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Spatial variations of temperature, redox potential, and contaminants in horizontal flow reed beds

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Abstract

This study investigated the simultaneous variations of temperature, redox potential (E_H), and contaminants over the width, length, and depth of horizontal flow reed bed (HFRB) systems treating wastewater. The hydrodynamic behavior of HFRBs was also assessed. Experiments were carried out on two HFRB systems. One of the systems treats wastewater from a housing scheme in four pairs of lined, parallel beds with almost equal surface areas (54–56 m^2 each bed) and different length-to-width (L:W) ratios, granular medium sizes, and water depths. The other system treats the domestic wastewater from a hotel in two parallel beds, each with a surface area of 187.5 m^2. The results indicate that temperature does not vary across the width, while changes with length and depth can be significant, especially those associated with depth. Vertical temperature gradients are very important in unplanted beds in summer (12 °C/m) but are greatly reduced in planted beds due to shading (3.4 °C/m). Daily variations in temperature gradients do not have a clear effect on the quality of the effluents from the HFRBs. E_H, organic matter, and ammonia do not vary significantly across the width, but they do change with length and depth. These changes are attributed to the fact that the mechanisms involved in water oxygenation mainly occur at the top of the gravel beds. Tracer studies demonstrated that the HFRB systems evaluated had preferential bottom water flow near the outlet.

Keywords: Constructed wetlands; Subsurface flow constructed wetlands; Horizontal flow reed beds; Reed beds; Wastewater; Temperature; Redox potential

1. Introduction

Horizontal flow reed beds (HFRBs) (horizontal subsurface flow constructed wetlands) are bioreactors that are excavated in the ground, lined, filled with a granular medium, planted with macrophytes, and used to treat wastewater. Currently they are a popular method for urban wastewater treatment in small rural communities of all over the world. Most energy exchange in horizontal flow reed beds occurs at the open, upper surface; lateral and bottom heat exchange is negligible (Smith et al., 1997; Kadlec, 2001). Heat associated with the incoming water is dissipated in the entry region and beds tend towards equilibrium

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water temperature which is achieved when the energy gains are balanced by evaporative cooling and other heat loss processes (Kadlec and Knight, 1996). Temperature gradients occur vertically through the beds, but not to the extent that the systems are considered to be stratified. For example, in Brix (1990), water temperature variation was only observed in the top 4 cm of the bed, below which the temperature maintained almost constant. The presence or absence of plants is an important parameter of the thermal environment of the beds. Tanner et al. (1995) found that planting had little effect on outflow temperatures in winter, but lowered temperatures in summer by 0.5–1 °C. Brix (1994, 1997) points out that one of the functions of macrophytes is to reduce variations in environmental factors such as water temperature, mainly through the reduction of surface wind velocities, the attenuation of light, and the insulation provided by the vegetation. In cold climate HFRBs, the dead and still standing plant material is covered by snow and provides effective insulation and helps keep the bed medium free of frost. However, the vegetation and litter layer also prevent the direct impact of light on the gravel and keep the bed cooler in summer.

Contaminant variation over length transects of HFRBs has been previously studied. For TSS and BOD_5 in general the data display a sharp decline near the inlet followed by little further change (Kadlec and Knight, 1996). Information on vertical chemical gradients in conjunction with longitudinal variations is presently limited. Bowmer (1987) and Breen and Chick (1995) have observed these chemical gradients in the vertical dimension of the beds. Vertical changes in contaminant concentrations (with higher concentrations at the bottom) in these two studies were related to a combination of the distribution and density of roots within the vertical profile and system hydrodynamics. Thus, these authors found that the headloss increases in the upper zones of the beds because of the high density of roots and bottom flow is promoted causing greater contaminant concentrations near the bottom. Breen and Chick (1995) concluded that HFRBs are incompatible with the vertically uniform plug flow assumption and plant mediated nutrient removal in HFRBs, and as a result they recommend a vertical flow format for treatment purposes. Preferential bottom water flow has also been reported in other studies. Rash and Liehr (1999) indicate that these preferential pathways are attributed to density differences (in their case between leachate and rainwater), effluent removal by means a drainage pipe located at the bottom of the wetland, and gravel and root densities which prevent vertical mixing. Marsteiner et al. (1996) have shown that excessive traffic on the beds during construction reduces the porosity of the upper layers of the medium, causes an increasing vertical porosity gradient, and in turn greatly affects the flow pattern, promoting bottom flow. Furthermore, the macrophytes contribute to the reduction of porosity of the upper medium layers. This work proved that the location of the effluent drainage pipe did not influence the preferential water flow.

