Removal of organic matter and nitrogen in an horizontal subsurface flow (HSSF) constructed wetland under transient loads

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ABSTRACT

A monitoring campaign in a horizontal subsurface flow constructed wetland under the influence of transient loads of flow-rate, organic matter, nitrogen and suspended solids showed an irregular removal of COD and TSS and lower both removal efficiencies and mass removal rates than the ones observed in other studies for similar operating conditions. This circumstance is associated to the presence of large amount of particulate organic matter from non-point sources. The mass removal rate of ammonia increased 39% as both the water and soil temperatures increased from weeks 1–8 to weeks 9–14. A good correlation between mass load and mass removal rate was observed for all measured parameters, which attests a satisfactory response of the bed under to transient loads.

Key words | constructed wetlands, nitrogen removal, organic matter removal, transient loads

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INTRODUCTION

Most of the wastewater treatment systems in small communities of the Beira Interior region (Portugal) are based on constructed wetlands (CW) with horizontal subsurface flow (HSSF). The systems are normally sized based on international design criteria and experience (EPA 1999; IWA 2000; Vymazal & Kropfelova 2008): 3 to 6 m^2/p.e. (as specific surface area–SSA), 2 to 12 g BOD_5/m^2 d or 5 to 20 g COD/m^2 d (as organic loading rate–OLR), 5 to 12 g TSS/m^2 d (as solids loading rate–SLR), 2 to 20 cm/d (as hydraulic loading rate HLR) and 5 to 14 d (as hydraulic retention time–HRT). The German guideline ATV-A 262 (2006) 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.

The Beira Interior region is influenced by the moderate Mediterranean climate (annual average temperature of 14.5°C), which could be an advantage to enhance a good performance of HSSF since the most common pathways for organic matter and nitrogen removal are dependent on temperature (IWA 2000; Kadlec & Wallace 2008; Vymazal & Kropfelova 2008). According to EPA (1999), IWA (2000), Vymazal (2003), Wallace & Knight (2006) and Vymazal & Kropfelova (2008), HSSF gravel beds usually provide high removal of organic matter (BOD_5 and COD) but lower N removal (lower than 50%). Gajewska & Obarska (2008) observed removal efficiencies (RE) of 85%, 50% and 60% in terms of COD, TN and NH_4-N, respectively, and mass removal rates (MRR) from 1.2 to 23.3 g COD/m^2 d and 0.1 to 0.9 g TN/m^2 d.

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Organic matter is normally removed though precipitation, filtration and both aerobic and anaerobic biological pathways carried out by heterotrophic bacteria. N losses in the bed are related to volatization, filtration, sedimentation, adsorption, plant uptake and biological removal pathways such as nitrification and denitrification (IWA 2000; Vymazal 2003; Kadlec & Wallace 2008; Vymazal & Kropfelova 2008). However, as HSSF beds present low oxygen concentrations (EPA 1999; Wallace & Knight 2006) some authors (Dong & Sun 2007; Paredes *et al.* 2007; Albuquerque *et al.* 2009) pointed out that N removal through non-conventional mechanism (e.g. partial nitrification, heterotrophic nitrification, autotrophic anaerobic ammonia oxidation (anammox) or oxygen-limited autotrophic nitrification–denitrification) could have an important role in N losses.

Therefore, the objective of this study was to evaluate the removal of organic matter and nitrogen in an HSSF bed located in a small rural community in the Beira Interior region (Portugal), under transient conditions of hydraulic, organic, nitrogen and solid loads for the vegetative months with higher temperature.

MATERIAL AND METHODS

Constructed wetlands system

The Wastewater Treatment Plant (WWTP) of Capinha (Cova da Beira region, Portugal) was designed for 800 p.e. and includes an Imhoff tank and two parallel HSSF beds. Each bed has 50 × 15.5 (length and width), a total area of 773 m^2 and was colonized with common reed (*Phragmites australis*). The media bed was composed of gravel (0.95 m of total depth) and the water depth was 0.65 m. The beds were designed for flow rates from 45 to 90 m^3/d, HLR from 7 to 15 cm/d, HRT from 4.5 to 9 d, SSA of 2.5 m^2/p.e. and COD concentrations from 300 to 500 mg/L (maximum OLR of 21.8 g COD/m^2 d).

