Design and configuration criteria for wetland systems treating greywater
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ABSTRACT
Design and configuration for wetlands treating greywater are usually based on literature data obtained from domestic wastewater operating wetlands. It is very important to determine proper criteria for design and configuration to provide efficiency and minimum maintenance, avoiding bad odour and clogging amongst others, ensuring the acceptance of householders. The aim of this work was to design a wetland system treating greywater for a household and determine whether the chosen criteria were appropriate. Some of the criteria taken into consideration for design and configuration were: quantitative and qualitative characteristics, desired removal of biochemical oxygen demand (BOD) and suspended solids (TSS), substrate and ornamental aspect of the system. The system was composed of a grease trap (kitchen), sedimentation tank, a horizontal flow constructed wetland (HF-CW), intermittent feeding system, and a vertical flow constructed wetland (VF-CW). The results showed that the suggested design and configuration were in accordance with the expected efficiency. Being a compact system, it was susceptible to peak flows, temporarily deteriorating the performance of the HF-CW. The hybrid system, however, showed to cope well with influent fluctuations. The overall performance of the system shows that the removal of turbidity, TSS, COD and BOD were over 88%, reaching 95% removal for both BOD and turbidity.

Key words | greywater, ornamental plants, performance, reuse, sizing, vertical flow

INTRODUCTION
The term greywater is used when designating all the wastewater produced in a household, not being toilet wastewater (Morel & Diener 2006), i.e. bath, dish and laundry water. The reuse of greywater at household level has been stimulated for water saving reasons, and its end use in the household depends on its quality. Most common applications of untreated greywater are non-edible garden irrigation, washing cars or sidewalks (Paulo et al. 2007), while treated greywater is generally used for toilet flushing (Jefferson et al. 2004).

Greywater has to be handled carefully to avoid waterlogging, smell, and the uncontrolled release of chemicals and anthropogenic elements, including microorganisms, into the environment (Ridderstolpe 2004). A potential concern about greywater characteristics is the high COD/BOD ratio and nutrient deficiency in terms of both macro and micro nutrients, which demonstrates potential retardation of the efficacy of biological processes (Jefferson et al. 2004). Besides, certain components in greywater, like surfactants and salts, amongst others, may alter soil properties and damage plants (Garland et al. 2000; Gross et al. 2005; Wiel-Shafran et al. 2006). Despite of the greywater characteristics, the most common treatment systems for greywater at household or small communities level are constructed wetlands (CW). Reeds and rushes are considered useful plants for wastewater treatment, taking...
up and storing nutrients themselves, providing a growing area for microorganisms, stimulating the soil activity by root excretion and reducing the volume of the effluent by evapotranspiration (Mars et al. 2003).

For household level greywater treatment, the required area and construction costs are matters of concern. The segregation of greywater and blackwater, no matter the environmental and health related benefits, is generally considered an extra expense at first sight. To stimulate domestic wastewater segregation, effective and low-cost systems should be developed or optimised allowing safe greywater reuse for different purposes. Gross et al. (2007) developed a system based on a combination of a vertical flow constructed wetland (VF-CW) with water recycling and a trickling filter, achieving very good results. Recycling in CW seems to be a very effective way of improving oxygen transfer and avoiding clogging but increases investment and operation costs due to the required pump.

Problems with clogging in horizontal flow constructed wetlands (HF-CW) in the inlet area are regularly reported in literature for both domestic sewage and greywater treatment (Behrends et al. 2007; Paulo et al. 2007; Tuszyńska & Obarska-Pempkowiak 2008). However, clogging of the top layer and odour release is also reported for VF-CW (Platzer et al. 2007; Tuszyńska & Obarska-Pempkowiak 2008). Apparently, clogging problems are related to (i) the level of pre-treatment the wastewater is subjected to before being directed to the wetland, as well as to (ii) the porosity and hydraulic conductivity of the substrate (media) used. With respect to the required pre-treatment, the findings in literature diverge: some authors suggest a septic tank with a HRT varying from 1–5 days as pre-treatment (Phillipi & Sezerino 2004; Jenssen et al. 2005) while others obtained good results with a combination of sedimentation tank and grease trap (Shrestha et al. 2001). Platzer et al. (2007) suggest that, for the treatment of greywater using VF-CW, only a grease trap for the kitchen fraction is enough as a pre-treatment, provided that the VF-CW is properly designed, i.e. ensuring good distribution and rapid infiltration of greywater on the surface of the CW and allowing for 4–8 hours intervals between each application.

