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Evaluation of clogging in planted and unplanted horizontal subsurface flow constructed wetlands: solids accumulation and hydraulic conductivity reduction

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ABSTRACT

This study aimed to evaluate the behaviour of two horizontal subsurface flow constructed wetland units regarding solids build up and clogging of the filter medium. In order to analyse the causes of this process, which is considered the major operational problem of constructed wetlands, studies were carried out to characterize accumulated solids and hydraulic conductivity at specific points of the beds of two wetlands (planted with *Typha latifolia* and unplanted units) receiving effluent from an upflow anaerobic sludge blanket reactor treating sanitary sewage (population equivalent of 50 inhabitants each unit). The experiments were performed after the units were operating for 2 years and 4 months. This study presents comparative results related to the quantification and characterization of accumulated solids and hydraulic conductivity along the length and width of the filter beds. Approximately 80% of the solids found were inorganic (fixed). Near the inlet end, the rate interstitial solids/attached solids was 5.0, while in the outlet end it was reduced to 1.5. Hydraulic conductivity was lower near the inlet of the units (as expected) and, by comparing the planted wetland with the unplanted, the hydraulic conductivity was lower in the former, resulting in larger undesired surface flow.

Key words | accumulated solids, clogging, hydraulic conductivity, sewage treatment, wetlands

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INTRODUCTION

The system of horizontal subsurface flow constructed wetlands (HSSFCWs) usually presents a very good performance in the removal of organic matter and suspended solids, being regarded as a natural and simple solution to sewage treatment. It is widely used worldwide for secondary and tertiary treatment, and there are currently thousands of systems in operation. However, the main operational problem of horizontal subsurface flow wetlands still remains: clogging of the internal spaces between grains at the inlet of the bed due to accumulated solids in the filter media (Cooper 2010). The main consequences are the reduction of hydraulic conductivity and increased head loss, with possible surface flow of the influent after a certain period of operation.

As a result of the continued operation of HSSFCWs, solids tend to accumulate as biofilms and in the void spaces of the filter medium, leading to a reduction of the effective free area for flow and to increased headloss. Water levels may rise inside the filter bed, until surface run-off takes place. This occurs whenever the hydraulic conductivity of the support medium is insufficient to transport the applied influent. Surface run-off of untreated sewage can create favourable conditions for the production of bad odours and proliferation of flies, pose health risks to animals and humans that may come into contact with the exposed effluent, and decrease the effective hydraulic retention time (HRT) and the performance of the treatment system (USEPA 2000).

Clogging of the bed is the main operational problem in HSSFCW (Cooper 2010), and it is believed that clogging is an inevitable phenomenon (Puigagut *et al.* 2006; Wallace & Knight 2006). Nivala *et al.* (2012) present a detailed literature review, which deals with the measurement of the development, the mathematical modelling and possible control measures associated with clogging in subsurface flow wetlands. A wider cross-section, in order to decrease horizontal flow velocity and hence head loss has been also proposed, together with the possibility of reversing the

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flow (outlet to inlet) after some time in order to feed at a region with less accumulated solids (Verlicchi *et al.* 2012).

According to Kadlec & Wallace (2008), apparently there are two distinct steps in the process. (i) *Short-term effects*: reduction of the hydraulic conductivity as early as in the first year of operation. This is related to the development of plant roots (first in the upper region of the bed) and to the biomass formed occurring mainly at the inlet of the bed. (ii) *Long-term effects*: gradual reduction of the hydraulic conductivity. This is related to the deposition of mineral (inert) suspended solids, accumulation of refractory material and formation of insoluble chemical precipitates.

Regarding short-term effects, most of the void spaces seem to decrease during the first year after the system starts operating. This is the main period in which the roots and rhizomes of macrophytes grow and the biofilm develops. The macrophytes in HSSFCW develop their roots preferentially in the upper region of the bed. The morphology of roots and rhizomes depends strongly on the conditions of the existing redox potential (Lockhart 1999). This limitation on the penetration of roots can create preferential flows in the deeper parts of the bed (USEPA 2000).

