Simultaneous Removal of Organic and Solid Matter and Nitrogen in a SSHF Constructed Wetland in Temperate Mediterranean Climate

Presented in 12th International Conference on Integrated Diffuse Pollution Management (IWA DIPCON 2008).
Research Center for Environmental and Hazardous Substance Management (EHSM)

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Abstract

In Portugal, small rural communities present low service levels in terms of wastewater treatment when compared to large urban areas. The hydraulic and pollutant loads are variable over time due to the incoming of non-point sources (namely from agricultural activities). The use of ecological treatment systems as horizontal subsurface flow (HSSF) constructed wetlands seemed to be a good solution for dealing with such load variability and without entailing excessive operation and maintenance costs. However, they should also allow fulfilling the goals of the *Urban Wastewater Treatment Directive* (91/271/EEC) and the *Water Framework Directive* (2000/60/EEC). The objective of the study was to evaluate the behavior of a HSSF system in the Cova da Beira region (Capinha) under the influence of transient loads, namely in terms of the variability of incoming flow-rate, organic matter (COD), nitrogen forms (total N, ammonia and nitrate) and suspended solids (TSS). The system showed an irregular removal of COD and TSS during the monitoring period, with lower removal efficiencies and lower areal removal rates when compared to the ones observed in other studies in Mediterranean countries, which was associated with the characteristics of the influent and its variability over time, as well as to a partial clogging of the bed. However, a good correlation between mass removal rate and mass load was observed for all measured parameters, which attests a satisfactory response of the bed to the oscillatory incoming loads. The system had a very good performance in terms of nitrogen removal (total N, $N\text{-}NO_3$ and N-NH4) presenting higher removal efficiencies and similar areal nitrogen removal rates when compared to the ones observed in other studies in Mediterranean countries. Some discrepancy in the system performance was also observed in the spring and summer periods, which may be related to load fluctuations and changes in average temperature and pH. Both mass removal rates and removal efficiencies were much higher in the second period, especially in terms of nitrogen removal.

Although the specific surface area of the bed (2.5 m^2/PE) seems to be enough for enhancing a higher removal of pollutants, the characteristics and variability of the incoming organic and solid loads may have contributed for a considerable bed clogging and, consequently, for the decrease of the effective area for pollutant uptake, which is affecting especially the organic matter removal.

Keywords: Horizontal Subsurface Flow, Constructed Wetlands, Transient Loads, Removal Rates

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Introduction

The Cova da Beira region is located in the interior center of Portugal and is influenced by the moderate Mediterranean climate. It has an area of 1375 km^2, the annual average temperature is 14.5°C and the average rainfall is 820 mm. Approximately 59% of the population lives in rural agglomerates with less than 2,000 inhabitants (INE, 2006).

These small rural communities are responsible by point source (domestic sewage) and non-point source pollution (livestock slurries, agricultural runoff from fertilizers and pesticides and runoff from roads and parking lots), which are contributing for significant environmental impacts on water bodies (e.g. eutrophication in some influents of the Zêzere River).

On the other hand, approximately 6,282 thousand m^3 of fresh water are treated each year, but only 70% is allocated to public water-supply use. The current level of service for sewage treatment (centralized and onsite/decentralized systems) is 75%, but only 43% of the population is properly served by treatment facilities, the majority of which is located in urban centers (Korkusuz, 2005). The water demand for agricultural and tourism activities (e.g. irrigation and livestock production) reaches more than 80% of the total water consumption in the region.

Considering the variability of volumes and pollutant loads produced in these areas, the significant number of small disperse communities, the lack of specialized human resources and the financial availability, water management authorities are adopting ecological wastewater treatment systems such as constructed wetlands (CW), which seems to be an appropriate system to deal with such loads. In the last decade, several systems have been built in the Cova da Beira region, most of them with horizontal subsurface flow (HSSF-CW). It is believed that those systems are economically and environmentally sustainable without entailing excessive operation and maintenance costs, allowing to fulfill the discharge standards set in the *Urban Wastewater Treatment Directive* (91/271/EEC) and the goals established in the *Water Framework Directive* (2000/60/EEC), which requires water bodies to achieve a good ecological status by 2015.