Design and configuration of constructed wetlands treating greywater are usually based on literature data obtained from domestic wastewater operating wetlands. Both vertical and horizontal flow are considered, as well as hybrid systems. Literature suggests an area of 0.5–3 m² per person when scaling down for household application (Shrestha et al. 2001; Buenfil 2004; Jenssen et al. 2005). However, it is very important to determine proper criteria for dimensioning and configuration, to provide efficiency and minimum maintenance, and to avoid, amongst others, bad odour and clogging, in order to ensure the acceptance by householders.

The aim of this work was to design a wetland system treating greywater based on pre-determined criteria and to evaluate whether the chosen criteria were appropriate, based on system removal efficiency and operation and maintenance requirements.

**METHODS**

The system was conceived to treat the greywater (shower, kitchen sink and laundry fractions) of a 9 persons household, located in Campo Grande, MS, Brazil (54°39’ W, 20°31’ S). A detailed qualitative and quantitative characterisation of the greywater was previously performed in the household (Pansonato et al. 2007). Three watermeters were installed (kitchen, bathroom and laundry area), to permit daily measuring of the individual greywater fractions during the monitoring period. The data thus obtained were used to compare with the previous characterisation and to evaluate interferences on system performance.

**Sizing and design criteria**

The system configuration was proposed based on the following criteria: i) removing suspended solids and nutrients, up to a level where solar disinfection can be applied to the treated effluent without interferences; ii) avoiding odour and clogging problems and, iii) aiming at a system as compact as possible (cost effective). To allow the expected performance, a hybrid system, consisting of a subsurface HF-CW followed by a VF-CW was proposed. The sizing of the system was based on average flow (700 L.d⁻¹) and an inlet BOD of 500 mg L⁻¹, determined in the characterisation mentioned above. The complete proposed system comprises of 1) a commercial grease trap
(for the kitchen fraction), 2) an inspection box (where the 3 greywater fractions join), 3) a sedimentation tank (designed for a 3 hours HRT based on peak flow and average number of hours of greywater production in the house—16 h/day), 4) a HF-CW, 5) a siphon-feeding tank (hydromechanics) and 6) a VF-CW. The HF-CW was designed based on the required surface area (Rousseau et al. 2004a), for a 70% BOD removal and 20% nitrogen removal. The fibreglass HF-CW (dimensions of 1.6 m \times 2.9 m \times 0.4 m), was filled with fine gravel (porosity of 0.44), while inlet and outlet zones were filled with coarse gravel. Two piezometers were placed next to inlet and outlet zone for level monitoring and sample collection when necessary. The effluent of the HF-CW was applied intermittently to the VF-CW through a siphon system and distributed with a fish-bone like pipeline on the top of the VF-CW. The VF-CW was designed based on O2 balance required to remove the remaining BOD and nitrogen present in the HW effluent (Platzer et al. 2007). The VF-CW was a round-shaped fibreglass tank (diameter: 1.7 m, height: 1 m) filled with layers (from bottom to top) of 20 cm of coarse gravel, 10 cm of fine gravel, 55 cm of coarse sand and 5 cm of fine gravel. No flow regulation was applied in order to assess the performance under regular conditions and load and hydraulic peaks.

**System operation and monitoring**

The ornamental plants were chosen based on previous studies and some literature available (Lorenzi & Souza 2001; Asmus et al. 2007; Paulo et al. 2007). The chosen plants for the HF-CW were *Heliconia psittacorum* L. F (popularly known as heliconia or andromeda). *Cyperus isoelodus* (the dwarf type) and *Canna sp* (populary known as Beri). For the VF-CW the chosen plants were *Arundina bambusifolia* (a terrestrial multiperennial orchid, know as bamboo orchid) and *Alpinia purpurata* (Red ginger). The ornamental plants were planted 1 month before the operation of the CW started, allowing the roots to acclimatise to the new substrate before being subjected to the greywater. Before planting, the roots were washed to remove the soil. Survival and growth of seedlings, height, colour of leaves, strength of stalks and flowering were simple parameters observed (visually), to be able to compare with the same species grown in their natural environment and available literature.