The loss of porosity of the filter bed results in a decrease in the residence time of the liquid. Marsteiner *et al.* (1996) report a reduction around 10% of HRT for planted wetlands (PWs), compared to unplanted wetlands (UPWs), and Tanner *et al.* (1998) estimate that the roots and rhizomes represent a decrease of 4% in the calculated HRT. The non-uniform distribution of roots and biomass along the length of the bed results in a non-uniform distribution of hydraulic conductivity in the bed. Planted and unplanted systems exhibit reduced conductivity, and the planted system seems to present lower hydraulic conductivity (Sanford *et al.* 1995). According to USEPA (2000), the presence of roots and rhizomes in the filter medium has a negative effect on hydraulic conductivity, with an estimation that the planted system decreases the void spaces in the bed in the range of 2–8%, while in systems without plants this reduction is around 0.1–0.4%. Brasil and Matos (2008) observed an average decrease in hydraulic conductivity from 15.4 to 9.1 m/d in just 5.5 months in HSSFCW which used gravel (5–10 mm) as support medium and had been recently (4 months) planted with cattail (*Typha* sp.).

Another factor that has short-term effects on the decrease of hydraulic conductivity is the development of microbiological biofilm formed as a result of the soluble and particulate organic material applied. This biofilm contains inorganic and organic solids, whose characteristics vary according to the type of the influent to be treated. The biofilm is larger at the inlet of the wetland bed, where the organic load is greater. The organic material is removed from the effluent along the wetland, leading to a decline in the formation of biofilm.

Tanner & Sukias (1995) reported on the importance of the by-products from macrophytes on the contribution of solids in the beds, in the range of 1.2–2.0 kg of VSS/m^2 more than in UPWs, over a 2-year period. It was also observed that more than 90% of these organic solids were composed of recalcitrant fractions, probably originating from lignocellulose materials.

Regarding long-term effects, bed porosity in HSSFCWs tends to decrease as a result of continuous input of particulate matter. The accumulation of inert sediments and refractory organic material occurs mainly at the inlet of the bed and leads to a reduction of the hydraulic conductivity in this region. Chemical reactions that occur in HSSFCW can form insoluble chemical precipitates. The formation of precipitates is caused by the existing redox potential along the wetland, and the reduction of hydraulic conductivity is not restricted to the inlet of the bed, but takes place over the entire length of the wetland.

Caselles-Osorio *et al.* (2007) found significant variations in the accumulation of solids, especially at the inlet of the wetlands when compared with the outlet. These authors also found that the organic fraction, represented by the VSS/TSS (volatile suspended solids/total suspended solids) ratio, was around 10–20% in most cases.

Wetlands are usually used after a preceding treatment, which removes part of the organic matter and suspended solids. The treatment process used varies from place to place around the world and may vary from simple units such as septic tanks (in which case the wetlands will act as secondary treatment) to more complex systems, such as activated sludge (in which case the wetlands will play the role of a tertiary treatment step). In Brazil, due to the frequent use of upflow anaerobic sludge blanket (UASB) reactors, wetlands have also been used as a post-treatment of the effluent from these reactors (Souza *et al* 2004; Dornelas *et al.* 2009; von Sperling *et al.* 2010). Since the behaviour of this combined system has not been widely reported by the international literature, there is a need to understand in more detail the hydraulic behaviour and the evolution of hydraulic conductivity reduction in wetlands acting as post-treatment of anaerobic effluents.

The main objective of this study is to quantify and characterize the accumulation of solids and the hydraulic conductivity in a full-scale system consisting of two HSSFCWs (a planted unit with *Typha latifolia* and an unplanted one) in the post-treatment of effluents from an anaerobic UASB reactor after 2 years and 4 months of operation of the system.

MATERIALS AND METHODS

Two HSSFCWs were used as post-treatment of the effluent from a UASB reactor in the Centre for Research and Training in Sanitation (CePTS UFMG/Copasa), located at the Arrudas wastewater treatment plant, at coordinates 19°53′42′S and 43°42′52′W, in the city of Belo Horizonte, Brazil. Both were filled with blast furnace slag and were designed for a population equivalent of 50 inhabitants each. The treatment units, constructed in parallel, received an average flow of 8.25 m^3/d each. One of the units (PW – planted wetland) was planted with cattail (*Typha latifolia*) and the other (UPW – unplanted wetland) was not planted (control unit). The operational characteristics of each horizontal subsurface wetland unit are shown in Table 1.

The system was operational for approximately 2 years and 4 months (after start-up) before the undertaking of the experiments of solids characterization and measurement of hydraulic conductivity. The tests were conducted over a period of 2 months, without rainfall. Weekly samples of the major wastewater constituents were collected at the raw sewage and effluent from all units.

The support medium was characterized by grain size distribution analysis, with the following results: $d_{10} = 19$ mm, non-uniformity coefficient $d_{60}/d_{10} = 1.2$ and volume of voids (porosity) = 40%.