On the other hand, the final effluent may be reused in rural communities (e.g. agricultural and tourism activities), thus constituting an important benefit to compensate the agricultural and tourism water demand, particularly in dry weather years.

In Portugal, as in most of the Mediterranean countries (except for France, Germany and Italy), there are no specific regulations for CW and the systems are sized based on design criteria and experience from USA and Northern European countries (Kowalik, 1995; Etnier and Guterstam, 1997; Vymazal, 2003; IWA, 2000; EPA, 1999); Specific surface area (SSA):

3 to 6 m^2/EP Organic loading rate (OLR)
5 to 16 g COD/m^2.d Solids loading rate (SLR)
5 to 20 g TSS/m^2.d
Hydraulic loading rate (HLR): 5 to 20 cm/d
Hydraulic retention time (HRT): 5 to 10 d

The systems are generally gravel-based with a bed slope between 1% and 3% and a submerged depth between 0.3 and 0.7 m. The German guideline DWA A-262 also suggests maximum allowable influent concentrations of COD and TSS of 400 mg/L and 100 mg/L respectively, OLR and SLR not greater than 16 g COD/m^2.d and 6 g TSS/m^2.d respectively, and a HLR lower than 4 cm/d, in order to minimize bed clogging (Rustige, 2005).

Several studies carried out in other Mediterranean countries (Masi et al., 2000; Korkusuz, 2005; El-Khateeb and El-Gohary, 2002; Masi and Martinuzzib 2007) pointed out that HSSF-CW present a good potential for dealing with fluctuations in flow rate, organic mater, solid mater and nutrients content if well operated and if some variables can be controlled.

The most recent publications on treatment efficiency of CW in Portugal (Dias et al., 2006; Silva and Braga, 2006) reported that the systems normally present good performance in terms of BOD5, COD and TSS removal, but lower effectiveness for total P and N removal. It was also observed a high capacity to remove low concentration of organic substances(Silva and Braga, 2006). However, there is no data available concerning the behavior of the systems in rural areas under significant variability of incoming hydraulic load and pollutant load.

The objective of the study was to evaluate the performance of a HSSF system located in the Cova da Beira region (Capinha), under transient conditions of hydraulic, organic, nitrogen and solid loads.

Material and Methods

The constructed wetlands system of Capinha

The Wastewater Treatment Plant (WWTP) of Capinha (Cova da Beira region, Portugal) was designed for 800 PE. Preliminary treatment includes bar racks, screening and flow measurement followed by primary treatment in an Imhoff tank. The secondary treatment includes two parallel HSSF-CW with 50 x 15.5 x 1 m (length, width and total depth), filled with gravel and mould (first 5 cm). The submerged depth during the monitoring period was 0.65 m. Each bed has a total area of 772.5 m^2 (effective area of 309 m^2) and was colonized with common reed (*Phragmites australis*). The beds were designed for flow rates of 45 to 90 m^3/d, HLR of 7 to 15 cm/d, HRT of 4.5 to 9 d, SSA of 2 m^2/PE and COD of 300 to 500 mg/L.

Experimental procedure

A four month monitoring campaign was set up, for spring (May and June) and summer (July and August) periods, including the measurement of flow rate (inflow and outflow of the HSSF-CW) and the collection of weekly samples (approximately at the same hour) at the influent of the WWTP and at the influent and effluent of one of the HSSF-CW to determine the pH, temperature, DO, total and soluble COD (CODt and CODs), total nitrogen, NH_4-N, NO_3-N, VSS and TSS.

Analytical methods

The measurements of DO, pH and temperature were carried out directly using a multiparametric WTW Multi 340i. The CODt and CODs (after sample filtration with Chromafil GF/PET 0.45 m filters) were determined with cuvette tests LCK 314 (15 - 150 mg L-1 O2) and LCK 514 (100 - 2000 mg L-1 O2), following DIN 38049-4, and a CADAS 50 Lange spectrometer. Ammonia and nitrate were obtained using the cuvette tests LCK 303 (2 - 47 mg L-1 NH4-N) and LCK 339 (0.23 - 13.50 mg L-1 NO3-N), following the standards DIN 38406-E 5-1 and DIN 384 02-A51, and the same spectrometer. TSS and VSS were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA-AWWA-WPCF, 1995).

