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Potential for CSO treatment with horizontal flow constructed wetlands: influence of hydraulic load, plant presence and loading frequency

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Abstract This study aimed at analysing the performance of horizontal subsurface flow constructed wetlands (CWs) to treat combined sewer overflow (CSO). Four horizontal subsurface flow CWs, organized in two groups (A and B) each with a planted (*Phragmites australis*) and a non-planted bed, were loaded with simulated CSO, with group B receiving twice the hydraulic load of group A. Beds were monitored for pH, dissolved oxygen, conductivity, redox potential, chemical oxygen demand (COD), total suspended solids (TSS) and enterococci. Porosity variations were also estimated. Monitoring was conducted during spring and wintertime, with regular and irregular loading frequencies. Results showed an average treatment efficiency of 90–100 % for TSS, 60–90 % for COD and 2–6 log for enterococci. Removal rates were especially relevant in the first 24 h for COD and TSS. TSS and enterococci removal did not exhibit the influence of macrophytes or the applied hydraulic load while COD's removal efficiency was lower in the higher load group and in planted beds.

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Introduction

In recent years, there has been an increased attention given to the treatment of storm water and combined sewer overflow (CSO) due to the fact that in many cases these flows do not receive any treatment, therefore becoming a major source of global pollution (Fournel et al. 2012; Meyer et al. 2012; Van de Moortel et al. 2009). Combined systems with insufficient treatment capacity during rain events lead to direct discharges, often with significant impacts on the environment. Also, the deposition of mineral and organic matter inside sewage pipes, as well as on paved surfaces during dry periods, can lead to a "first-flush event" when runoff washes out impermeable areas and the higher wet weather flows resuspend and transport accumulated sediments inside the drainage system (Li et al. 2010).

When the treatment capacity of the wastewater treatment plant (WWTP) is exceeded, due to rain events, several solutions can be applied to reduce CSO pollutant load prior to discharge, including the widely used CSO storage tanks (Urbonas and Stahre 1993). Despite their capacity to minimize peak flows and promote solids sedimentation, they require high maintenance and a WWTP final treatment. Therefore, this type of systems is becoming less appealing and new solutions are being developed. An example is the installation of constructed wetlands (CWs) downstream of CSO tanks, turning this storage structure into inlet structures and sedimentation basins (Meyer et al. 2012).

Although mostly used to treat domestic sewage from small agglomerations, CWs have been used to treat CSO for more than two decades (Green and Martin 1996; Woźniak et al.

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2007) and studies have shown that this technology can be an alternative solution to the treatment of CSO prior to their discharge in the water bodies (Fournel et al. 2013; Lucas et al. 2014; Meyer et al. 2012).

In fact these systems have been used to treat different types of effluents, existing nowadays numerous works evolving the treatment of industrial effluent, leachate from landfills and agriculture effluents as well as "first-flush" pollution in storm water runoff (Färm and Waara 2005; Malaviya and Singh 2012; Masi and Martinuzzi 2007; Vymazal 2009, 2010, 2011). However, only a few studies have focused on CSO treatment through CW systems and also a large part of the experimental works (including in full scale treatment plants) are usually focused on the treatment response in vertical flow systems (VSSF CW) (Fournel et al. 2012, 2013; Henrichs et al. 2007; Li et al. 2010; Torrens et al. 2009).

One of the studies using horizontal flow systems (HSSF CW) was developed by Van de Moortel et al. (2009), concluding a good treatment solution for CSO treatment. Nevertheless, a loading interruption and a constant water layer were both necessary in order to achieve a more sustainable lifetime of this systems. Amaral et al. (2013) also analysed CSO treatment in HSSF CW and obtained removal efficiencies for chemical oxygen demand (COD) between 50–100 %, demonstrating a promising CSO-treatment capacity.

Still, little information exists about the use of CWs to treat CSO and there remains a need for more research to be developed in order to better understand this type of solution and evaluate its viability.

The purpose of this study was to increase the existing knowledge about the influence of hydraulic load and plant presence in a horizontal subsurface flow CW (regarding COD, total suspended solids (TSS) and enterococci). Experiments were conducted during spring and wintertime, with regular and irregular loading frequencies. In order to better understand the COD-removal process, $k - C^*$ expressions for COD decay (Kadlec and Knight, 1996) were also calculated.