Table 1 | Operational characteristics for each horizontal wetland unit

Parameter	Unit	Value
Total bed height	m	0.4
Water height in the beds (net height)	m	0.3
Length	m	24.1
Width at the top	m	3.0
Longitudinal slope at the bottom	%	0.5
Total volume of slag in each bed	m^3	28.9
Useful volume of slag in each bed (wet volume)	m^3	21.7
Surface area	m^2	72.3
Average influent flow	$m^3\ d^{-1}$	8.25
Average surface hydraulic loading rate	$m^3\ m^{-2}\ d^{-1}$	0.11
Average theoretical hydraulic retention time (=*V*.porosity/*Q*)	d	1.05

For the characterization of solids in the filter medium of each wetland, eight paired sampling points were used, at a distance of 3, 6, 12 and 18 m from the inlet of the bed, and located on the left and right-hand sides. Sampling in each of the points was conducted at a depth of 0.20 m (half of the bed depth). In each point 0.5 L of the support medium, attached and suspended biomass, together with the liquid effluent, were collected. The slag sample was first passed through a sieve (opening = 2.38 mm) and washed twice with the wetlands effluent with gentle stirring in order to prevent detachment of the attached biomass. This liquid was characterized as containing interstitial solids. Distilled water was added to the beaker containing the pre-washed slag sample and, to detach the adhered biomass, ultrasound equipment was used for a 15-min period. The sample was sieved again, now with the distilled water containing the loosened biomass. This liquid was characterized as containing solids of the attached biomass. Quantification and characterization of solids were carried out by the method described in AWWA/APHA/WEF (2005), for analysis of total solids (TS), fixed solids (FS) and volatile solids (VS).

Local hydraulic conductivity in the filter medium was measured in the same eight sampling points used for solids characterization. The procedure used a simple permeameter, consisting of a tube inserted at a pre-determined water level in the bed. A known volume of water (20 L) was applied in the tube in the form of a pulse, and the time the water took to infiltrate into the bed was measured.

Hydraulic conductivity at each point was estimated using Equation (1), obtained by combining the principle of mass conservation and Darcy's law (Caselles-Osorio & García 2006; Caselles-Osorio *et al.* 2007; Pedescoll *et al.* 2009; Nivala *et al.* 2012):

$$K = \frac{d^2 \ln\left(\frac{2L}{d}\right)}{8Lt} \ln\left(\frac{h_1}{h_2}\right) \quad (1)$$

where K = hydraulic conductivity (m/s); h_1 = initial height of water in the tube (m); 0.30 or 0.40 m (depending on the sampled point); h_2 = height of water in the tube at time t (m): 0.13 m; d = inner tube diameter (m): 0.20 m; L = height of the tube that is submerged (m): 0.13 m; t = time (s).

The cited authors point out that this is a methodology for determination of 'apparent' saturated hydraulic conductivity and that the values obtained should not be used to compare with other different experimental wetlands systems due to different scales and projects, mainly regarding the water level in the system. However, for comparison of similar systems, as is the case, in which the difference is only between the presence (PW) and absence (UPW) of macrophytes, the experiment is valid.

Tracer tests with pulse addition of ^{82}Br were undertaken to characterize the flow pattern in the two units.

RESULTS

Overall treatment performance

Although it is not the objective of this paper to discuss the treatment performance, simple descriptive statistics of the concentrations of organic matter and suspended solids during the overall operational period (before and during the experiments) are presented in Table 2 in order to allow a general view of the system's behaviour. Further details of the treatment performance can be found in De Paoli (2010), and a broad evaluation of the system behaviour and comparison of units is presented in von Sperling *et al.* (2012).

It is seen that the incoming wastewater is relatively weak, and also that the UASB reactor plays a very important role in decreasing the concentrations. As a result, the influent to the wetland units has low concentrations of organic matter and solids. Furthermore, the excellent effluent quality from both treatment units should be emphasized.

Solids in the filter medium

During the overall operational period, the wetlands received an influent (effluent from the UASB reactor) with an average concentration of TSS of 37 mg/L, and an average VSS/TSS ratio of 70%. The average surface solids loading rate in each wetland unit was 0.004 kgSS m^{-2} d^{-1}.

