₅), chemical oxygen demand (COD) and the macronutrients total nitrogen (TN) and total phosphorus (TP). The span of concentrations for graywater originating from mixed sources are: TSS 23–298 mg/L, BOD₅ 56–477 mg/L, COD 13–1585 mg/L, TN 0.6–47.8 mg/L and TP

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et al. and to estimate design values for graywater treatment units. Machines) with respect to organic matter and nutrients and bathrooms (hand basins, showers, bathtubs, washing solids originating from kitchens (kitchen sinks, dishwasher) this paper is to characterize graywater and graywater material characteristics of the material non-existent (Eriksson et al. 2010). Therefore, the aim of this paper is to characterize graywater and graywater solids originating from kitchens (kitchen sinks, dishwasher) and bathrooms (hand basins, showers, bathtubs, washing machines) with respect to organic matter and nutrients and to estimate design values for graywater treatment units.

MATERIAL AND METHODS

Sampling sites

The six sampling campaigns were carried out in three different graywater systems in Berlin, Lübeck and Kiel. The model project ‘Block 6’ is located in the district Friedrichshain-Kreuzberg in Berlin, Germany. Three sampling campaigns were realized in a multistorey building of ‘Block 6’ comprising 20 apartments and 51 residents. The graywater from showers, bathtubs and hand washing basins, as well as kitchens and washing machines, is purified in a decentralized treatment plant and used for toilet flushing (Nolde 2014). The sampling campaigns were carried out for a period of 7 days in November 2012, 10 days in April 2013 and 10 days in March 2014. All samples were taken directly from a collection pipe inside the building (Sievers 2017).

The housing estate ‘Flintenbreite’ is located in Lübeck, Germany, and was one of the first source separation projects in Germany on a larger scale. Graywater from baths and kitchens is treated in a decentralized vertical subsurface loaded reed bed system. The sampling campaigns were conducted for 12 days in November/December 2013 and 11 days in May 2014. The location of the measuring point was in front of the first sedimentation tank of the graywater treatment unit. Twelve semi-detached houses with 43 to 44 residents are connected to this sedimentation tank. The length of the graywater pipe to the tank is about 116 m and has a nominal diameter of 150 mm (Sievers 2017).

The third residential area ‘Kieler Scholle e.G.’ is located in Kiel, Germany. The graywater is drained by gravity flow pipes with a total length of about 350 m and treated in a decentralized treatment plant. The graywater treatment facility consists of a mechanical treatment unit, a two-stage subsurface loaded reed bed system and a maturation pond. During the sampling campaign 44 to 46 inhabitants were connected to the graywater system. Sampling took place in September 2016 for 7 days. The sampling point was in front of the first sedimentation tank of the graywater treatment facility (Sievers 2017).

Sampling of graywater

The sampling device for the first two campaigns in ‘Block 6’, Berlin, essentially consists of a solid separation unit with filter bag, a culvert (siphon) and a pump-well. The graywater solids are retained in the filter bag while the liquid phase of the graywater flows through a culvert where the sampling took place. Subsequently, the graywater was pumped from the pumping sump via a second flow meter back to the graywater collection pipe (cf. Sievers et al. 2014). During the first sampling campaign, the samples were taken time proportional in 10-minute intervals with 150 mL sample volume. In the second sampling, the samples were taken in an interval of 2 minutes with 30 mL sample volume. The sampling was performed with an automatic sampler with cooling system and 24 bottles of one litre each. After sampling, the raw incremental graywater samples were mixed into daily flow-proportional samples and subsequently analyzed.

The sampling device of the other four campaigns was similar to the first two ones, but the flow was measured with an ultrasonic flow meter upstream of the sump pit. This setup allows a sampling frequency as a function of flow. A second flow meter was installed behind the pump sump. The auto-sampler took one sample of 50 mL for every 15 L of graywater. Due to the control of the auto-sampler by the flow meter, all samples were taken proportional to the flow. The bottles of the auto-sampler were replaced twice a day and the samples were stored at 4 °C.