For monitoring the CW system, samples were taken at 3 different points: after the sedimentation tank (P1), after the HF-CW (P2) and after the VF-CW (P3). Samples were taken twice a week for some parameters during the first 3 months and once a week afterwards. Parameters analysed twice a week were: total solids (TS), total suspended solids (TSS), pH, temperature, turbidity, conductivity and COD. Parameters analysed once a week were: total nitrogen (TN), nitrate (NO3-N), nitrite (NO2-N), ammonium (NH4-N), total phosphate (TP), total coliforms, *Escherichia coli* (E. Coli), chloride and dissolved oxygen (DO). Samples for BOD were collected every 2 weeks. Sampling, physico-chemical and bacteriological analysis were performed according to the “Standard methods for the examination of water and wastewater” from the American Public Health Association (APHA 2005).

**RESULTS AND DISCUSSION**

To design a very efficient and compact greywater treatment system using CWs is somehow difficult, considering that the volume and characteristics of greywater greatly vary in a household, depending on the activities. Figure 1 shows the daily variation of the greywater flow while Figure 2 shows the monthly average flow and origin (percentage) of the greywater.

It should be noted that water consumption has increased in the last 60 days, with the system continuously being subjected to the average flow (700 L.d\(^{-1}\)) (or over) considered for the design of both vertical and horizontal constructed wetlands.

Also, peak flows were found to be much higher (over 2500 L.day\(^{-1}\)) than those measured during the characterisation (around 1,200 L.day\(^{-1}\)), for which the ST was
designed. Figure 2 also illustrates that the fractions of greywater slightly changed over 6 months of flow measurement. The fraction of kitchen greywater was almost twice the one determined during characterization (Pansonato et al. 2007), reflecting a drop of the bathroom water consumption due to a problem in the shower.

To allow stable performance in a compact system it is necessary either to control the inflow or to consider a pretreatment, such as a septic tank or a sedimentation tank (Phillipi & Sezerino 2004), which could buffer peak flows and load shocks (organic load or soap load, for instance). For the present study we proposed a 3 hours HRT sedimentation tank. Considering the sizing of the HF-CW it is important to mention that there was a difference between the calculated required useful volume and the measured volume afterwards. For a 70% BOD and 20% nitrogen removal, the calculated required volume (based on superficial area and lab-determined substrate porosity and $K_{s}$), the required volume was 0.8 m$^3$ allowing a HRT of 1.2 days. After filling the HF-CW with the fine gravel, the volume of the CW was measured, showing an actual volume of 0.5 m$^3$, allowing a lower HRT of 0.8 days. For a proper evaluation of the system performance the actual volume will be considered. The design parameters for the ST and both horizontal and vertical flow CW are shown in Table 1, as well as the variation of each parameter during the 120 days of operation assessed in the present study.

The flow instability is reflected by the design parameters, affecting mainly the performance of the HF-CW. Table 2 shows the removal efficiency of several parameters over a period of 120 days. It can be noticed that the standard deviations for the removal efficiencies of the VF-CW are always lower than the ones for the HF-CW, except for nitrogen compounds, where large variations are observed for both. Peaks in the influent concentrations are strongly reflected in the effluent concentrations for the HF-CW but less noticeable for the VF-CW, unless the peak load was accompanied by a peak flow, which decreased the interval between the applications compromising the performance of the VF-CW. For the days/periods where the HRT in the HF-CW was 1.2 days (intended design HRT) or more, the HF-CW presented more stable and better performance. A value below that, as for instance 0.8 days, was detrimental to the system efficiency.

The combination of different reed beds offers more flexibility and provides significantly better effluent qualities (Gómez Cerezo et al. 2001; Rousseau et al. 2004b). When considering a hybrid system, the most common configuration for domestic sewage is a VF-CW followed by a HF-CW to stimulate nitrification in the VF-CW while denitrification is further promoted in the HF-CW. We proposed the opposite

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<th>Design parameters</th>
<th>ST</th>
<th>HF-CW</th>
<th>VF-CW</th>
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<td>HRT (days)</td>
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$^{a}$Avg—average.
$^{b}$Min—minimum value.
$^{c}$Max—maximum value.
$^{d}$The HRT is given in hours for ST.
$^{e}$NA—not applicable.
$^{f}$Applic.day—number of applications of effluent on the VF-CW.
configuration (a HF-CW followed by a VF-CW) considering that greywater contains relatively low nitrogen concentrations, when compared to domestic sewage (Eriksson et al. 2002; Jefferson et al. 2004), and that a VF-CW seems to not cope well with hydraulic peaks, and that the top layer tends to clog in such situations (Platzer et al. 2007).

