Comparison of grey water treatment performance by a cascading sand filter and a constructed wetland

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ABSTRACT

A novel unplanted vertical flow subsurface constructed wetland technology comprising three shallow beds (0.6 m length, 0.45 m width and 0.2 m depth) arranged in a cascading series and a standard single-pass Vertical Flow Planted Constructed Wetland (VFPCW, 6 m^2 and 0.7 m depth) were tested for grey water treatment. Particular focus was on meeting consent for published wastewater reuse parameters and removal of anionic surfactants. Treatment performance at two hydraulic loading rates (HLR) of 0.08, and 0.17 $m^3 m^{-2} d^{-1}$ were compared. Both technologies effectively removed more than 90% turbidity and more than 96% for organics with the prototype meeting the most stringent reuse standard of <2 NTU and <10 mg/L. However, surfactant removal in the VFPCW was higher (76–85%) than in the prototype which only achieved more than 50% removal at higher loading rate. Generally, the prototype performed consistently better than the VFPCW except for surfactant removal. However, at higher loading rates, both systems did not meet the reuse standard of <1 mg L^{-1} for anionic surfactants. This observation confirms that shallow beds provide a more oxidised environment leading to higher BOD_5 and COD removals. Presence of plants in the VFPCW led to higher anionic surfactant removal, through increased microbial and sorption processes.

Key words | cascading wetland beds, constructed sand filter, grey water, shallow beds wetland

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INTRODUCTION

Extensive treatment technologies for grey water treatment prior to reuse are attracting a growing interest due to their applicability at small-scale and positive public perception. Grey water reuse has advantages in water-scarce areas and also where centralised disposal infrastructure coverage is poor (Otterpohl *et al.* 2003). Different technologies such as membrane bioreactors (MBRs) or rotating biological contactors (RBCs), and biological aerated filters (BAFs) have been studied for grey water treatment and showed high removal efficiencies for most of the water quality parameters (Surendran & Wheatley 1998; Jefferson *et al.* 2001; Pidou *et al.* 2007). However, these technologies are high-tech and therefore not economically suited for small-scale applications. Technical innovations are required to simplify the treatment technologies so as to increase the attractiveness of grey water reuse at smaller scales.

Constructed wetlands (CW) are an extensive technology with the robustness (Vymazal 2005) and treatment efficiency necessary to handle diverse types of wastewaters such as municipal wastewater (Cooper *et al.* 1996; International Association on Water Quality 2000), storm water, industrial water and grey water (Kern & Idler 1999; Frazer-Williams *et al.* 2008). CWs have achieved high BOD removal rates of >90%, and removals of >98% for total coliform, faecal enterococci, (Vymazal 2005), COD, and suspended solids (Frazer-Williams *et al.* 2008). Surfactant removal was shown to be generally good (Gross *et al.* 2007*b*), albeit individual compounds behave differently

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depending upon isomeric form and molecular weights (Kadlec & Wallace 2009). The main pollutant removal processes in constructed wetlands are filtration (physical), ion exchange (chemical) and microbial metabolism (biological) working in concert during attenuation of organic chemicals. Additionally, plant uptake (phytoextraction and phytovolatilization) of inorganic chemicals contributes to the transformation and attenuation of organic chemicals (Susarla *et al.* 2002) through the release of organics into the media which alter the physico-chemical conditions and removal of contaminants by the plants. Indeed there are a growing number of studies on the performance of different designs of constructed wetland and different combinations of such designs in order to improve grey water treatment to meet published reuse standards. Design parameters of subsurface flow wetlands (SSF) have also been extensively studied for hydraulic and organic loading rates, and for nutrient removal (Vymazal 2005). The focus in these studies has been on influent and effluent characteristics. However, the effects of media and vegetation have not been adequately studied (Brix 1999; Maltais-Landry *et al.* 2009).