Graywater solid samples were collected separately with a filter bag (200 μm) which was placed in the inflow of the sampling device. The filter bag was emptied once a day. This approach of the separate collection of solids and liquid phase was developed by Hartmann (2009) and adapted to the graywater sampling campaigns. The schematic configuration of the sampling device for Berlin (3rd campaign), Lübeck and Kiel is shown in Figure 1.

Analytical methods

The analyses were performed on raw graywater and graywater solids. All graywater samples were stored at 4 °C
and analyzed within 24 h after completion of the sampling events. The samples were analyzed regarding suspended solids (TSS), COD, BOD₅, TN and TP. COD, TN and TP were analyzed using Hach Lange cuvette tests and a Hach Lange DR 3900 spectrophotometer. For the determination of the BOD₅ the respirometric method with OxiTop® systems of WTW was used. The analyses of TSS of the liquid phase (0.45 μm membrane-filter) as well as dry matter (DM) and the organic part of the dry matter (ODM) of the graywater solids were performed according to authorized German standard methods.

The graywater sludge was dewatered by gravity for 2 hours and then homogenized using an IKA T 50 Ultra-Turrax with S 50 N – W 65 SK cutting head. The dewatering-filtrate was discarded because it accounted for less than 0.1% of the total amount of graywater. Thus it had no influence on the result. During the first two sampling campaigns in Berlin the sludge samples were preserved by deep-freezing. In the subsequent sampling campaigns the samples were stored at 4 °C and transported to accredited laboratories within 12 hours after each of the completed sampling events. All analyses of solids were performed by accredited laboratories in Weimar, Lübeck and Berlin. COD, TN and TP were analyzed in accordance with German standard methods.

Statistical methods

The presented data of inhabitant-specific loads and concentrations were calculated as mean (M) values and medians (Mdn). Standard deviation (SD) and ranges of minimum and maximum values are given allowing the estimation of value ranges and the data quality. The measured data were tested using the Kolmogorov–Smirnov test whether a normal distribution can be assumed. Control for outliers in the data base was done using the Grubbs test.

RESULTS AND DISCUSSION

The sampling device used during the measurement campaigns allows a separate assessment of the liquid and the solid phase of the graywater flow. The existing information regarding the composition of graywater solid phase is extremely sparse. With respect to particles, organic parameters and nutrients, this information is essential in order to determine the best available practice for sludge management of graywater systems (Eriksson et al. 2010). The 24 h composite samples of graywater solid phase showed, after dewatering, minimum and maximum wet masses (WM) between 324 and 1,371 g/d with an average value of 740 g/d. A specific load of the wet mass of 15.5 grams per inhabitant per day (g/inh·d) was found on average. The dry residue (DM) and the ODM of the graywater solid phase had mean values of 2.3 g/inh.d and 1.8 g/inh.d respectively. The ignition loss of graywater solid phase showed a mean of 78 ± 8% with a range of 58–93%. For the COD₅ (subscript ‘s’ refers to the solid phase), an arithmetic mean of 152 g/d and 3.1 g/inh.d respectively was found. COD₅ loads were in a range of 0.6–8.8 g/inh.d. The arithmetic means of the inhabitant-specific load for TP₅ and TN₅ were very low with about 0.01 g/inh.d and 0.08 g/inh.d. The statistical characteristics of the graywater solid phase are given in Table 1.