Methodology

Experimental setup

The current investigation involved an experimental facility with four horizontal subsurface beds, located in Frielas WWTP (Portugal). This experimental facility was previously used by Amaral et al. (2013), during the start-up phase that took place between April and June 2011. Frielas WWTP treats the effluents from a combined sewage system with a total catchment area of 256 km^2.

Each CW was installed in a polyvinyl chloride box (55.5 cm long, 36.1 cm wide and 40.0 cm high) and had a filling media with diameters of 4–8 mm and a porosity of 30 %. Filling media height inside each bed was approximately 35 cm. A throttle structure was installed at the end of each bed, near its base, allowing the total discharge of the beds and to set the maximum water level to about 5 cm below the surface. The beds were exposed to local weather conditions in order to better analyse the system's real performance.

More details regarding the experimental setup can be found in Amaral et al. (2013).

Loading procedure and sampling

The beds were organized in two different groups, A (A-NP + A-P) and B (B-NP + B-P), each one with a planted (A-P and B-P) and an unplanted bed (A-NP and B-NP) in order to analyse plant effect in the treatment process. The chosen plant was *Phragmites australis* due to the fact that it is widely used in CWs with subsurface horizontal flow all over Europe and has been proven to be a good plant for various types of wastewater treatment using constructed wetlands (Vymazal 2011).

During both experimental phases the four beds were batch-loaded, group A with 10 L/load and B with 20 L/load in order to analyse the influence of different loadings in CSO treatment. During phase I of the experience (springtime—from 3 April 2012 to 8 June 2012) beds were loaded weekly with an average of 232 mg/L of COD. This loading frequency was set to study the development of the beds following the start-up period previously studied (Amaral et al. 2013). During phase II (wintertime—12 December 2012 to 29 January 2013) the loading frequency was set to reproduce the irregular sequence of CSO discharge from Frielas WWTP observed during the winter of 2010/2011, with an average COD of 364 mg/L (except for a concentration peak of 1165 mg/L on 01 May 2013).

The loading was conducted using wastewater collected after the screening step in Frielas WWTP whenever there was a significant rain event. When there were no rain events prior to loading, CSO was simulated by a dilution with potable water (approximately 1/3 sewage and 2/3 water). The water used had previously been stored in order to ensure the absence of free chlorine.

In phase I, in the beginning of every loading event the beds were completely emptied, and both the water level and the volume discharged in each bed was measured. After all beds were emptied, a continuously stirred reservoir was filled with screened flow from the WWTP. The beds were then loaded from the reservoir through a perforated pipe installed inside each bed. During phase I samples were collected from the inflow CSO and also at the outflow of each bed 24 h and 7 days after loading. This procedure allowed the study of the effect of retention times of 1 and 7 days for both loading groups.

During phase II although the loading procedure was the same, the beds were not emptied before each loading event in order to simulate a more realistic CSO operation. Also, at the end of this phase a minor adjustment was made in the

loading procedure of bed B-P, since it was no longer practical to use the loading pipe in this bed due to clogging evidence. Loading was then changed to a surface-loading mode, at the inlet area as close as possible to the loading pipe. During phase II samples were collected from the inflow CSO and also at the outflow of each bed before each loading event. Because the beds were not emptied before the next load, hydraulic retention time (HRT) varied during phase II. The average HRT for this phase was 2.8 days for group A and 1.4 days for group B.

Whenever there was no outflow, the outlet throttle height was lowered in order to induce the necessary flow for sampling. Once collected, samples were carefully and rapidly transported to the laboratory in a refrigerated vessel and analysed immediately. When the laboratory was not available (e.g. during weekends in phase II), samples were kept refrigerated and analysed within 48 h. All samples were analysed for COD, TSS and enterococci, except during phase II, where only COD was analysed due to budget constraints.