The study reported here investigated the performance of a full scale multiple–bed constructed wetland design with shallow beds (arranged in a cascading pattern) and compared its operation with a more typical vertical flow reed bed. Typically the depth for vertical flow SSF wetlands ranges from 0.6–1.2 m, yet the main degradation of substances takes part in the upper 0.2–0.4 m of the reactor-beds regardless of the bed depth (Felde & Kunst 1997; Platzer 1999). Hence, shallower bed design (0.2 m deep) was used informed by an understanding of vertical flow constructed wetlands for grey water treatment.

MATERIALS AND METHODS

Pilot plants

The tested pilot technologies were (i) a small-scale rig (the prototype; WPL, UK) comprising a header tank followed by three shallow beds (0.6 m length by 0.45 m width, 0.20 m depth) (Figure 1) and (ii) a single bed reactor (Vertical flow Planted Constructed Wetland: VFPCW, 6 m^2 surface area and 0.7 m deep). A header tank was incorporated for storage and to maintain adequate flow pressure into the top prototype bed thereby ensuring constant volume flow. The prototype beds contained 0.15–4.0 mm sand (d_{10} of 1.0 mm and d_{90} of 4.0 mm) and thin gravel (5–10 mm) at the bottom in a 9:1 ratio. The prototype was designed to operate as a constructed wetland but was tested initially without plants (this study), consequently running as a constructed sand filter. The VFPCW was planted with *Phragmites australis* and contained a mixture of sand, soil and organic matter as media.

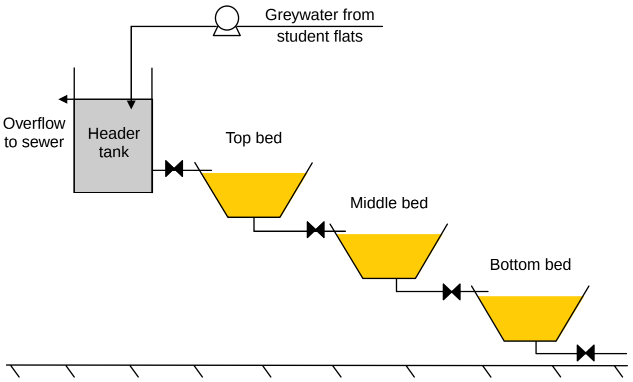

Figure 1 | Schematic of the prototype constructed wetland—cascaded shallow bed vertical flow constructed wetland.

Influent grey water was collected from eighteen specially plumbed student flats at Fedden House, Cranfield University. Water from baths, showers and bathroom sinks was drained to an underground communal sump and then pumped to two inter-connected holding tanks. The grey water source was of low organic strength (BOD_5 30 ± 11 mg/L and BOD:COD ratio ranging from 0.29–0.45) which was thought to reflect the dilution effect of showers and degradation within the pipe works. To enable higher feed strengths to be tested, a supplementary dosing system was installed. The high strength supplementary solution was a 10% (v/v) mixture of a shampoo in tap water. The high strength supplementary solution and the real grey water were pumped, at a ratio of 1:55, into a second holding tank. The dosed grey water was then pumped to the pilot plants at hydraulic loading rates (HLR) indicated in Table 1, and the two treatment units were run in parallel. The corresponding organic strengths (Organic Loading Rates: OLR) of the influent grey water are indicated in terms of BOD and COD.

Table 1 | Mean values of hydraulic and organic loading rates during the study duration

	HLR ($m^3 m^{-2} d^{-1}$)		OLR ($g BOD_5 m^{-2} d^{-1}$)		OLR ($g COD m^{-2} d^{-1}$)	
Time (weeks)	**Prototype**	**VFPW**	**Prototype**	**VFPW**	**Prototype**	**VFPW**
1–17	0.08	0.08	10.0 ± 3.4	3.1 ± 0.7	35.0 ± 14.7	10.6 ± 6.2
18–33	0.17	0.08	14.4 ± 4.3	3.7 ± 0.9	47.8 ± 25.9	8.5 ± 1.6