Figure 1 | Schematic figure of the sampling device. (T) temperature measurement, (pH) pH-probe, (p) hydrostatic level probe, (EMF) electro-magnetic flow meter, (UFM) ultrasound flow meter, (S) automatic sampling (Sievers 2017).
Table 1 | Average loads of graywater solid phase in the field studies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n</th>
<th>Unit</th>
<th>M</th>
<th>SD</th>
<th>Mdn</th>
<th>Range</th>
<th>Unit</th>
<th>M</th>
<th>SD</th>
<th>Mdn</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic matter</td>
<td>WM</td>
<td>g/d</td>
<td>740</td>
<td>270</td>
<td>715</td>
<td>324-1371</td>
<td>g/inh.d</td>
<td>15.5</td>
<td>5.1</td>
<td>14.6</td>
<td>3.8-26</td>
</tr>
<tr>
<td></td>
<td>DM</td>
<td>g/d</td>
<td>108</td>
<td>51</td>
<td>104</td>
<td>33-278</td>
<td>g/inh.d</td>
<td>2.3</td>
<td>1</td>
<td>2</td>
<td>0.64-5</td>
</tr>
<tr>
<td></td>
<td>ODM</td>
<td>g/d</td>
<td>85</td>
<td>46</td>
<td>84</td>
<td>29-258</td>
<td>g/inh.d</td>
<td>1.8</td>
<td>0.8</td>
<td>1.7</td>
<td>0.6-4</td>
</tr>
<tr>
<td></td>
<td>CODs</td>
<td>g/d</td>
<td>152</td>
<td>97</td>
<td>128</td>
<td>28-447</td>
<td>g/inh.d</td>
<td>3.1</td>
<td>1.9</td>
<td>2.8</td>
<td>0.6-8.8</td>
</tr>
<tr>
<td>Nutrients</td>
<td>TP</td>
<td>g/d</td>
<td>0.7</td>
<td>0.42</td>
<td>0.53</td>
<td>0.18-2.8</td>
<td>g/inh.d</td>
<td>0.01</td>
<td>0.006</td>
<td>0.01</td>
<td>0.003-0.04</td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>g/d</td>
<td>4.1</td>
<td>1.8</td>
<td>3.9</td>
<td>1.2-11</td>
<td>g/inh.d</td>
<td>0.08</td>
<td>0.04</td>
<td>0.08</td>
<td>0.03-0.22</td>
</tr>
</tbody>
</table>

Table 2 presents the average concentrations and loads of the liquid graywater phase after solid phase separation. The collected graywater showed mean inhabitant-specific TSS-loads of 7.5 g/inh.d and concentrations of about 110 mg/L. Inhabitant-specific loads for BOD5 and COD were determined as 28 g/inh.d and 46.1 g/inh.d, ranging from 16-54 g/inh.d and 23-45 g/inh.d respectively. The mean values of BOD5- and COD-concentrations were 405 mg/L and 167 mg/L. In contrast to the results of Almeida et al. (2009), the inhabitants showed higher values than those reported elsewhere (Almquist & Håneus 2006; Vinnerås et al. 2006; Knerr et al. 2008; Meinzinger & Oldenburg 2009). The results of the field studies as well as the literature values demonstrate that the graywater flow highly depends on the users’ behavior, socio-economic conditions and ecological awareness of the inhabitants.

TSS-concentrations between 107 mg/L and 324 mg/L were determined in the field studies. The mean TSS-concentration of 167 mg/L is higher than the values reported by Almquist & Håneus (2006), Lesjean & Gnirss (2006) and Elmitwali et al. (2003), but in a similar range to the concentrations found by Karabelnik et al. (2012). The inhabitant-specific load has a mean value of 11.2 g/inh.d, ranging from 6 to 22 g/inh.d. The determined average TSS-load is in a similar order of magnitude as the value of the German standard DWA-A 272 (DWA 2014) of 13 g/inh.d and the results of Almeida et al. (1999), Almquist & Håneus (2006), Jönsson et al. (2005) and Londong & Hartmann (2006). On the basis of the experimental setup, it was noted that graywater solids with particle sizes >200 μm had a percentage of 21% of the total TSS-load.

The organic parameters BOD5 and CODt showed loads of 16-54 g/inh.d and 26-86 g/inh.d with average values of 28 g/inh.d and 49.3 g/inh.d, respectively. The corresponding concentrations were 417 mg/L and 734 mg/L. In contrast to the average CODt-load which was in the same range as the orientation value given in the German standard (DWA 2014), the organic parameters BOD5 and CODt showed higher values than those reported elsewhere (Almquist & Håneus 2006; Vinnerås et al. 2006; Knerr et al. 2008; Meinzinger & Oldenburg 2009). The results of the field studies as well as the literature values demonstrate that the graywater flow highly depends on the users’ behavior, socio-economic conditions and ecological awareness of the inhabitants.