TSS and enterococci were analysed according to Standard Methods (APHA-AWWA-WPCF 1995) and COD concentrations were obtained using colorimetric methods (C4/25, WTW, Germany). Also, general characteristics of the effluent were analysed in terms of pH, temperature, oxidation-reduction potential (ORP) (Crison, Barcelona, Spain), DO (YSI ProODO, Ohio, USA) and conductivity (WTW Cond 340i, Munich, Germany).

It is also worth noticing that the evapotranspiration rate in beds planted with *Phragmites australis* was substantial. This situation was combined with a previous dry winter and a hot summer, which probably lead to a low survival rate of plants in A-P. Also, during some days in phase I samples were not collected in planted beds (A-P and B-P) due to high evapotranspiration rate, which reduced outflow to a zero discharge condition.

An estimate of bed porosity was obtained through the water level difference immediately before and after each loading, combined with the water volume displaced by the complete discharge of the bed, before the next loading. These values were probably affected by interstitial air contained in the media, since only the water level and displaced volume were measured, proving an approximate measurement. However, the values were useful and necessary to understand in what way the organic and solid matter inside the beds evolved during the year and when submitted to different loads.

Data analysis

All multivariate statistical analyses were carried out with SPSS statistical software. For each variable, the tests of normality and homogeneity of variance were performed in order to ensure the use of the correct statistical analysis.

To analyse the COD-removal efficiency during phase I a MANOVA test was performed and for TSS removal

efficiency a Kruskal-Wallis test was conducted. The ANOVA test was used to compare different loadings and the existence/non existence of plants in the COD-removal efficiency (phase II), and to test the hydraulic retention time influence in enterococci removal efficiencies (phase I). As previously stated, in order to better analyse the COD decay inside the beds, $k - C^*$ expressions were calculated for each bed and time of the year (Eq. 1) (Kadlec and Wallace 2009):

$$C_i = C^* + (C_0 - C^*)e^{-k_v t} \tag{1}$$

where C_0 represents the inflow concentration (mg/L); C^* represents the residual concentration (mg/L); k_v represents the volumetric parameter (per day) and t the hydraulic retention time (day).

A temperature correction was also performed on the k_v value based on the Arrhenius equation used by Caselles-Osorio and García (2006):

$$k_v = k_{v,20}\theta^{(T-20)} \tag{2}$$

where $k_{v,20}$ represents the volumetric parameter at 20 °C; $\theta = 1.04$ is the temperature coefficient, dimensionless and T is the operating temperature, in °C.

Results and discussion

Overall, the treatment in the first 24 h was invariably high in both experimental phases. The reduction of the concentration of microbial parameters in phase I was also very good, achieving values of more than 1.5 log.

Bed porosity

During phase I, porosity values ranged between 20 and 40 %, as observed in Table 1. The bed with the highest porosity was A-NP with values in the range 38–42 % and the lowest was B-P with a porosity value around 20 %. B-NP and A-P exhibited intermediate values, being A-P the bed with the highest porosity between the two. The presence of macrophytes seemed to lead to a porosity decrease (A-P vs. A-NP and B-P vs. B-NP), especially in the case of higher loadings (B-P vs. A-P), which is likely related to the root density and/or subsequent accumulation of particles near the root zones.

In fact, when installing a perforated pipe in B-P to check the water level inside the bed, before the beginning of phase I, an extremely high root density was observed. Whenever the bed was loaded, it had a much lower infiltration velocity at the inlet, indicating some clogging of the bed media.

When analysing the bed porosity during phase II, a general increase can be observed in comparison to phase I (Table 1). B-P continued to present the lowest porosity with values

Table 1 General characteristics of the influent and effluent during phases I and II (standard deviation in round brackets)