Sampling and analytical procedures

Influent and effluent samples were collected once a fortnight between 08:00–10:00 am. Conventional water quality analyses were monitored as follows: Total organic carbon (TOC) ($mg L^{-1}$), using a total organic carbon analyser Shimadzu TOC-5000A (Shimadzu, UK); Biochemical Oxygen Demand (BOD_5), using the standard 5 day procedure from the *Standard Methods for Examination of Water and Wastewater* (APHA 1998); Turbidity (NTU), using a Turbidimeter Hach 2100N; pH and conductivity, using the Jenway 3540 pH and conductivity meter; and Merck cell tests (Merck [VWR International], Poole, UK) for chemical oxygen demand (COD). Samples for anionic surfactants were filtered through microfiber filter paper and stored at 4°C until analysis using the Methyl Blue Active substances (MBAS) method (APHA 1998). Amberlyst A-26 anion exchange resin (^{-}OH form) was used for ion exchange and absorbance was measured at 652 nm in 1 cm cuvettes using the Jenway 6505 UV/Vis spectrophotometer.

Statistical analysis

Statistica 8 advanced was used to carry out comparisons. Significant differences between the prototype and the VFPW were determined by analysis of variance (ANOVA) where a *P*-value of less than 0.05 was interpreted to declare that the differences were statistically significant. Comparisons were also conducted for performance at different HLRs for the prototype.

RESULTS AND DISCUSSION

Treatment performance

The BOD concentration of the un-supplemented influent grey water in this study was in the low end ranges of typical grey water strength from similar sources (bath, hand basin and sink) reported in literature (Al-Jayyousi 2003; Pidou *et al.* 2007) and domestic wastewater (Metcalf and Eddy Inc. 2003), typically around 30 mg/L and 200 mg/L respectively. The low BOD:COD ratios (<0.3) give an indication that the influent grey water is less treatable by biological means than typical domestic wastewater and there is a need for acclimated microorganisms (Metcalf and Eddy Inc. 2003). However, the BOD:COD ratios of the spiked grey water which was used for the trials were of the range 0.30 to 0.45 demonstrating a better biodegradability. The very low BOD:COD ratios (<0.1) of the treated effluent clearly show very good BOD removal by both plants. Effluent pH of both pilot plants was found to be close to neutral showing buffering capacity of the sand media environment in the pilot plant.

The prototype, operating without plants, had granular media essentially making it comparable to a slow filtration system. Sand filtration systems have been shown to be suitable for wastewater with turbidities below 50 NTU (Kadlec & Wallace 2009). Despite, the influent grey water turbidity ranging from low turbidity levels to well over 50 NTU, the prototype was able to treat the grey water to meet the US EPA reuse standard (US EPA 2004). In most extensive systems, clogging is by far the biggest concern affecting performance. This is due to the reduced adsorption efficiency with age and decreased porosity (Blazejewski & Murat-Blazejewska 1997; Langergraber *et al.* 2003). However, in this study, clogging was not experienced, which, perhaps indicates that physical processes were not solely responsible for treatment. This indicates that other removal processes (e.g. biological degradation of trapped solids) played an important part in the grey water treatment in the prototype. The rate of microbial growth and sludge production did not affect the media porosity. The prototype treated effluent achieved more than 90% (approx 10 mg/L) dissolved oxygen (DO) saturation. DO concentration of 7 mg/L, such as the one achieved by the VFPCW, is usually indicative of good quality effluent. Hence the prototype shows better treatment, and this without the contribution expected from plants. The dissolved oxygen concentration for the prototype during the summer (September) (11.7 mg/L; Mean Temp: 17.6°C) indicates supersaturation. This could have been a result of increased oxygen production by phytoplankton in the shallow beds due to the availability of solar energy (Marks 2008). This phenomenon usually occurs where nutrient levels are high. However, in this study the levels of nutrients were not measured systematically to confirm this. The lower DO concentration in the VFPCW effluent (compared to the prototype) was initially thought to be a result of oxygen usage to deal with nitrogen removal. However, a one off measurement of nitrogen (as total nitrogen) showed no significant difference in the residual concentrations in the two pilot systems (3.30 ± 1.1 mg/L and 2.65 ± 0.35 mg/L for the prototype and the VFPCW respectively against an influent concentration of 6.20 ± 0.57 mg/L).