Table 2 | Average loads and concentrations of the liquid graywater phase in the field studies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n</th>
<th>Unit</th>
<th>M</th>
<th>SD</th>
<th>Mdn</th>
<th>Range</th>
<th>Unit</th>
<th>M</th>
<th>SD</th>
<th>Mdn</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic matter</td>
<td>TSS</td>
<td>26</td>
<td>g/inh.d</td>
<td>7.5</td>
<td>1.7</td>
<td>7.0</td>
<td>3.2-11</td>
<td>mg/L</td>
<td>110</td>
<td>26</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>COD</td>
<td>54</td>
<td>g/inh.d</td>
<td>46.1</td>
<td>13.4</td>
<td>43.7</td>
<td>23.4-85</td>
<td>mg/L</td>
<td>680</td>
<td>135</td>
<td>690</td>
</tr>
<tr>
<td></td>
<td>BOD5</td>
<td>51</td>
<td>g/inh.d</td>
<td>28.0</td>
<td>8.8</td>
<td>27.4</td>
<td>16-54</td>
<td>mg/L</td>
<td>405</td>
<td>96</td>
<td>415</td>
</tr>
<tr>
<td>Nutrients</td>
<td>TP</td>
<td>54</td>
<td>g/inh.d</td>
<td>0.37</td>
<td>0.1</td>
<td>0.38</td>
<td>0.18-0.62</td>
<td>mg/L</td>
<td>5.6</td>
<td>1.8</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>55</td>
<td>g/inh.d</td>
<td>0.93</td>
<td>0.28</td>
<td>0.94</td>
<td>0.46-1.7</td>
<td>mg/L</td>
<td>13.8</td>
<td>3.2</td>
<td>13.5</td>
</tr>
</tbody>
</table>
the BOD$_3$-load was about 35% higher than the corresponding guide value (DWA 2014). Compared to the studies of Oldenburg et al. (2008) and DBU (2005) the COD$_t$-loads found were slightly higher than the loads in Lübeck Flintenbreite. Other authors like Palmquist & Jönsson (2003), Parkinson et al. (2005), Vinneras et al. (2006), Kujawa-Roeleveld & Zeeman (2006) or Hernández Leal (2010) detected COD-loads in a similar range of 45–52 g/inh.d. In contrast to the BOD$_5$-loads found during the field-measurements, the BOD$_5$-values based on literature are usually lower (Palmquist & Hanæus 2003; Almquist & Hanæus 2006; Kujawa-Roeleveld & Zeeman 2006; Vinneras et al. 2006; Knerr et al. 2009). The average COD- and BOD$_5$-loads comprise about 41% and 47% respectively of the ‘common’ specific loads in municipal wastewater. About 6.3% of the COD$_t$ is attributable to the COD$_s$ of the graywater solids with particle sizes $>$200 μm. The major share of the organic pollution has been found in the liquid graywater phase. On the basis of the collected data of the field studies a mean COD/BOD$_5$ ratio of 1.8 was calculated, which is slightly lower than for domestic wastewater and indicates a good aerobic biodegradability. This COD/BOD$_5$ ratio matches well with other literature studies (DBU 2005; Palmquist & Hanæus 2003; Almquist & Hanæus 2006; Knerr et al. 2008).