According to a review paper from Tuszyńska & Obarska-Pempkowiak (2008), removal of organic matter and suspended solids in a HF-CW treating domestic sewage varies from 72% to 95% for SS, 71.2% to 94.1% for BOD$_3$ and from 59.7% to 89% for COD. The overall performance of the system proposed here shows that the removal of turbidity, suspended solids, COD and BOD are over 88% reaching 95% removal for both BOD and turbidity. Interestingly, in a study conducted by Rousseau (2005) in a pilot scale hybrid system (a VF-CW followed by a HF-CW) treating pre-treated domestic sewage, the better performance of the VF-CW was attributed to the fact that it was the higher loaded unit and that reversing the wetland order in that hybrid system would result in the highest removal efficiency being found in the HF-CW. For the present study, the removal efficiency in absolute values of the HF-CW was superior; however, despite the lower influent concentration in the VF-CW this unit presented higher removal for all measured parameters.

The inlet total nitrogen concentration was 8.8 ± 4.1 mg L$^{-1}$ with an overall removal of 82% ± 20%. We still expect better nitrogen removal due to plants uptake that is not playing an important role at this moment considering the slow growth and development. Mars et al. (2003) found that 75% of nitrogen (total cumulative removal in a 4 months experiment) was removed from greywater when making a N balance in a subsurface flow CW, using washed sand as substrate, operating with 10 days HRT as compared with a control without plants, showing the importance of plants uptake and the efficiency of the species used (Triglochin huegeli).

The VF-CW presented a better removal efficiency for phosphate, probably due to the combination of different substrate layers. Phosphate concentration in the system effluent averaged 2.1 ± 2.0 mg L$^{-1}$. The level of dissolved oxygen increased along the system (from 0.6 ± 0.9 mg L$^{-1}$ to 3.2 ± 1.5 mg L$^{-1}$) as well as the pH value which changed from slightly acidic when leaving the sedimentation tank (5.8 ± 0.5) to about neutral when leaving the VF-CW (7.2 ± 0.4).

Total Solids (TS) was the parameter with the lowest removal efficiency. Figure 3 shows the average distribution of TS over the 120 days of the experiment at the 3 different sampling points. The effluent of the system was virtually free of suspended solids, clearly showing that the proportion of dissolved solids (TDS) was increasing after each CW unit. The non-removed TDS fraction might be related to the non-biodegradable COD fraction in the greywater composition,
due to inorganic and colloidal substances present in cleaning and personal care products (Eriksson et al. 2002; Morel & Diener 2006). The average COD/BOD ratios for the 3 sampling points during the same period were $1.6^{\pm0.4}$, $2.2^{\pm0.7}$ and $3.5^{\pm2.6}$ for points 1, 2 and 3, respectively, showing a higher ratio after each treatment unit. This fact must be taken into consideration when reusing greywater for irrigation and also for the selection of plants used in the wetlands, since such characteristics can cause detrimental effects on soil/substrate and plants. In the case of the present study, one of the criteria, for instance, was to use ornamental plants so that the system could be integrated into the garden. Ornamental plants previously tried in our studies using pre-treated domestic sewage, had more difficulties in adapting to the greywater used in the present study. Another reason for the slow development of the plants can be the fine gravel used as substrate since some of the plants had developed properly with greywater and fine sand (Paulo et al. 2007).

No clogging was observed for any of the wetlands units, however, cleaning of the grease trap and sedimentation tank was performed at least once a month. The interval between cleaning procedures can be extended with some changes in habits and behaviour of householders, lowering the maintenance requirements. Smell problems were not reported so far. The system operation was quite simple and hardly required any attention. The hydromechanical system was checked regularly to ensure proper application of the effluent to the VF-CW.

CONCLUSIONS

- The suggested configuration consisting of a sedimentation tank followed by a hybrid system (HF-CW followed by a VF-CW) showed to be appropriate to fulfill the criteria for which it was designed.
- Fine gravel (porosity $= 0.44$ and $K_s = 3.37 \times 10^{-5}$ m s$^{-1}$) showed to be a good option to avoid clogging in a HF-CW receiving greywater with an average SS inflow of $546 \pm 256$ mg L$^{-1}$.
- The suggested compact system was susceptible to peak flows that could temporarily deteriorate the performance of the HF-CW, however the VF-CW was very efficient as the second stage ensuring a stable overall performance.
- The results achieved so far are still not sufficient for suggesting the adjustments for reaching the proper hydraulic retention time and hydraulic loading rate for the HF-CW as well as the number of applications for the VF-CW, since the plants are not yet fully developed.

ACKNOWLEDGEMENTS

This research was supported by the International Foundation for Science (IFS, Sweden) grant n° W/4150-1.

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