Throughout the monitoring period, performance of the pilot plants in removing BOD_5 was greater than 99% (Table 2). Fluctuations observed for other tested parameters were dependent on the HLR. To illustrate, COD removal performances were 94.8% and 93.3% at low loading and 82.4% and 89.2% at higher loading for the prototype and the VFPCW respectively. Nevertheless, both technologies were able to appreciably reduce varying COD loading throughout the study period despite this being presented as one of the major difficulties in grey water treatment (Al-Jayyousi 2003). The high strength spiked grey water in this study was of decreased biodegradability because it essentially had higher COD (COD:N:P) levels. Data from individual beds (not shown in Table 2) indicate that most of the treatment occurred in the top bed while the middle and bottom beds were effectively polishing steps. The prototype unit met the most stringent reuse standards (US Environmental Protection Agency USEPA 2004) for $\text{turbidity}_{\text{out}} < 2.0$ NTU, $\text{BOD}_{\text{out}} < 10$ mg/L and the usual range for irrigation water (Ayers & Westcot 1985) of

Table 2 | Summary of influent characteristics and grey water quality for the different technology designs (prototype vs VFPCW). Removal percentages are given in parentheses; SEM is the standard error of the means

	Influent	**Prototype unit**	**VFPCW**	**Influent**	**Prototype unit**	**VFPCW**
	Lower loading rate (weeks 1–17)			**Higher loading rate for prototype unit only (weeks 18–33)**		
Mean temp (°C)		19.2			17.6	
Turbidity (NTU)	57.6	1.0 (98.3)	10.4 (81.9)	14.4	2.7 (81.3)	10.9 (24.3)
SEM	14.7	0.4	7.2	10.4	0.9	2.8
Conductivity (mS)	510	662	710	396.3	421	417.8
SEM	26	61	70	89.6	52.7	22.9
pH	7.3	7.7	7	7.3	8.1	7.2
SEM	0.4	0.6	0.5	0.4	0.2	0.4
DO ($mg\,L^{-1}$)	0.9	8.9	6.4	0.9	11.7	4.9
SEM	0.6	0.8	2.7	0.4	0.4	1.1
BOD ($mg\,L^{-1}$)	43.9	0.2 (99.5)	1.7 (96.1)	42.6	0.15 (99.6)	1.2 (97.2)
SEM	10.6	0.4	1.5	22.2	0.05	1.4
COD ($mg\,L^{-1}$)	151	7.9 (94.8)	10.1 (93.3)	119.4	21 (82.4)	12.9 (89.2)
SEM	88	12.4	7.3	30.2	18	5.2
TOC ($mg\,L^{-1}$)	10	4.5 (55.0)	6.8 (26.5)	14.7	8.5 (42.2)	7.5 (49.0)
SEM	4.9	3.4	3.6	8.8	3.5	1.4
Anionic surfactants ($mg\,L^{-1}$)	1.39	0.87 (37)	0.34 (76)	17.1	4.56 (74)	2.48 (85)
SEM	0.2	0.1	0.1	0.6	1.3	0.9

pH_{out} 6–9, $COD_{out} < 150$ mg/L, (Table 2). An appreciable removal of turbidity (40%) and BOD and COD (10%) occurred in the header tank, where the grey water was held on average for one day before being released into the top bed. The high removal of organics by the prototype was not significantly different from the VFPCW. This performance is consistent with reported results for vertical flow constructed wetlands (Gross *et al.* 2007*a*; Frazer-Williams *et al.* 2008). Hence the prototype which was designed and operated as a constructed wetland but was initially trialled without plants in this study (thereby essentially operating as a constructed 'sand filter' system, albeit without back-washing) was as effective at removing organics as a fully-fledged (planted) constructed wetland (Vymazal 2002) and other advanced technologies (Pidou *et al.* 2007).