With respect to the parameters TN$_t$ and TP$_t$ mean concentrations of 15 mg/L and 5.9 mg/L and average inhabitant-specific loads of 1 g/inh.d and 0.38 g/inh.d, respectively, were detected. TN$_t$- and TP$_t$-loads were in the range 0.5–1.75 g/inh.d and 0.2–0.63 g/inh.d, respectively. The inhabitant-specific ammonia (NH$_4$-N) and nitrate (NO$_3$-N) loads were on average 0.18 ± 0.1 g/inh.d and 0.06 ± 0.02 g/inh.d corresponding to concentrations of 2.8 ± 0.17 mg/L and 0.9 ± 0.2 mg/L, respectively. Consequently, most of the nitrogen was organically bonded. This may be a result of the small-sized sewer networks of the sampling sites. Due to the lack of urine and feces, the nitrogen and phosphorus loads of graywater are substantially lower compared to domestic wastewater. In contrast to the mean TP$_t$-load, which is about 24% lower than the given guide value of the German guideline (DWA 2014), the average TN$_t$-load meets the value of the guideline. Compared to many other literature values, the average TN$_t$- and TP$_t$-loads found during the sampling campaigns were slightly lower (Palmquist & Hanæus 2005; Almquist & Hanæus 2006; Vinneras et al. 2006; Hernández Leal et al. 2007; Knerr et al. 2009), but nevertheless the ranges of the TN$_t$- and TP$_t$-loads determined showed a good comparability to the loads found in the literature. Similar can be observed for the NH$_4$-N-loads which were in the same range of values found by Jönsson et al. (2005); Karabelnik et al. (2012) and Parkinson et al. (2005). With regard to the daily TN$_t$- and TP$_t$-loads, it can be stated that the graywater solids with particle sizes $>$200 μm have average shares of 8% and 3.2% of the daily loads. Based on the collected data a BOD$_5$/TN$_t$/TP$_t$ ratio of 100/3.6/1.4 was calculated. This ratio is lower compared to domestic wastewater and indicates a nitrogen deficiency, which could lead to problems in the context of biological wastewater treatment processes.

The values of loads and concentrations established during the sampling campaigns varied by a factor between about two to four. In Germany, the derivation of design values for wastewater plants is commonly based on the technical guideline ATV-DVWK-A 198 (2003). In accordance with the ATV-DVWK-A 198 guideline, parameters for design purposes are given as 85%-percentiles. Based on the sampling campaigns, 85th percentiles of about 56, 37, 12.5 and 0.5 g/inh.d were determined for the parameters COD, BOD$_5$, TN and TP, respectively. These loads can also be considered as approximated design values.

**CONCLUSION**

This paper describes the results of six field studies in Germany conducted in order to characterize the quantity and quality of individual domestic graywater. Based on the
The majority of the COD-, BOD$_5$-, TN- and TP-loads were detected in the liquid phase of the graywater. The BOD$_5$/TN$_t$/TP$_t$ ratio was 100/3.6/1.4 and has a theoretical nitrogen deficiency and therefore a sub-optimal nutrient distribution for aerobic degradation. The inhabitant-specific loads of the macronutrients TN$_t$ and TP$_t$ were 1 g/inh.d and 0.38 g/inh.d, respectively. The contribution of the graywater solids with particle sizes over 200 microns in relation to the total inhabitant-specific loads of TN$_t$ and TP$_t$ were 8% and 3.2%, respectively.

- On average, an inhabitant-specific graywater flow of 68 lpcd can be expected.
- The mean inhabitant-specific loads for the organic pollution were 49.3 g/inh.d and 28 g/inh.d for the parameters COD$_t$ and BOD$_5$, respectively. The BOD$_5$ load was significantly higher than most values found in literature. The average COD load is corresponding to over 45% of the average COD-load of domestic wastewater. For the organic parameters, a COD/BOD$_5$ ratio <2 (1.8) was found. This indicates a good degradability in aerobic treatment units.
- With regard to the inhabitant-specific COD$_t$-load, the share of the graywater solid was 6.3% of the daily load.
- The inhabitant-specific loads of the macronutrients TN$_t$ and TP$_t$ were 1 g/inh.d and 0.38 g/inh.d, respectively. The contribution of the graywater solids with particle sizes over 200 microns in relation to the total inhabitant-specific loads of TN$_t$ and TP$_t$ were 8% and 3.2%, respectively.
- The BOD$_5$/TN$_t$/TP$_t$ ratio was 100/3.6/1.4 and has a theoretical nitrogen deficiency and therefore a sub-optimal nutrient distribution for aerobic degradation.
- The majority of the COD$_t$, BOD$_5$, TN$_t$- and TP$_t$-loads were detected in the liquid phase of the graywater.

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