Figure 1 shows the result of the analysis of quantification of TS present in the filter medium of each wetland. The results show that the planted unit, when compared with the unplanted one, accumulated or produced larger amounts of TS along the bed, and, as expected, in greater quantity at the inlet area. The concentration of TS at the bed inlet of the planted unit was 2.6 times greater than in unplanted one at a distance of 3 m from the inlet, and two times higher for a distance of 6 m. This larger amount of TS in the PW occupied more volume in the void spaces of the porous medium and consequently reduced the hydraulic conductivity. This was probably the cause of the undesired runoff observed at a greater length in the planted unit after 2 years and 4 months of operation (6 m of length for the PW and 2 m for the UPW).

This variation in the profiles of PW and UPW was less marked than in the six full-scale horizontal subsurface flow wetlands evaluated by Caselles-Osorio *et al.* (2007), which had more accumulated solids near the inlet (3–57 kgTS/m^2)

Table 2 | Descriptive statistics of constituents related to organic matter and suspended solids along the treatment system

	Raw sewage		UASB		Planted unit		Unplanted unit	
Constituents	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
COD	390	137	142	44	44	15	51	25
BOD	175	59	43	16	14	7	15	9
TSS	204	128	37	19	7	6	5	5
VSS	151	81	26	13	3	2	2	2
Turbidity	–	–	74	25	9	8	8	11

COD: chemical oxygen demand; BOD: biochemical oxygen demand.

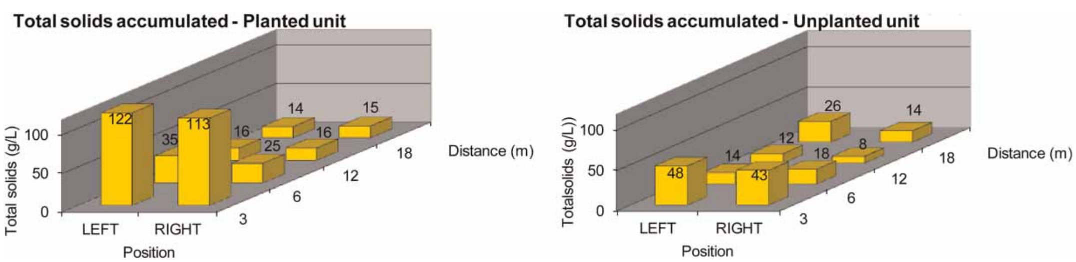

Figure 1 | Distribution of total solids in the filter medium along the planted wetland PW (left chart) and unplanted wetland UPW (right chart).

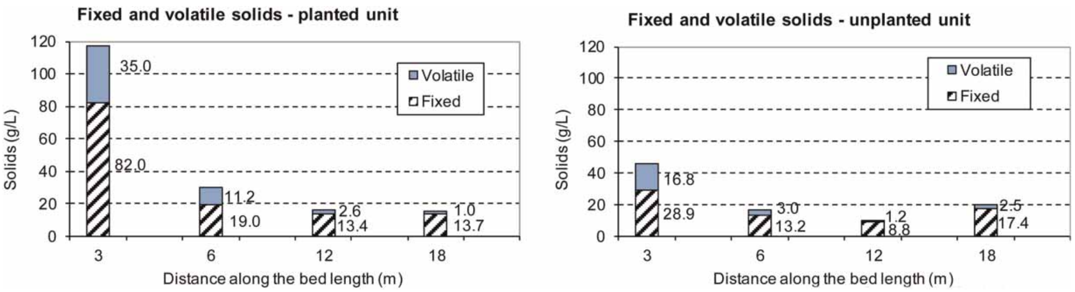

Figure 2 | Distribution of fixed and volatile solids along the bed length of the planted and unplanted units.

than near the outlet (2–12 kgTS/m^2) and that had annual solids accumulation rates ranging from 0.7 to 14.3 kgTS/m^2 year. The design of the wetlands studied by Caselles-Osorio *et al*. (2007) followed the recommendation of USEPA (2000), with length/width (L/W) close to 1, approaching a square geometry, whereas the wetlands here show a larger L/W ratio (=8). On one hand, the elongated geometry used in the present study minimizes the non-uniform distribution of the influent, avoiding an irregular accumulation of solids in the bed and dead volumes in the inlet area, and is also more favourable in terms of reactor hydrodynamics for constituents that decrease following first-order kinetics, such as organic matter (De Paoli & von Sperling 2010). However, on the other hand, it increases the rate at which clogging occurs, since the solids load and the high concentration of organic matter are larger in a smaller cross-sectional area at the bed inlet. In addition, in a more elongated wetland, the cross-section is smaller, leading to an increase in the horizontal flow velocity and to greater head losses.