Experimental procedure

A four month monitoring campaign was set up in one of the beds (May to August 2007), including the measurement of flow-rate (inflow and outflow of the HSSF beds) and the collection of weekly samples (one single sample by week, during 14 weeks, approximately at the same hour) in three points: raw wastewater and at the influent and effluent of one of the HSSF beds to determine the pH, temperature, dissolved oxygen (DO), total and soluble COD (CODt and CODs), total nitrogen (TN), ammonia nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), total suspended solids (TSS) and volatile suspended solids (VSS). The soil temperature was evaluated near the influent and effluents points.

Analytical methods

The measurements of DO, pH and temperature were carried out *in situ* using a multiparametric Multi 340i (WTW, Germany). The CODt and CODs (after sample filtration with Chromafil GF/PET 0.45 μm filters) were determined with cuvette tests LCK 314 (15–150 mg COD/L) and LCK 514 (100–2,000 mg COD/L), following DIN 38049-4, and a CADAS 50 spectrometer (Hach-Lange, Germany). The CODp was calculated trough the difference between CODt and CODs. Total nitrogen, ammonia nitrogen, nitrite nitrogen and nitrate nitrogen were obtained using the cuvette tests LCK 238 (5–40 mg N/L), LCK 303 (2–47 mg NH_4-N/L), LCK 342 (0.6–6 mg NO_2-N L^{-1}) and LCK 339 (0.23–13.50 mg NO_3-N/L), following standards DIN 38406-E 5-1 and DIN 38402-A51, and the same spectrometer. TSS and VSS were determined according to the Standard Methods for the Examination of Water and Wastewater (APHA 1998).

RESULTS AND DISCUSSION

Analysis of the operating conditions and performance

The average values for the three sampling points are presented in Table 1. No nitrite was detected in the measuring points. The evolution of COD and TN over time is presented in Figure 1. The HLR applied to the bed (average flow-rate over the total area) is also presented in order to observe the relationship between pollutants variation and hydraulic load.

Table 1 | Average operating conditions at the WWTP of Capinha

Parameter	Raw wastewater	Influent HSSF	Effluent HSSF
Flow-rate (m^3/d)	–	67.0 ± 6.7	43.4 ± 2.7
Water temperature (°C)	–	21.5 ± 0.4	22.4 ± 0.6
Soil temperature (°C)	–	24.2 ± 1.0	24.4 ± 0.9
CODt (mg/L)	744.6 ± 85.7	413.6 ± 45.3	140.4 ± 26.7
TN (mg/L)	55.5 ± 7.03	31.0 ± 3.2	7.4 ± 2.6
NH$_4$-N (mg/L)	48.4 ± 8.1	26.8 ± 3.0	5.7 ± 2.4
NO$_3$-N (mg/L)	2.31 ± 0.59	1.60 ± 0.48	0.45 ± 0.13
VSS (mg/L)	212.0 ± 415.2	77.9 ± 9.0	27.3 ± 5.1
TSS (mg/L)	309.0 ± 39.2	118.6 ± 9.0	51.7 ± 7.8

Note: average values and confidence interval (calculated for a confidence level of 95% and 14 measured values).

A statistical analysis on the results showed coefficients of variation (CV) in the raw wastewater of 22%, 24%, 32%, 48% and 24% for COD, TN, NH$_4$-N, NO$_3$-N and TSS, respectively, which suggests that a significant change has occurred in its characteristics over time. Since during the monitoring period there was no considerable rainfall, this variation is mainly associated with contributions from small agro-industrial activities, namely cattle feedlots, piggeries and dairies, which were discharged into the local sewer network connected to the WWTP.