Results and Discussion

Operating conditions and performances

The average values obtained for the HSSF CW are presented in Table 1. The pH ranged from 6.8 to 7.9 (influent) and 6.6 to 7.4 (effluent), the average DO was 1.2 ± 0.3 mg/L (influent) and 1.7 ± 0.4 mg/L (effluent) and the average temperature was 21.6 ± 0.3 °C (influent) and 22.4 ± 0.6 °C (effluent).

A statistical analysis on the results showed coefficients of variation (CV) between 22% and 58% for all the chemical parameters in the raw influent of the WWTP (the evolution of COD, NH_4-N and TSS are presented in Figures 1 to 3), which would mean that a significant change has occurred in its characteristics over time. Since during the monitoring period there was no considerable rainfall, this variation can be mainly associated with small agro-industrial activities, namely cattle feedlots, piggeries and dairies whose effluents are not separately treated and, therefore, are discharged into the municipal sewer network.

Table 1. Average operating conditions for the HSSF

Parameter	Influent	Effluent
Flow-rate (m3/d)	67.0 ± 6.7	43.4 ± 2.7
CODt (mg/L)	413.6 ± 45.3	140.4 ± 26.7
TN (mg/L)	31.0 ± 3.2	7.4 ± 2.6
NH_4-N (mg/L)	26.8 ± 3.0	5.7 ± 2.4
NO_3-N (mg/L)	1.60 ± 0.48	0.45 ± 0.13
VSS (mg/L)	77.9 ± 9.0	27.3 ± 5.1
TSS (mg/L)	118.6 ± 9.0	51.7 ± 7.8

The CV for the influent and effluent flow rate were 19% and 12% respectively, indicating a relatively stabilized flow at the discharge point. The CV for all the chemical parameters in the influent and effluent of the HSSF-CW were in the ranges of 22% to 48% and 20% to 58% respectively, indicating a considerable changeability of its characteristics over time.

Although the Imhoff tank could have acted as a buffer to attenuate the variation of incoming loads to the secondary treatment, it was detected a significant oscillation of COD, nitrogen forms and TSS in the bed inlet (Figures 1 to 3).

More significant variation of COD and TSS influent to the HSSF-CW was noted in the first seven weeks (spring period) and of nitrogen in the last seven weeks (summer period). Nevertheless, there was no significant linear relationship (R^2 < 0.2) between the variation of the concentrations of COD, nitrogen forms and TSS in the raw influent and in the influent of the HSSF-CW