	Bed	N samples	pH		T (°C)		O.R.P. (mV)		Conductivity (µS/cm)		Porosity (%)
			Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	
Phase I	A-NP	18	7.7 (0.6)	7.5 (0.3)	22.4 (4.7)	23.4 (6.6)	7 (52)	55 (68)	628 (122)	584 (145)	37
	A-P	18		7.3 (0.2)		23.7 (6.9)		0–3 (673)		610 (109)	34
	B-NP	18		7.4 (0.2)		23.1 (6.1)		−37 (80)		599 (104)	30
	B-P	17		7.1 (0.2)		23.4 (6.7)		0 (62)		696 (148)	21
Phase II	A-NP	24	7.7 (0.5)	7.5 (0.3)	16.4 (1.6)	16.8 (2.6)	18 (151)	37 (127)	613 (142)	598 (136)	39
	A-P	23		7.5 (0.2)		16.8 (2.6)		40 (123)		588 (133)	40
	B-NP	24		7.4 (0.2)		16.1 (1.0)		46 (136)		596 (137)	39
	B-P	23		7.3 (0.2)		16.4 (2.3)		45 (103)		613 (122)	34

between 33 and 35 %, with the remaining bed porosities very similar, with values around 40 % in this experimental phase.

This general increase can be due to a solids digestion inside the media during the resting period (June to December of 2012).

General characteristics of the outflow

The characteristics of the effluent in terms of pH, temperature, O.R.P. and conductivity were very similar between the four CWs and also between phases I and II, as can be seen in Table 1.

A decrease of 7 °C in the effluent temperature was observed from phase I to phase II as a reflection of season change. It can also be seen that both conductivity values as well as pH values (very close to neutrality) show very little variation between phases, suggesting that neither the time of the year or the presence of macrophytes influence these two parameters. The low conductivity values observed in these systems are in the same range of values reported in other CWs studies (Hijosa-Valsero et al. 2012).

The increase in the average ORP values from phase I to phase II reflected the variability of this parameter within each phase (data not show). In fact, there was an overall decrease in ORP values from phase I to phase II, most likely due to the higher organic load in phase II. Given the range of values observed, the oxidation of organic matter within the media

was possibly associated with iron and manganese reduction (Kadlec and Wallace 2009).

TSS and enterococci removal

Treatment efficiency was very high in terms of TSS and enterococci removal, with values up to almost 100 % for TSS at the end of phase I (Table 2).

The sharpest TSS reduction occurred in the firsts 24 h after the loading, which is likely related to filtration and adsorption processes provided by the filling media. It was also observed an improvement in TSS removal efficiency (after 7 days) during phase I, which could reveal the influence of a biological treatment process (degradation of volatile suspended solids). In fact, since before phase I the beds had 10 months with no loading, when loading resumed there was probably a biofilm development during the course of this phase.

When analysing the data there seems to be no difference between beds in terms of TSS removal, suggesting that TSS removal in CWs is not influenced by neither the load applied nor by the presence/absence of macrophytes. However, a more detailed statistical analysis, using the Kruskal-Wallis test, revealed the influence of the applied load in the removal of TSS (for $p < 0.10$), with lower efficiencies for group B.

Regarding enterococci, an almost linear decrease (in a logarithmic scale) was observed after each loading. Removal efficiencies were between 3 and 5 log at the beginning of phase I, increasing slightly to 4–6 log at the end of this phase. These

Table 2 TSS and enterococci removal rates for phase I (standard deviation in brackets)

	Bed	N samples	TSS	TSS removal (%)		Enterococci	Enterococci removal (log)	
			Influent (mg/L)	1 day	7 days	Influent	1 day	7 days
Phase I	A-NP	18	120 (48)	94.2 (3.7)	98.6 (0.9)	1.15 E+06 (8.21 E+05)	2.0 (0.4)	4.8 (0.5)
	A-P	18		95.6 (1.9)	98.0 (1.4)		1.9 (0.6)	4.8 (0.5)
	B-NP	18		90.0 (6.5)	96.8 (2.6)		1.7 (0.4)	4.9 (0.5)
	B-P	17		84.7 (6.0)	88.2 (2.1)		1.6 (0.9)	4.6 (0.7)

Table 3 COD influent and effluent concentrations and removal efficiencies for each bed with different HRT (phase I) and resting periods (phase II) (standard deviation in round brackets)