Figure 2 shows the distribution of FS and VS along the bed of each wetland. The data are an average of the left and right profiles. The ratio of FS/VS increased along the length of the bed. Therefore, the volatile fraction was larger in the inlet of the bed, in which the biomass that decomposes the organic matter developed in greater quantity. Along the longitudinal distance in the beds, solids tend to be mineralized, reducing the volatile fraction.

The presence of VS in PW at the inlet of the bed (distances of 3 and 6 m), where clogging is more evident, was two times greater than that found in the UPW, and for the first sampling point (3 m) the presence of FS in the planted unit was almost three times that found in the unplanted one.

The proportion of FS/VS was larger in the UPW (fixed/volatile = 3) than in the planted one (fixed/volatile = 2) for the mean values at distances of 3 and 6 m. It is likely that the macrophytes roots contributed to increasing the surface area for biomass attachment and created more favourable environmental conditions for the development of bacteria, including aerobic and facultative ones. However, the contribution of particulate plant material in the quantification and characterization of solids, specifically volatile, is a fact that must be considered.

Despite the great difference in the amount of solids accumulated and/or produced by plants, when compared with the unplanted control unit, the ratio VS/TS remained close for most of the length of the bed, except for the 6 m sampling point. At this point the VS/TS ratio was much higher for the PW, as shown in Figure 3. This suggests that the main effect of the roots in the solids contribution lies in the interaction with the initial high concentration of organic matter, either dissolved or particulate. Probably, this interaction occurs due to better environmental conditions for the development of a greater diversity of microorganisms.

Similarly to the results from Tanner & Sukias (1995) and Caselles-Osorio *et al*. (2007), most of the accumulated solids in the bed consisted of inorganic solids. For these authors the FS fraction was 90 and 85%, respectively. In this research the average FS fraction along the beds was 78 and 80%, for the PW and UPW, respectively.

Figure 4 shows the proportion of interstitial and attached solids for each wetland (average of the left and right profiles). As mentioned before, the PW had a larger amount of solids, especially at the bed inlet. These solids were formed largely by the development of bacterial biomass that developed in the interstices of the filter medium. This material resembled

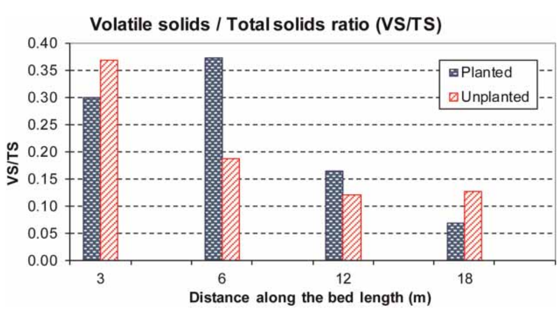

Figure 3 | Ratio of volatile and total solids along the planted and unplanted units.

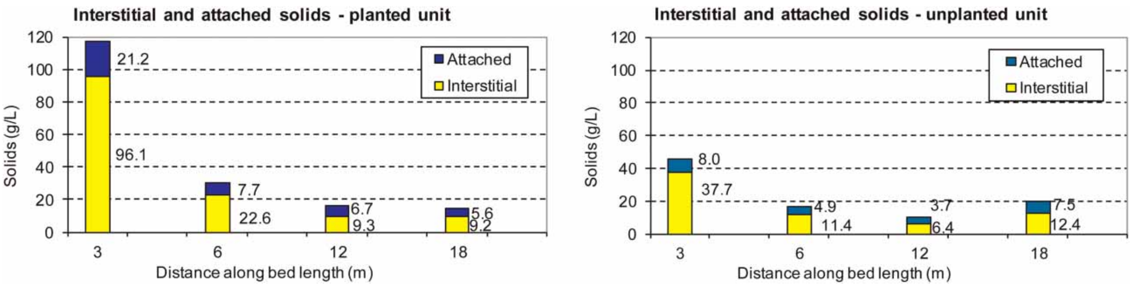

Figure 4 | Proportion of interstitial and attached solids along the bed in the planted and unplanted units.

in appearance the biological sludge blanket that develops in UASB reactors. In both wetlands, and in all sampling points, most of the solids were interstitial, with the attached biomass representing a lower fraction.

An important conclusion can be reached by observing Figure 5. The interstitial solids/TS ratio was almost the same for the two wetlands along the bed, even when the quantity and characteristics of the interstitial and attached solids were very different, as at the bed inlet. Therefore, other factors, besides the surface area of the support medium, are probably associated with this behaviour.