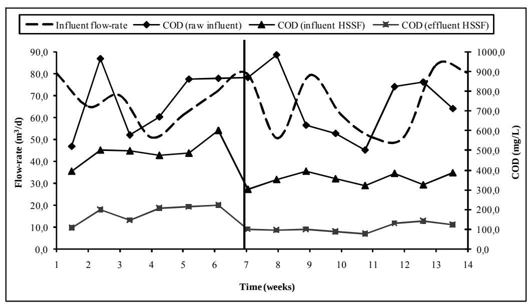

Figure 1. Flow-rate and COD variation for the monitoring period

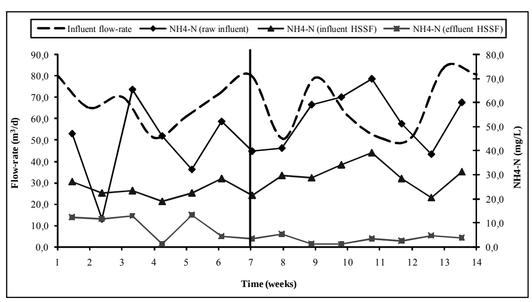

Figure 2. Ammonia nitrogen variation for the monitoring period

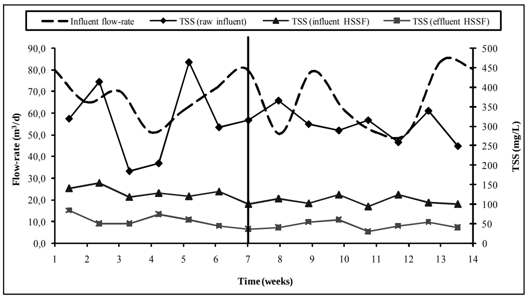

Figure 3. TSS variation for the monitoring period

The overall removal efficiency (RE) of COD, TN, NH_4-N, NO_3-N and TSS in the HSSF-CW was 66.7%, 76.0%, 78.6%, 71.9% and 56.4%, respectively. The influent and effluent concentrations of COD were unstable and increasing over time during the first seven weeks, reaching the highest values of 602 mg/L and 222 mg/L, respectively. For the TN and NH_4-N a significant variation of the concentrations in the final effluent (highest values of 11.3 mg/L and 9.3 mg/L, respectively) was observed during the spring period and in the influent during the summer period (highest values of 41.6 mg/L and 39.1 mg/L, respectively).

Nevertheless, the bed seems to have had a bigger yield in the summer period, presenting the highest RE (69.4%, 86.0%, 88.6% and 79.6% for COD, TN, NH_4-N and NO_3-N, respectively), except for TSS which was approximately the same. The highest average temperature registered in the second period (23.2 °C) could also have contributed for these results.

The average influent concentrations of TSS also changed between the spring period (132 mg/L) and the summer period (108 mg/L). However, the RE was low and quite similar (53.8% and 58.5%, respectively). The influent VSS concentration was quite stable over time and the average RE was 64.5% (68.6% in the summer period).

The obtained results are in the range of the Mediterranean-wide experience for HSSF-CW operated in comparable conditions (i.e. similar average temperatures, HRT, HLR and SA and contribution of non-point sources) as it can been seen in Table 2, except for TSS that presented an average RE in Capinha lower than the normal values found in all the consulted international studies (Mediterranean and non-Mediterranean countries).

Although the RE of COD was lower than expected, and lower than the values found in Italy and Egypt, only 28% of the effluent concentration slightly exceeded the limit of the 91/271/EEC Directive (125 mg/L). However, this circumstance was only observed in the spring period. For TSS, approximately 86% of the effluent concentrations exceeded the limit of 35 mg/L imposed by that Directive. Nevertheless, it should be noted that the measuring point for the HSSF-CW outlet is not the final discharge point and, therefore, the comparison of the results with the limits of the 91/271/EEC Directive are only made for the purpose of treatment analysis.

Table 2. Comparative RE in HSSF-CW for different Mediterranean countries

Reference	RE (%)				HLR	HRT	SSA
	COD	TN	NH_4-N	TSS	(cm/d)	(d)	(m^2/PE)
Capinha (Portugal) (this study)	66.7	76.0	78.6	56.4	8.5-13.8	4.8-9.0	2.5
Florence (Italy) (Masi and Martinuzzib, 2007)	94.0	60.0	85.0	84.0	14.0-15.6	3.0-4.3	1.2
Corbins (Spain) (Osorio, 2006)	43.0	—	25.0	73.0	18.0	3.0	1.0
Cairo (Egypt) (El-Khateeb and El-Gohary, 2002)	78.0	35.0	22.6	78.0	3.6	5.0	2.3
Sakhnin (Israel) (Avsara et al., 2007)	64.2	—	55.1	90.4	7.3-14.9	2.5-5.0	—
M.Diq (Marocco) (Cadelli et al., 2004)	—	50.0	—	77.0	19.0	9.0	2.3
Mediterranean-wide experience (Korkusuz, 2005)	48.0-93.0	23.0-96.0	20.0-98.0	58.0-99.0	6.0-8.0	< 14.0	2.0-5.0
World-wide experience (Kowalik, 1995; Etnier and Guterstam, 1997; Vymazal, 2003; IWA, 2000; EPA, 1999)	40.0-95.0	42.3-79.2	48.3-78.6	74.6-89.8	5.0-20.0	5.0-10.0	3.0-6.0