Loading frequency		HRT (phase I)/resting time (phase II) (days)	N samples	COD influent (mg/L)	COD-removal efficiency (%)				COD effluent (mg/L)			
					A-NP	A-P	B-NP	B-P	A-NP	A-P	B-NP	B-P
Phase I	Weekly	1	9	233 (53)	85 (3)	76 (9)	81 (3)	69 (3)	37 (7)	55 (13)	46 (12)	73 (14)
		7	9		89 (3)	83 (5)	90 (3)	77 (3)	24 (5)	41 (15)	26 (7)	60 (14)
Phase II	3 to 4 consecutive	1	9	352 (120)	85 (3)	79 (9)	75 (7)	63 (18)	55 (13)	65 (10)	81 (17)	103 (38)
	days	>1	4	357 (183)	90 (6)	83 (5)	87 (6)	60 (9)	41 (19)	53 (16)	78 (59)	155 (40)
	>5 consecutive days	1	10	390 (165)	66 (11)	73 (6)	57 (13)	56 (16)	127 (46)	96 (46)	159 (44)	159 (50)
		>1	1	410 (−)	71 (−)	78 (−)	57 (−)	59 (−)	117 (−)	89 (−)	176 (−)	170 (−)

removal efficiencies are substantially higher than the values obtained by Morató et al. (2014) for HSSF CW planted with *Phragmites australis* (1.4–2.3 log. with HRT of 5/6 and 3 days) validating the good treatment performance of all four CWs monitored in the present study.

The decrease pattern observed for enterococci concentration indicates a strong dependence on retention time. This behaviour is more consistent with removal mechanisms where contact time is more relevant, such as predation processes and natural die-off rather than filtration or adsorption. This result is consistent with the work of Wand et al. (2007) where predation and biolytic processes played a dominant role in bacterial removal.

All the beds have demonstrated similar treatment efficiencies for enterococci, indicating a reduced influence of organic load and macrophytes presence (Table 1). These results were confirmed by a multivariate MANOVA test, where enterococci removal rates (log reduction) were not statistically different between beds ($p > 0.05$).

COD removal

Organic matter removal performance in the CWs was evaluated in phases I and II, with average removal efficiencies of 80 % in phase I and 77 % in phase II. Since COD concentrations varied with each loading, the measured effluent concentrations and the corresponding removal efficiencies are directly influenced by the previous loading event. However, the obtained removal efficiencies are similar to the values obtained by Masi et al. (2016) for VF-CW treating CSO.

Phase I

The results for COD removal in phase I demonstrate a strong concentration reduction within the first 24 h, showing behaviour similar to TSS removal. This also indicates that filtration and adsorption processes are probably the main removal mechanisms and also that COD could have been mostly in the particulate form (García et al. 2005).

The COD-removal efficiency values showed a considerable difference between the beds with no plants (A-NP + B-NP), which presented an 81–90 % efficiency, and the ones planted with *Phragmites australis* (A-P + B-P), with efficiency values from 69 to 83 %. This was confirmed by a multivariate MANOVA test, which revealed statistically different results for COD-removal efficiencies between planted and