Hydraulic conductivity

Hydraulic conductivity tests taken at specific locations indicated a large difference between the two systems analysed. Figure 6 shows the results of localized hydraulic

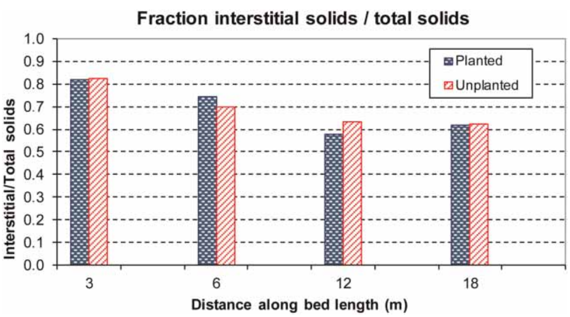

Figure 5 | Interstitial and total solids ratio along the planted and unplanted wetlands.

conductivity along the beds of PWs and UPWs. As expected, the hydraulic conductivity increased along the bed, showing an inverse relationship with accumulated solids.

Field observations showed that surface runoff occurred in the first 6 m of PW, that is, there was a preferential pathway on the surface in this area, probably due to the low hydraulic conductivity. In the following stretches (12 and 18 m) there was considerable variation between the left and right profiles. It is possible that due to the plant growth dynamics, and consequently that of the roots, preferential flow pathways have been created. The variability of hydraulic conductivity along the longitudinal and transverse dimensions has also been identified by Knowles *et al.* (2010) in a study which investigated the clogging tendency in horizontal subsurface flow wetlands.

Tracer tests (^{82}Br) performed in the two wetlands indicated a similarity between the actual HRTs, with mean values of 1.30 and 1.43 d for the PW and UPW, respectively (De Paoli 2010; De Paoli & von Sperling 2010). Under the test conditions, the theoretical HRT calculated on the basis of the net volume (average length 24.1 m; average width 3.0 m; average height of liquid in the bed, taking into account clogging during the test period = 0.35 m and porosity = 0.4), of the average influent flow during the test period (7.15 m^3/d, without considering water gains or losses), was 1.42 d; also similar to the measured ones. This indicated a high hydraulic efficiency of the two wetlands, since the actual HRT was similar to the theoretical one. In terms of the

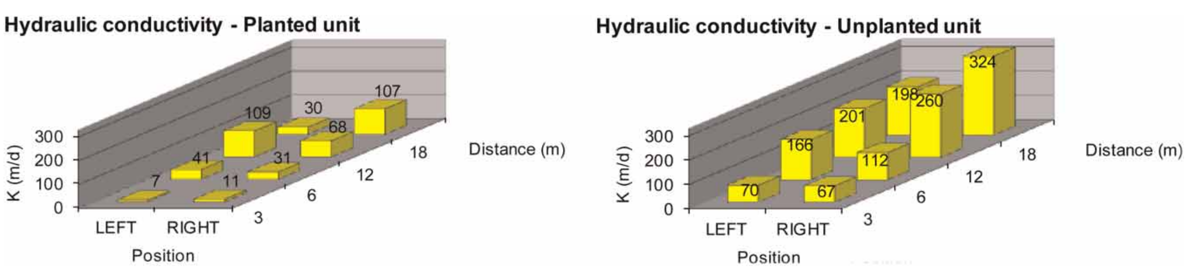

Figure 6 | Distribution of hydraulic conductivity in the filter medium along the planted wetland PW (left chart) and unplanted UPW (right chart).

differences between the planted and unplanted units, other reports in the literature (Shepherd *et al.* 2001) found lower actual HRT in planted systems if compared with unplanted systems, based on tracer tests.

It is noteworthy that the estimation of hydraulic conductivity in planted systems presents more difficulties and inaccuracies than in unplanted systems, due to the occurrence of preferential flow, short circuit and porosity obstruction (as a result of variations in growth and degradation of roots and build-up/degradation of solid residues on the surface of the wetland) (Brasil 2005).

The hydraulic conductivity values in the UPW were much higher than in the PW and more uniform along the bed, with a steady decrease toward the influent inlet. The unplanted unit showed a clear relationship between the reduction of hydraulic conductivity and accumulated solids. Whenever a smaller amount of solids at a given point was observed, this was reflected in the increased hydraulic conductivity. These observations suggest that the predominant factor in the hydrodynamic changes in unplanted systems is the presence of solids in the bed, which can occur in a non-homogeneous way, depending on the design and operation of the system, but which is less variable than in planted systems. This should be an important reason for the lower occurrence of preferential pathways in unplanted systems, leading to higher actual HRT.