These results may indicate that the lower removal of COD may be related to the lower removal of TSS as a result of the incoming of a large amount of particulate organic matter which was difficult to biodegrade. Approximately 61% of the raw influent COD was particulate (CODp) and it was observed a good correlation (R^2 = 0.62) between CODp and TSS which reinforces the conviction of a significant contribution of non-point sources from agro-industrial activities. Approximately 48% of the influent CODt of the HSSF-CW was particulate and 66.2% was observed in the effluent, which would mean that a considerable amount of slowly biodegraded organic matter and inert matter was not retained in the bed, even if admitting that some fraction of the effluent CODp may be associated with decay sub-products (approximately 20%, according to Korkusuz (Orhon and Artan, 1994)).

Although it was observed a large amount of particulate organic matter in the raw influent, there was a good RE of COD observed in the primary treatment (42.2% for CODt and 54% of CODp against 23% for CODs). The primary CODt and CODp removal in the spring period was only 46% and 44%, respectively, and this lower yield would be responsible by the detected influent COD oscillations of the HSSF-CW (Figure 1) and, therefore, have influenced the behavior of the bed in the same period. This circumstance may be associated with a lower behavior of the Imhoff tank during that period.

However, the amount of slowly biodegraded organic matter that reached the bed, mainly as TSS, was not properly retained (only 49.5% of the CODp was removed whilst the removal of CODt and CODs was 66.7% and 77%, respectively). The ratio of

VSS/TSS in the effluent of the HSSF-CW was 0.53, which indicated a low degree of mineralization of the effluent and the presence of considerable organic matter content.

Although it was observed a significant oscillation of the incoming concentrations of TN and NH_4-N of the HSSF-CW over time, the bed performed very well, presenting a RE for both parameters higher than the ones registered in similar systems in Italy, Spain, Egypt, Israel and Morocco (Table 2). The effluent concentrations of TN were always bellow the limit stipulated for discharge in the 91/271/EEC Directive (15 mg/L) and the bed outperformed the minimum required RE (70%).

Removal rates for the HSSF-CW

The areal mass removal rates (in g/m^2.d) were calculated based on the influent and effluent concentrations of the analyzed parameters, the influent and effluent flow rates and the total area of the bed. A significant linear correlation was observed between incoming mass load of COD, NH_4-N, TN and TSS and the respective mass removal rates ($r_{(COD)}$, $r_{(NH4-N)}$, $r_{(TN)}$ and $r_{(TSS)}$), in particular for COD (R^2 = 0.81) and NH_4-N (R^2 = 0.55) as shown in Figures 4 to 6.

The $r_{(COD)}$ increased linearly up to 14.1 g COD/m^2.d as the incoming organic load increased up to 22.3 g COD/m^2.d (Figure 4) and decreased as the organic load decreased. It was not observed a stabilized pattern for $r_{(COD)}$, which would mean that the bed may have a higher removal capacity than it has been shown.