The pH in the bed ranged from 6.8 to 7.9 (influent) and 6.6 to 7.4 (effluent) and the average DO was 1.2 ± 0.2 mg/L (influent) and 1.6 ± 0.4 mg/L (effluent). The CV for influent COD, TN, NH$_4$-N and TSS were 21%, 20%, 21% and 15%, indicating a significant fluctuation of the characteristics over time. The inflow flow-rate was more stabilized over time (CV of 15%). The Imhoff tank had no significant effect to stabilize the transient raw incoming loads of COD, N and TSS. There was no significant linear relationship ($R^2 < 0.2$, $p > 0.05$) between the variation of the concentrations of COD, N forms and TSS in the raw wastewater and in the influent of the HSSF bed.

The influent concentrations of COD were higher and more unstable during weeks 1–7, reaching the highest value of 602 mg/L and stabilized in weeks 8–14 (302 to 395 mg/L). However, this stabilization did not influence significantly the COD removal. A significant variation of TN and NH$_4$-N concentrations was observed in the influent during weeks 8–14 (highest values of 41.6 mg/L and 39.1 mg/L, respectively), however, the bed showed higher RE for TN, NH$_4$-N and NO$_3$-N in the same period (86%, 89% and 80%, respectively).

Although the COD removal was lower than the observed in Mediterranean countries for HSSF beds

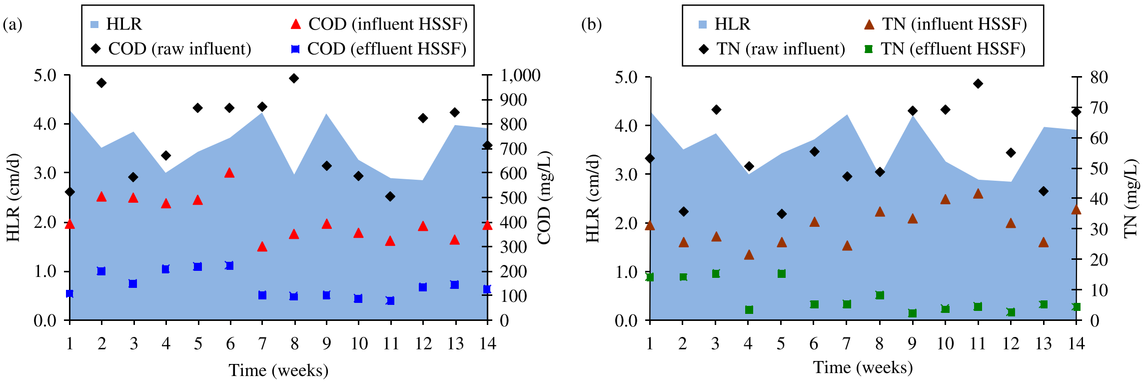

Figure 1 | Variation of HLR and COD (a) and HLR and TN (b) over time.

Table 2 | Comparative RE in HSSF CW for different studies

Operating conditions				**Removal efficiency (%)**				
OLR (g COD/m^2 d)	**HLR (cm/d)**	**HRT (d)**	**SSA (m^2/p.e.)**	**COD**	**TN**	**NH$_4$-N**	**TSS**	**Study**
9.4–22.3	8.5–13.8	4.8–9.0	2.5	66.7	76.0	78.6	56.4	Capinha, Portugal–study case
26.4–52.7	7.3–14.9	2.5–5.0	–	64.2	–	55.1	90.4	Avsara *et al.* (2007), Israel
2.2–34.1	14.0–15.6	3.0–4.3	1.2	94.0	60.0	85.0	84.0	Masi & Martinuzzib (2007), Italy
18.4–54.5	18.0	3.0	1.0	43.0	–	25.0	73.0	Osorio (2006), Spain
38.1	3.6	5.0	2.3	78.0	35.0	22.6	78.0	El-Khateeb & El-Gohary (2002), Egypt

operated in comparable conditions (Table 2), only in weeks 4–6 28% of the effluent concentration slightly exceeded the limit of the Directive 91/271/EEC (125 mg/L). For TSS, approximately 86% of the effluent concentrations exceeded the limit imposed by that Directive (35 mg/L). Although the significant variability of TN and NH$_4$-N the RE of both nitrogen forms was generally higher than the ones registered in similar studies. The effluent concentrations of TN were always bellow the limit stipulated in Directive (15 mg/L) and the bed outperformed the minimum required RE (70%).