The variation of hydraulic conductivity at the inlet zone (3 and 6 m) of the wetlands was from 7 to 41 m/d for PW and from 67 to 166 m/d for UPW. The variation in the outlet zone (18 m) was from 30 to 107 m/d for PW and from 198 to 324 m/d for UPW. Although the comparison of the results of these conductivity tests with those of the literature is not recommended, the values obtained for the PW are within the wide amplitude reported by Caselles-Osorio *et al.* (2007) and Knowles *et al.* (2010).

CONCLUSIONS

Based on the analyses of TS, the presence of plants increased the accumulation/production of solids throughout the filter medium and intensified clogging at the bed inlet, generating greater headloss and possible surface flow at the inlet of the PW, when compared to the control system without plants. Approximately 80% of the solids present along the bed of the two units were characterized as fixed.

The mass of solids present in the first third of the length of the PW was two to three times larger than the mass found in the same area of the UPW. Although the two units presented a large difference in the amount of solids distributed along the bed, the interstitial and attached solids ratio followed the same pattern, with a ratio close to 5.0 at the inlet and 1.5 at the outlet area of the beds. Therefore, the void spaces of the porous medium were more important in terms of solids mass than the capacity of the biofilm to attach to the filter medium, leading to the decline of hydraulic conductivity.

Hydraulic conductivity was lower near the bed inlet, indicating an inverse relationship with the accumulation of solids. This relationship proved to be more direct for the UPW, whereas the planted unit presented very low hydraulic conductivity values and high variation along the length and width of the bed. This evidence can be attributed to the existence of the plant root system, suggesting that the hydrodynamic changes of planted systems does not depend only on the presence of solids in the filter medium, but also on the roots in the medium.

Despite the fact that the impact of the design of the two wetlands (mainly the length/width ratio) was not specifically investigated here, it is believed that the elongated configuration used in this study, with a small cross-sectional area to receive the entire influent hydraulic, organic and solids load, was a preponderant factor in the fast clogging and formation of surface flow at the bed inlet zone. On the other hand, the high length/width ratio probably resulted in a smaller dispersion of the flow inside the reactor.

Since this is a system strongly influenced by environmental conditions, monitoring over a longer period of time, associated with operational and management aspects, can provide important information on the issue of the actual contribution of the use of macrophytes on subsurface wetlands.

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REFERENCES

APHA, AWWA, WEF 2005 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. APHA, Washington.

Brasil, M. S. 2005 *Desempenho de sistema alagado construído para tratamento de esgoto doméstico. Tese (Doutorado em Engenharia Agrícola)*. Universidade Federal de Viçosa – UFV, Viçosa, MG, 160p. (in Portuguese).

Brasil, M. S. & Matos, A. T. 2008 Avaliação de aspectos hidráulicos e hidrológicos de sistemas alagados construídos de fluxo subsuperficial. *Engenharia Sanitária e Ambiental* **13** (3), 323–328 (in Portuguese).

Caselles-Osorio, A. & García, J. 2006 Effect of physico-chemical pretreatment on the removal efficiency of horizontal subsurface-flow constructed wetlands. *Environmental Pollution* **146**, 55–63.

Caselles-Osorio, A., Puigagut, J., Segú, E., Vaello, N., Granés, F., García, D. & García, J. 2007 Solids accumulation in six full-scale subsurface flow constructed wetlands. *Water Research* **41**, 1388–1398.

Cooper, P. 2010 Constructed wetlands after 25 years of application: A review of the developments that we have made and the problems that we still have to overcome. In: *12th International Conference on Wetland Systems for Water Pollution Control*. International Water Association, 4–9 October 2010, Venice, Italy.

De Paoli, A. C. 2010 Análise de desempenho e comportamento de wetlands horizontais de fluxo subsuperficial baseado em modelos hidráulicos e cinéticos. Dissertação (Mestrado em Saneamento, Meio Ambiente e Recursos Hídricos). Universidade Federal de Minas Gerais, Belo Horizonte, MG. 159p. (in Portuguese).

De Paoli, A. C. & von Sperling, M. 2010 Comparison between simple performance models applied to planted and unplanted subsurface-flow constructed wetlands for the post-treatment of Uasb reactor effluents. In: *12th International Conference on Wetland Systems for Water Pollution Control. International* Water Association, 4–9 October 2010, Venice, Italy.