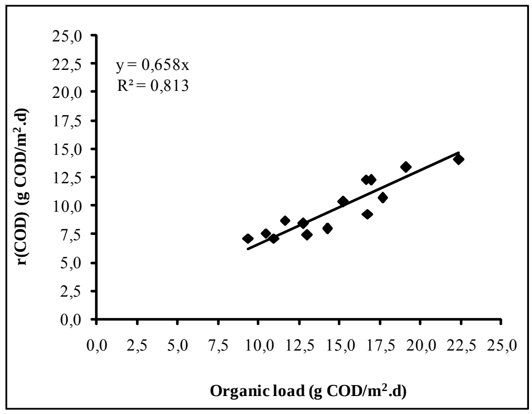

Figure 4. Relationship between organic load and COD removal rate

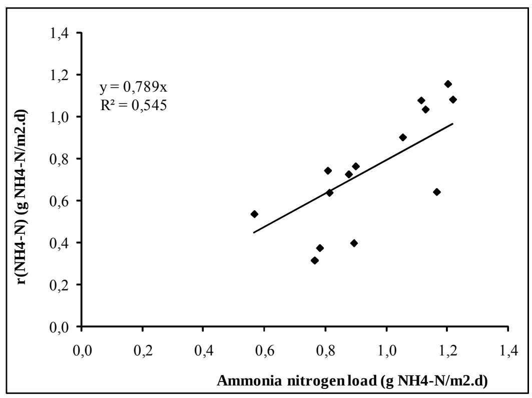

Figure 5. Relationship between ammonia nitrogen load and NH_4-N removal rate

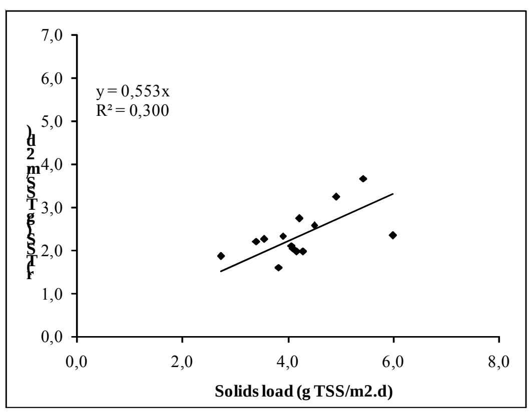

Figure 6. Relationship between suspend solid load and TSS removal rate

Ammonia removal rates have presented higher and linear correlations with the ammonia loads during the summer period (R^2 = 0.91) where it was observed the highest $r_{(NH4-N)}$ (0.9 g NH_4-N/m^2d). These results would mean that the bed deals well with the variability of incoming nitrogen loads rather than a decrease in the incoming load.

Similar correlations for COD have been found in a study in Israel (Avsara et al., 2007) and for COD and NH_4-N in Turkey (Ayaz and Ak□a, 2001), however, the dependency was much stronger and linear (R^2 between 0.95 and 0.98 for COD and over 0.85 for NH_4-N). In the first case, the applied loads and removal rates were quite similar for equivalent operating conditions (Table 2), but the raw influent had less contribution from agro-industrial or agricultural sources. For the second case, the COD and NH_4-N loads were up to three and five times, respectively, greater than the ones observed in Capinha and the RE for both parameters was 88%. These better results are, however, associated with the feeding regime (intermittently) and the lower submerged depth (approximately 0.30 cm), which promotes the oxygenation of the bed and, therefore, the aerobic removal of organic matter and ammonia.

The $r_{(COD)}$ and $r_{(TSS)}$ were lower than the ones obtained for similar systems in Mediterranean countries (Table 3), however, they are still in the range of the world-wide experience. These results may be associated to the presence of large amount of particulate organic matter in the influent to the HSSF-CW.

The low average DO concentrations in the influent (1.2 mg/L) and effluent (1.7 mg/L) of the HSSF-CW may indicate that the water inside the bed had strong reducing conditions. Thus, it could be reasonably assumed that the main mechanisms involved in the removal of organic matter were anaerobic pathways such as methanogenesis. Since the yield coefficient of the methanogenic microorganisms (0.21 g COD_{VSS}/g $COD_{substrate}$) (Grady et al., 1990) is lower than the one for the aerobic heterotrophic microorganisms (0.67 g COD_{VSS}/g $COD_{substrate}$) (Grady et al., 1990) it could be admitted that the removal of organic matter, especially the particulate fraction, occurred at low rates.

Although the HSSF-CW of Capinha has a SSA and HRT similar to the ones found in similar systems in the Mediterranean area (Table 2), it seems that they were not sufficient to deal with higher and variable organic loads. During the four months of monitoring, the detected HLR, HRT and average COD were in the range of the design criteria used in Capinha, however, there were detected peaks of COD higher than 500 mg/L. Nevertheless, during the warmer months the results showed that a SSA less than 3 m^2/EP would be appropriate to maintain the minimum treatment requirements.

Renker (2006) previously evaluated the effect of load conditions on the performance of a HSSF-CW in the Cova da Beira region and concluded that the beds may not have the proper effective area for organic matter uptake due to either an inappropriate use of sizing criteria or the occurrence of quick clogging as a result of the variability of the wastewater characteristics and the excess of suspended solid matter.