Fig. 1 COD mass removal rates in phase I. *Points* correspond to observed values and *lines* to linear trend lines
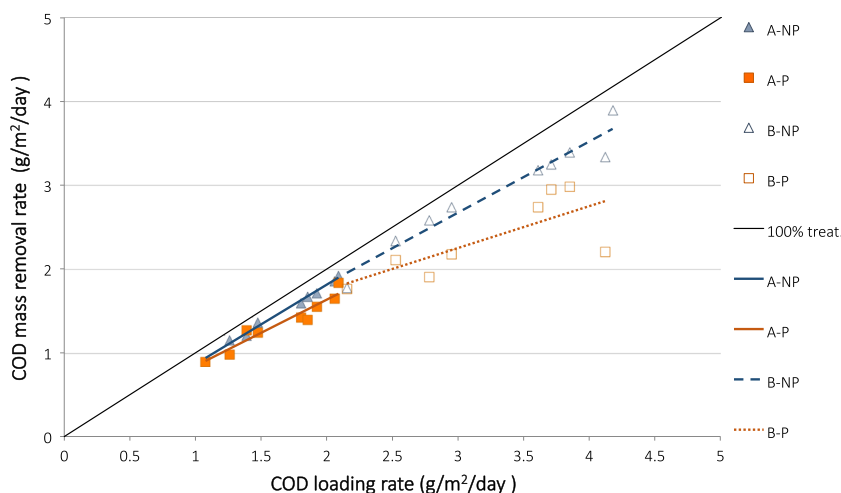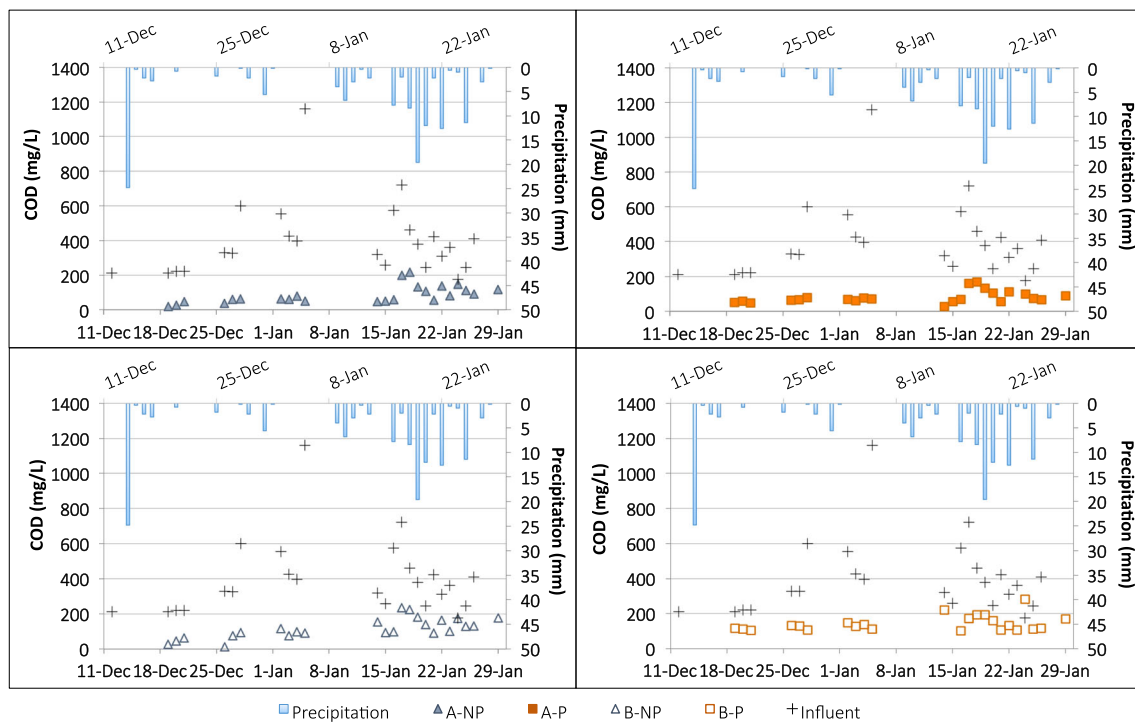
Fig. 2 COD concentrations during phase II

non-planted beds ($p < 0.01$). This difference may be related to the internal release of internal organic matter from macrophytes decay and decomposition, decreasing the COD treatment level in these beds (Pinney et al. 2000).

Average phase I removal efficiency after 1 day varied between 69 and 85 % and increased slightly to 77–90 % after 7 days (Table 3), emphasizing the relevance of the first 24 h of treatment.

When analysing the influence of mass loading rates in COD mass removal rates ($0.60 < R^2 < 0.99$, Fig. 1), it is clearly noticeable that for loads higher than 2.5 g/day/m² the difference between planted and non-planted beds increased substantially. In these operating conditions, unplanted beds

performed better, possibly due to the fact that planted beds were more affected by clogging.