Dornelas, F. L., Machado, M. B. & Von Sperling, M. 2009 Performance evaluation of planted and unplanted subsurface-flow constructed wetlands for the post-treatment of UASB reactor effluents. *Water Science and Technology* **60** (12), 3025–3033.

Kadlec, R. H. & Wallace, R. D. 2008 *Treatment Wetlands*, 2nd edn. CRC Press, Boca Ratton.

Knowles, P. R., Griffin, P. & Davies, P. A. 2010 Clogging in horizontal subsurface flow treatment wetlands in the UK: Conclusions from a three year investigation. In: *12th International Conference on Wetland Systems for Water Pollution Control*. International Water Association, 4–9 October 2010, Venice, Italy.

Lockhart, A. 1999 A Comparison of constructed wetlands used to treat domestic wastes: conventional, drawdown, and aerated systems. M Thesis, Department of Civil and Environmental Engineering, University of Iowa.

Marsteiner, E. L., Collins, A. G., Theis, T. L. & Young, T. C. 1996 The influence of macrophytes on subsurface flow wetland hydraulics. In: *5th International Conference on Wetland System for Water Pollution Control*, Universitat fur Bodenkultur, Vienna, Austria.

Nivala, J., Knowles, P., Dotro, G., García, J. & Wallace, S. 2012 Clogging in subsurface-flow treatment wetlands: measurement, modelling and management. *Water Research* **46**, 1625–1640.

Pedescoll, A., Uggetti, E., Llorens, E., Granés, F., García, D. & García, J. 2009 Practical method based on saturated hydraulic conductivity used to assess clogging in subsurface flow constructed wetlands. *Ecological Engineering* **35**, 1216–1224.

Puigagut, J., Caselles-Osorio, A., Vaello, N. & García, J. 2006 Size distribution and biodegradability properties of the organic matter in horizontal subsurface flow constructed wetlands. In: *6th International Workshop on Nutrient Cycling and Retention in Natural and Constructed wetlands*, 31 May–4 June, Trebon, Czech Republic.

Sanford, W. E., Steenhuis, T. S., Surface, J. M. & Peverly, J. H. 1995 Hydraulic conductivity of gravel and sand as substrates in rock-reed filters. *Ecological Engineering* **4**, 321–336.

Shepherd, H. L., Tchobanoglous, G. & Grismer, M. E. 2001 Time dependent retardation model for chemical oxygen demand removal in a subsurface-flow constructed wetland for winery wastewater treatment. *Water Environment Research* **73** (5), 597–606.

Souza, J. T., Haandel, A. V., Lima, E. P. C. & Henrique, I. N. 2004 Utilização de wetland construído no pós-tratamento de esgotos domésticos pré-tratados em reator Uasb. *Engenharia Sanitária e Ambiental* **9** (4), 285–290 (in Portuguese).

Tanner, C. C. & Sukias, J. P. 1995 Accumulation of organic solids in gravel bed constructed wetlands. *Water Science and Technology* **32** (3), 229–239.

Tanner, C. C., Sukias, J. P. S. & Upsdell, M. P. 1998 Organic matter accumulation during maturation of gravel-bed constructed wetlands treating farm dairy wastewater. *Water Research* **32**, 3046–3054.

USEPA 2000 *Constructed Wetlands Treatment of Municipal Wastewaters*. United States Environmental Protection Agency, Cincinnati, OH, 154 p.

Verlicchi, P., Al Aukidy, M., Galletti, A., Zambello, E., Zanni, G. & Masotti, L. 2012 A project of reuse of reclaimed wastewater in the Po Valley, Italy: polishing sequence and cost benefit analysis. *Journal of Hydrology* **432**, 127–136.

von Sperling, M., Dornelas, F. L., Assunção, F. A. L., De Paoli, A. C. & Mabub, M. O. A. 2010 Comparison between polishing (maturation) ponds and subsurface flow constructed wetlands (planted and unplanted) for the post-treatment of the effluent from UASB reactors. *Water Science and Technology* **61** (5), 1201–1209.

von Sperling, M., De Apoli, A. C. & Costa, J. F. 2012 Performance and behaviour of planted and unplanted units of a horizontal subsurface flow constructed wetland system based on a four-year study. In: *13th International Conference on Wetland Systems for Water Pollution Control*. International Water Association, 25–29 November 2012. Perth, Australia.

Wallace, S. D. & Knight, R. L. 2006 Small-scale constructed wetland treatment systems: feasibility, design criteria, and O&M requirements, Final Report, Project 01-Cts-5, Water Environment Research Foundation (Werf), Alexandria, Virginia.

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