The results seem to indicate a relationship between the low removal of COD and the low removal of TSS. 60% of the raw wastewater COD was in particulate form (CODp) and it was observed a good correlation between the evolution of CODp and TSS in time (R^2=0.62, $p < 0.05$). Approximately 48% of the HSSF influent CODt was in particulate phase while 66% was observed in the effluent, which indicates that a considerable amount of slowly biodegradable organic matter was not removed in the bed, even admitting that some fraction could have been associated with decay sub-products (approximately 20%, according to Korkusuz (2005)). The amount of slowly biodegradable organic matter that reached the bed, mainly as TSS, was not properly retained (only 50% of the CODp was removed whilst the removal of CODt and CODs was 67% and 77%, respectively). The ratio of VSS/TSS in the effluent was 0.53, which could indicate a low degree of effluent mineralization and the presence of considerable organic matter content.

The bed was under OLR (9.4 to 22.3 g COD/m^2 d) higher than the values suggested in the literature (Table 2), which may be a risk for bed clogging since it exceeds the recommended value of 16 g COD/m^2 d (ATV-A 262 2006). The average influent TSS concentration (118.6 mg TSS/L) was also greater than the maximum suggested for clogging prevention (100 mg TSS/L).

Mass removal rates

The MRR ($r_{(X)}$ in g/m^2 d) for COD, TN, NH$_4$-N and TSS were calculated taking in account the influent and effluent concentrations, the average flow rate and the total superficial area of the bed. The average values are $r_{(COD)}$: 9.8 g COD/m^2 d, $r_{(TN)}$: 0.8 g TN/m^2 d, $r_{(NH_4\text{-}N)}$: 0.7 g NH$_4$-N/m^2 d and $r_{(TSS)}$: 2.4 g TSS/m^2 d.

A significant linear correlation was observed between incoming mass loads of COD, TN, NH$_4$-N and TSS and the respective MRR, in particular for COD (R^2=0.82, $p < 0.05$), TN ($R^2 = 0.61$, $p < 0.05$) and NH$_4$-N (R^2=0.59, $p < 0.05$). 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 2a)). The values are lower than the ones obtained for similar systems in other studies (17.1 g COD/m^2 d in Avsara *et al.* (2007), 23.7 g COD/m^2 d in Osorio (2006), and 20.4 g COD/m^2 d in El-Khateeb & El-Gohary (2002)) due to the presence of large amount of particulate organic matter in the influent.

Similar correlations for COD were found in Avsara *et al.* (2007) and for COD and NH$_4$-N in Ayaz & Akça (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 MRR were quite similar for equivalent operating conditions (Table 2), but the concentration of particulate organic matter was lower. 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

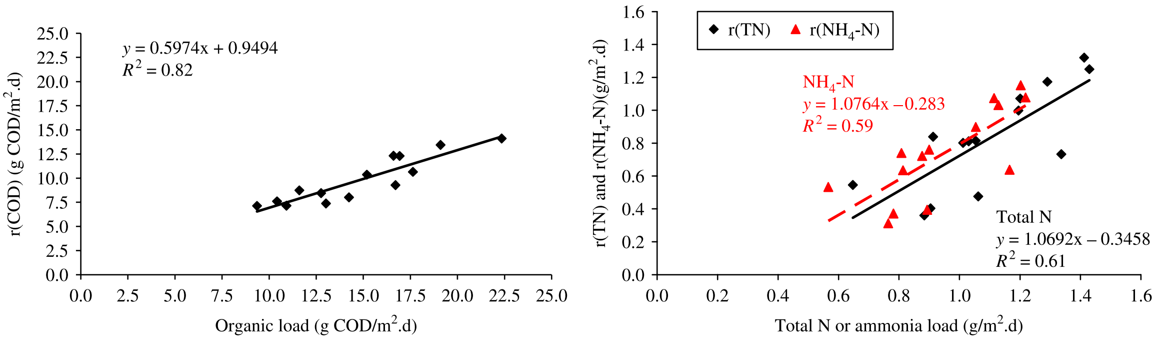

Figure 2 | Relationship between applied load and MRR: (a) organic load and $r_{(COD)}$; (b) nitrogen load and $r_{(TN)}$ and $r_{(NH_4\text{-}N)}$.

parameters was 88%. These better results are, however, associated with the feeding regime (intermittently) and the lower water depth (0.30 m), which promoted a better oxygenation of the bed and, therefore, the higher aerobic removal of organic matter and ammonia.