BOD_5 rate constant

Removal rate constants (κ_{BOD}) in constructed wetlands depend on the operational and structural characteristics of the wetland (Kadlec & Wallace 2009) and are influenced by hydraulic loading and influent loading parameters. The range of κ_{BOD} values for removal kinetics of the prototype (6.20–6.89 m d^{-1}) was much higher than for the VFPCW (0.33–0.36 m d^{-1}). Both these rate constant values were higher than the values (0.16 m d^{-1}) reported in other studies for vertical flow CWs treating grey water (Gross *et al.* 2007*b*; Frazer-Williams *et al.* 2008), implying better BOD_5 removal. However, the κ_{BOD} values for the prototype were clearly much higher than the reported range for domestic wastewater (Frazer-Williams *et al.* 2008). As both technologies were operated at the same HLR in the first instance, the implication of this finding is that structural characteristics (i.e. wetland size and probably the cascading design) contributed to the higher rate constant of the prototype.

Effect of hydraulic loading rate

Both the prototype and the VFPCW were operated as flood and drain systems because of the added advantage of increased oxygen transfer capacity (Kadlec *et al* 2000; Vymazal 2005). Fluctuations in organic strength in the influent grey water did not result in significant changes in overall treatment performance. However, except for BOD_5 removal, increases in HLR resulted in reduced treatment efficiency. This is in agreement with other studies on this technology (Frazer-Williams *et al.* 2008). Change in HLR was achieved by altering the frequency of flushes (flooding and draining cycles). The actual flooding and draining times were left constant, but the time lag (rest) between end of draining and beginning of next flooding was reduced with increase in HLR. This allowed the air compressed during previous flooding to be uniformly distributed throughout the media. Reducing the lag time may have affected recovery of the wetland media because of the reduced air entering through the top surface. This may have resulted in the media having less time to 'dry up' when the HLR was increased, which reduced air entry by convection (Forquet *et al.* 2009), and thereby affecting overall treatment performance.

Anionic surfactant removal

Surfactant removal was consistently higher in the VFPCW (76–85%) than in the prototype (37–74%). The prototype exhibited lower (<50%) anionic surfactant removals initially, probably because the filter bed was still ripening and so the microbial community was not yet acclimatized (Garland *et al.* 2004). Generally, surfactant behaviour depends largely on the molecular properties and residence time of the constituent chemical species in the medium into which they are discharged. Major processes governing transformations of surfactants and other synthetic compounds in wetlands include bio-uptake, sorption and photolysis (Kadlec & Wallace 2009). Many studies have shown increased surfactant degradation under aerobic conditions, but the shallow-bed prototype dwarfed the performance of the VFPCW. This was against expectations considering that the shallow beds provided a more oxidised environment leading to higher BOD_5 removal and higher saturated DO. The surprising results may be attributed to alkyl chain shortening of the surfactants, resulting from aerobic oxidation, which corresponds to lower surfactant removals (Inaba 1992; Thomas *et al.* 2003).

Microbial degradation of surfactants is usually high under aerobic conditions (Kuhnt 1993). The prototype effluent had higher dissolved oxygen concentration suggesting that the shallow beds were more aerobic compared to the VFPCW, yet exhibited lower anionic surfactant removal percentages. Nonetheless, appreciable removal rates (37 – 74%) were obtained at both low and high HLRs. This suggests that highly oxidised conditions alone are not sufficient for anionic surfactant removal. Indeed, the significantly higher removal rates achieved by the VFPCW indicate the added influence of the presence of the plants in that system. Plants provide surfaces for additional biodegradation by microbial communities which were not present in the prototype (Huang *et al.* 2004). In addition, the plants provide insulation for the surface of the wetland by trapping air thereby keeping the microbial community at a slightly higher temperature than that prevailing in the prototype thereby contributing to maintaining a higher microbial activity. This shows depth and plants to be important factors controlling the removal of anionic surfactants from grey water by the wetland technologies. Hence the more oxidised environment in the shallower bed-depth prototype wetland achieved good removals of general wastewater quality parameters, but this affected good performance for anionic surfactant removal. In contrast, for the VFPCW, a higher depth and presence of vegetation are crucial in maintaining better surfactant removal through reduced alkyl chain shortening and a more active microbial community for anionic surfactant degradation.