Table 3. Comparative removal rates for different Mediterranean countries

Reference	$r_{(COD)}$	$r_{(TN)}$	$r_{(NH4-N)}$	$r_{(TSS)}$
Capinha (Portugal, this study)	9.8	0.8	0.7	2.4
Gorgona (Italy) (Masi, 2002)	12.5		1.1	5.3
Corbins (Spain) (Osorio, 2006)	23.7	—	1.6	7.8
Cairo (Egypt) (El-Khateeb and El-Gohary, 2002)	20.4	0.8	0.3	6.4
Sakhnin (Israel) (Avsara et al., 2007)	17.1	—	2.4	7.9
Mediterranean experience (Korkusuz, 2005)	10.0-20.0	< 6.0	0.8-5.0	0.7-14.5
Worldwide experience (Kowalik, 1995; Etnier and Guterstam, 1997; Vymazal, 2003; IWA, 2000; EPA, 1999)	8.5-25.0	0.1-25.0	0.4-13.3	0.5-20.5

Although the higher RE of COD occurred in the summer period, due to the presence of lower concentrations, in the spring period the applied organic load and the mass load removal were superior (Figure 7). Therefore, the higher changeability in incoming concentrations in the spring period (Figure 2) seems to have no effect in the heterotrophic microorganism's activity rather than the amount of mass load.

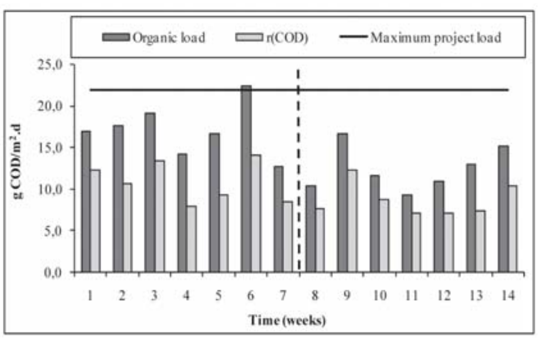

Figure 7. volution of organic load and r_{COD} in time

During the monitoring period it was observed some ponding conditions in the inlet corners. The average OLR was 14.8 g COD/m^2d, which is close to the maximum sizing criteria found in the literature (16 g COD/m^2d) (Kowalik, 1995; Etnier and Guterstam, 1997; Vymazal, 2003; IWA, 2000; EPA, 1999), as well as to the limit value for avoiding bed clogging (Rustige, 2005). Although the SLR (4.2 g TSS/m^2d) was lower than the ones recommended for sizing criteria (20 g TSS/m^2d) (Kowalik, 1995; Etnier and Guterstam, 1997; Vymazal, 2003; IWA, 2000; EPA, 1999) and for avoiding bed clogging (6 g TSS/m^2d) (Rustige,2005; EPA, 199) the average influent concentrations (118.6 mg TSS/L) were greater than the maximum suggested for clogging prevention (100 mg TSS/L) (Rustige, 2005). Therefore, the bed may be considerably clogged, which is a factor that could also have contributed for the decrease of TSS and COD removals since the effective area for organic matter uptake and the filterability capability were reduced.

Most of the studies performed in other Mediterranean countries presented higher RE and higher areal removal rates of COD and TSS, for higher incoming loads, when compared to the ones observed in Capinha (Tables 2 and 3). However, although it is referred some contribution of agricultural and agro-industrial sources, it wasn't detected neither the changeability of incoming loads nor the presence of higher particulate organic matter than in Capinha. According to Vymazal (Vymazal, 2003), for a SLR of approximately 5 g TSS/m^2d the average r_{TSS} should be approximately 4 g TSS/m^2d.