Phase II

During phase II, the beds were submitted to a different loading schedule, based on the frequency of Frielas WWTP CSO discharges during the winter of 2010/2011. At the end of this phase the CWs were loaded with sewage directly from the WWTP (no dilution) since precipitation between 16 January and 28 January 2013 was high enough to assume that the effluent characteristics were similar to a CSO discharge. This assumption was confirmed by WWTP staff. Since this

Fig. 3 COD mass removal rates in phase II. *Points* correspond to observed values and *lines* to linear trend lines
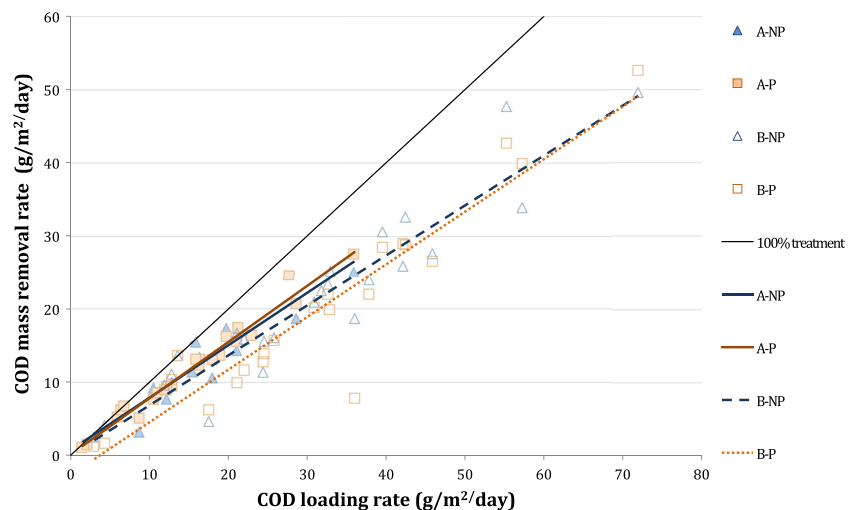
Table 4 $k - C^*$ model coefficients for COD in phase I, phase II and Amaral et al. (2013)

	A-NP			A-P			B-NP			B-P		
	k (per day)	C^* (mg/L)	R^2	k (per day)	C^* (mg/L)	R^2	k (per day)	C^* (mg/L)	R^2	k (per day)	C^* (mg/L)	R^2
Amaral (2013)	1.62	27	0.69	1.85	35	0.66	1.38	39	0.66	1.20	41	0.64
Phase I	2.47	25	0.92	2.26	41	0.87	2.08	26	0.91	1.80	49	0.87
Phase II	1.82	41	0.58	2.53	53	0.65	2.19	77	0.59	19.56	142	0.53

phase took place during winter, when more CSO discharges occur, it was possible to analyse the real response of a HSSF CW to CSO effluents.

Also, during this period, an unusually high COD load was registered on 5 January 2013 (Fig. 2) to which the beds had a significant treatment response (80–90 %). This behaviour was probably due to the higher retention time of this load (9 days between loadings), allowing enough time to achieve a stronger reduction of organic matter concentration.

During phase II B-P was once again at the lower end of the COD-removal efficiency range (Table 3) and a slight general reduction of COD treatment can be observed when compared with phase I. This could be attributed to the lower temperatures recorded during phase II (Garfi et al. 2012; Hijosa-Valsero et al. 2012) as well as due to plant senescence (winter conditions), since aboveground biomass can contribute to re-introduction biomass inside the bed and affect treatment process belowground (Kröger et al. 2007).

During phase II the beds with lower COD-removal efficiencies were B-NP and B-P, which seems to imply that during this period the macrophytes did not have a significant influence in the level of treatment. On the other hand, the applied load continued to influence performance in terms of COD-removal efficiency, confirmed with an ANOVA two-way test ($p < 0.05$) where the applied COD load caused a significant statistical difference in COD-removal efficiency with lower efficiencies in group B. Both the presence of plants as well as the interaction between factors was not statistically significant ($p > 0.05$).

Special attention is called for the final period of phase II where a relatively strong reduction of the systems efficiency occurred, which was probably associated with a daily loading frequency that lasted for 13 consecutive days. When compared with phase I, where most of the COD removal occurred during the first 24 h, in phase II a daily loading frequency appeared to lead to at least a partial saturation of the media. This suggests the need for a minimum rest period so the beds have time to degrade the COD retained in the first 24 h and restore the filtering capacity of the beds.

The influence of COD mass loading rates on COD mass removal rates was also very strong, and a clear correlation between these two variables was observed ($R^2 > 0.93$, Fig. 3).