Operation aspects and evaluation of the design

The design considerations of the prototype took into account the need for extensive and yet compact treatment systems that can be used in space constrained urban areas. The study has shown the viability of this novel small-scale design of vertical flow constructed wetland, which has a smaller footprint and relatively low hydraulic residence time compared to standard VFCWs. The design, (Figure 2), ensures that water can flow through the system under gravity, thereby reducing the need for pumping, which ensures low capital and operating costs. Ample space is available underneath the beds, for storage of treated water until needed. The shallow beds (0.2 m) ensure higher oxygen infiltration. Influent water lands onto a splash plate which aids the spreading of the water across the surface of the beds and increases mixing with oxygen and infiltration into the substrate media through convection. This contributes to maintaining aerobic conditions in the treatment beds and generally increasing oxygen transfer capacity which is crucial for VF wetland systems.

The prototype performed very well for the two hydraulic rates that were studied. It demonstrated robust performance

The prototype – cascaded vertical flow CW Standard CW –VFPCW

The prototype – bed flooding The prototype – in low temperature conditions

Figure 2 | The novel cascaded vertical flow constructed wetland and the VFPCW.

in the face of occasional fluctuations in influent grey water strength, but overall performance decreased slightly at higher HLR. This means that if there were to be higher volumetric throughput than the design limits, the performance would be compromised. Therefore, surplus untreated grey water storage might be required, influencing the size of the treatment system itself and probably increase energy requirements as well by necessitating pumping to the header tank. The residence time of the water in the header tank was less than 24 hours, so it was assumed that anaerobic reactions, which alter the grey water characteristics if storage is for 24–48 hours or longer (Dixon *et al.* 2000; Casanova *et al.* 2001) were not initiated. The one significant drawback was significantly reduced performance during cold spells. Unlike the VFPCW, which was still operating, albeit, at low rate and reduced efficiency, the prototype just stopped functioning completely at low temperatures (0–5°C) resulting from ice formation which, perhaps was accelerated due to absence of vegetation shielding and insulation from varying temperature conditions. Similarly at higher temperatures where conditions for increased formation of the biologically active layer, *schmutzdecke*, were highly favourable, hydraulic conductivity in the top bed of the prototype was affected.

CONCLUSION

Overall the performance of the cascading shallow bed constructed wetland design shows that sufficient treatment of grey water can be achieved because of the high oxygen infiltration through the porous (sand) media. Overall this study has shown that small-scale wetland technologies have a place within the partheon of reuse technologies. The following conclusions are drawn from this study.

1. Operational parameters such as hydraulic loading rate and number of flushes were crucial in the overall performance of both technologies. Good performance was exhibited by the prototype meeting stringent worldwide reuse standards.
2. The small-scale constructed wetland with multiple cascaded shallow bed depth ($\approx 0.2\,\mathrm{m}$) design provide higher pollutant removal rates for conventional water quality parameters than a standard CW.
3. Although the contribution of plants in wetland systems remains unclear, anionic surfactant removal was shown to be higher in the planted wetland (VFPCW) due to the significance of plant related microbial processes.
4. The prototype is compact, easy to run and service and can be located in one's backyard or garden. Most importantly, it is a "green" grey water treatment unit.
5. Clogging was not experienced in the prototype unit, which perhaps indicates that physical processes were not solely responsible for treatment. Hence, it can be concluded that other removal processes played an important part in the grey water treatment by the prototype.

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