The $r_{(TN)}$ and $r_{(NH4-N)}$ were closer than the ones found in Mediterranean systems (Table 3). Despite the significant variation observed in the influent concentrations (Figure 2), especially for the summer period, the areal removal rates were quite satisfactory, reaching the highest values in the summer period (1.3 TN g $/m^2d$ and 1.2 NH_4-N g $/m^2d$), as shown in Figure 8 for ammonia nitrogen. Although the DO was a limiting factor in bed, which enhanced the anaerobic pathways, according to Korkusuz (Masi and Martinuzzib, 2007) concentrations above 1 mg/L associated with a high HRT (above 5 d), as it was observed in Capinha, would lead to good conditions for nitrification. The higher temperature (23.3 ^oC) observed in the second period also contributed for higher kinetic rates of nitrifier microorganisms.

During the spring period the $r_{(NH4-N)}$ was very unstable and, since the DO did not change significantly, the major reason that may explain this occurrence is the presence of low pH values (values in the range of 6.8 to 7.3), most likely due to the presence of non-point sources, which are not favorable for a good nitrification (the optimum range is between 7.5 and 9.5 (Korkusuz, 2005; EPA, 1999; Osorio, 2006)).

Nevertheless, the available DO in the bed inlet also helps the activity of aerobic heterotrophic, which have higher energy yields, growth rates and oxygen affinity than the nitrifying bacteria and, therefore, nitrification was not the only mechanism responsible for nitrogen uptake. The ammonia uptake by *Phragmites australis* may reach up to 0.16 g NH_4-N/m^2.d (Vymazal, 2003)and additional nitrification may occur in the rhizosphere since the roots of that species may contribute with up to 3 g O_2/m^2.d (Vymazal, 2003; EPA, 1999). Therefore, it seems that all or most of the oxygen potentially available from direct and plant mediated flux and from plant uptake would not be enough to explain the observed $r_{(TN)}$ and $r_{(NH4-N)}$.

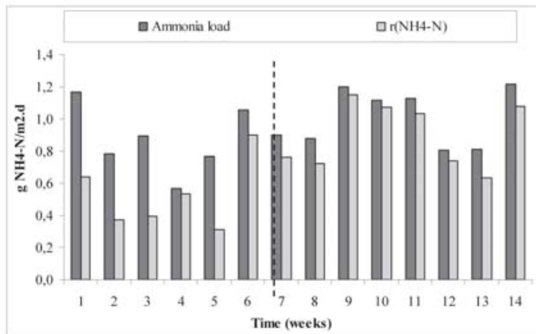

Figure 8. Evolution of ammonia load and r_{NH4-N} in time

Although the nitrate influent was low, denitrification seemed to have occurred in the bed, given the high ammonia removal rate, as well as the low nitrate concentration in the effluent and therefore would have given some contribution to organic matter removal.

Conclusions

Considering the influent characteristics of the HSSF-CW in Capinha and its variability over time, the bed showed a satisfactory removal of organic matter, nitrogen and solid matter.

The COD and TSS removal were lower than the values observed in the most of the studies found in other Mediterranean countries. This circumstance may be associated with a lower availability of the effective area for contaminant uptake, due to a partial clogging of the bed, as well as to the presence of a large amount of particulate organic matter which passed through the bed.

The system had a very good performance in terms of nitrogen removal (TN, NO_3-N and NH_4-N). Although TN and NH_4-N concentrations in the HSSF-CW influent had been unstable, the bed showed a good response to nitrogen transient loads, presenting removal rates in the range of the ones found in Mediterranean countries.

The influent was not very nitrified and the low nitrate concentration in the final effluent allows admitting that most of the nitrate generated by nitrification was removed by denitrification.

Nitrogen removal rates may be associated with the simultaneous occurrence of several mechanisms, such as nitrification, denitrification, anaerobic ammonium oxidation and plant uptake.

A good correlation was observed between mass removal rates and mass loads for COD and nitrogen forms, which would mean that the bed had a satisfactory response to changes in incoming loads.

As a final remark, this study clarifies that HSSF-CW subject to transient high loads should be designed for lower organic and solid loads and the inclusion of advanced primary treatment systems (e.g. filter screens or high-rate clarification) should be considered, in order to reduce the surface loading rate.

Acknowledgement

This work was financed through the project PTDC/AMB/73081/2006.

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