$k - C^*$ model

COD data obtained in the present study and its predecessor (Amaral et al. 2013) were adjusted to a modified first-order $k - C^*$ model (Kadlec and Wallace 2009). The rate constant (k) and residual concentrations (C^*) are presented in Table 4. The values obtained revealed a good similarity between Amaral et al. (2013) and phase I of the present study and a substantial difference when compared to phase II. Also, the C^* values obtained are very similar to the results of Van de Moortel et al. (2009) work and the k values are lower but still comparable.

In phase II, rate constant values varied between 1.80 and 2.53/day with an exception of $k_v = 19.56$/day obtained for B-P bed. This erroneously high value is probably strongly related with the C^* value obtained in this case (142 mg/L) which is

Table 5 Average COD, TSS and enterococci removal efficiencies for Amaral et al. (2013), phase I and phase II

Bed		COD (%)			TSS (%)		Enterococci (log)	
	HRT (days)	Amaral et al. (2013)	Phase I	Phase II	Amaral et al. (2013)	Phase I	Amaral et al. (2013)	Phase I
A-NP	1	88	85	85	95	94	2.3	2.0
	>1	97	89	90	99	99	5.0	4.8
A-P	1	88	76	79	94	96	2.7	1.9
	>1	96	83	83	96	98	5.0	4.8
B-NP	1	83	81	75	94	90	2.1	1.7
	>1	93	90	87	99	97	4.8	4.9
B-P	1	82	69	63	86	85	2.1	1.6
	>1	93	77	60	94	88	5.7	4.6

significantly higher than the rest of $C*$ values (<80 mg/L). This could be explained by the strong clogging observed in B-P, which reduced its filtering capacity yielding a high residual concentration. The high k value arises from the fact that residual concentrations are reached after a very short period of time (around 24 h).

Comparison with previous work

In order to better understand the maturation process of a CW, a comparison between the present study and the work of Amaral et al. (2013), which was the start-up of the pilot plant (from April to June 2011), was performed (Table 5).

The experimental phase most similar to the start-up conditions is phase I, which occurred from April 2012 until June 2012. When analysing the two experiments, it can be observed that the removal rates of most parameters are similar. However, in terms of pathogen removal, there was a lower efficiency removal during the present study when compared to Amaral et al. (2013). The efficiencies also demonstrated a more solid and stable removal process in 2012/2013 (after one complete vegetation cycle) than during start-up.

TSS removal rates in 2012/2013 showed values very close to start-up, with lower values at the beginning of the phase I. Despite this, the values for A-P reached higher values than in 2011, having almost 100 % efficiency removal.

In terms of organic matter, there is clearly a change in treatment performance from 2011 to 2012 since in 2011 the removal efficiencies were nearly the same for all beds while in phase I of 2012 a significant difference between planted and non-planted beds was observed. This evolution could be explained by the initial plant development (acclimatization during first growing season) that took place during the start-up phase (2011) which provided a lower treatment capacity than once the plants were fully established (2012).

Conclusions

The pollution caused by CSO discharges is a critical issue since it can affect the quality of the environment of the receiving waters, being CWs an alternative treatment solution prior to their discharge in the waterlines. The experimental work with four HSSF CWs, receiving simulated CSO from Frielas WWTP, presented an excellent treatment performance, proving to be a strong and feasible solution for the current urban storm water management scenario. The main conclusions and recommendations drawn from the present study are:

- The applied load, the absence of a resting period and presence of macrophytes, directly influenced the COD treatment efficiency of the CWs. Therefore, a minimum resting period and a maximum load are crucial in a HSSF CW to maximize removal efficiencies.
- The observed enterococci and TSS removal was extremely high and did not suffer the influence of macrophytes or the applied load.
- The efficiency of COD removal decreased during wintertime, probably due to low temperatures and a short HRT (1–3 days).
- The macrophytes low survival rate from 2011 to 2012 in A-P indicates a minimum water need during dry periods. This can be achieved by loading the beds with WWTP effluent during warmer period, ensuring a minimum water depth to cope with the evapotranspiration rates. It should be noted that this measure not only prevents water stress but also reduces the volume of effluent discharged into waterlines.

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