$r_{(TN)}$ and $r_{(NH_4\text{-}N)}$ presented linear correlations with the respective loads (Figure 2b)) with higher correlation coefficients during the last 6 weeks (R^2 equal to 0.92 and 0.95, respectively, $p < 0.05$). In the same period it was also observed the highest values for $r_{(TN)}$ and $r_{(NH_4\text{-}N)}$ (1.3 g N/m^2 d and 1.2 g NH$_4$-N/m^2 d). The bed dealt well with the oscillation of incoming nitrogen loads. The low DO concentrations seems to have had no effect on ammonia removal rather than the temperature since the average $r_{(NH_4\text{-}N)}$ increased 39% (from 0.58 to 0.95 g NH$_4$-N/m^2 d) from weeks 1–8 to weeks 9–14 as the water temperature increased approximately 2°C and the soil temperature increased approximately 1°C (Table 1 and Figure 3).

The average $r_{(COD)}$ in weeks 1–17 (11.3 g COD/m^2 d) was superior than in weeks 8–14 (8.6 g COD/m^2 d) as shown in Figure 3. The higher changeability in incoming COD concentrations found in the first 7 weeks (Figure 1a) seems to had no effect in the activity of the microorganisms which used organic carbon. Despite the significant variation observed in the influent concentrations (Figure 1b) the $r_{(TN)}$ and $r_{(NH_4\text{-}N)}$ were quite satisfactory, reaching the highest values in weeks 9–14 (1.3 TN g/m^2 d and 1.2 NH$_4$-N g/m^2 d), as shown in Figure 3b) for TN.

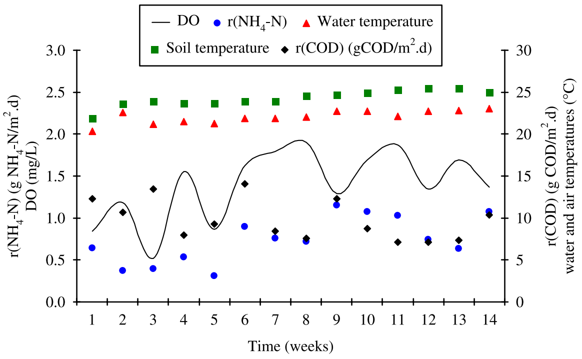

Figure 3 | Variation of $r_{(COD)}$ and $r_{(NH_4\text{-}N)}$ with temperature and DO.

Taking into account that ammonia uptake by *Phragmites australis* may reach only up to 15% of the removed load (Vymazal 2003) and DO in the bed was low to promote nitrification, it seems unlikely that there was sufficient oxygen flux to drive the ammonia removal rates observed in the bed via only nitrification pathway. The presence of non-conventional ammonia removal pathways (e.g. anammox or heterotrophic nitrification), already observed in other studies with HSSF beds (Dong & Sun 2007; Paredes *et al.* 2007), may therefore be investigated in futures studies.

As a final remark, this study clarifies that HSSF beds 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.

CONCLUSIONS

The HSSF bed of Capinha presented a good potential for dealing with fluctuations in flow rate, organic mater, nitrogen and solid mater, since it was observed a satisfactory removal of COD and TSS and a good removal of N forms.

The removal of COD and TSS was lower than the values observed in similar studies due to the presence of a large amount of incoming particulate organic matter. The bed had a very good performance in terms of nitrogen removal (TN, NH_4-N and NO_3-N) despite the TN and NH_4-N concentrations in the influent had been unstable. The respective removal rates increased as both water and soil temperatures increased. A good correlation was observed between mass removal rates and mass loads for COD and nitrogen compounds, which indicates that the bed had a satisfactory response to changes in incoming loads.

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