The objectives of the present study were: (1) to investigate the variations of temperature, redox potential (E_H), and contaminants simultaneously across the width, length, and depth of HFRB systems treating domestic or urban wastewater, and (2) to evaluate the hydrodynamic behavior of HFRBs in relation to the variations in the former parameters.

2. Methods

2.1. HFRB in Vilagrassa, Lleida, northeastern Spain (Fig. 1)

This system was set up in autumn 1999 to treat 11 m^3 per day of domestic wastewater generated from a hotel. The climate at the site is Mediterranean, with an average annual temperature and accumulated rainfall of 14.2 °C and 373 mm, respectively (data for 2000). The system consists of two baffled septic tanks in series from which the primary effluent is distributed to two parallel reed beds of 187.5 m^2 each. Both beds have a length-to-width (L:W) ratio of 1:1 and are filled to an average depth of 0.70 m with granitic gravel ($D_{60} = 4$ mm, $C_u = 1.82$). The porosity of the granular medium is 33%. During the experiments the water level was approximately 0.20 m below the gravel surface. The sloped bottom (1.5%) is lined with an impermeable plastic membrane. Nine perforated tubes (0.1 m in diameter) were inserted into the granular medium and uniformly distributed among three locations (rows) of three tubes along the length of the beds, permitting us to obtain intermediate samples and vertical profiles. These tubes were perforated all

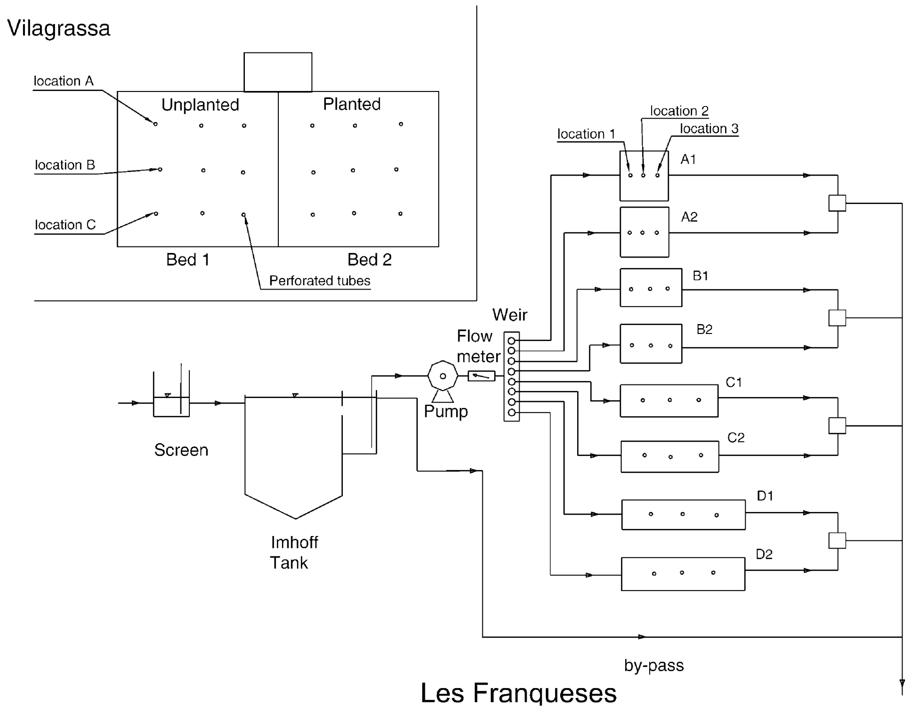

Fig. 1. Schematic diagram of the HFRB systems at Vilagrassa and Les Franqueses del Vallès. Tube locations are indicated in both systems. Note that for clarity the beds at Vilagrassa are numbered and the locations are designated by letters, while at Les Franqueses the opposite terminology is used.

along the depth, installed to the bottom of the beds, and they were not emptied before measuring or sampling. It should be taken into account that the perforated tubes had only a minor impact on the flow field because of their small size in relation to the width of the beds. Bed 1 remained unplanted while bed 2 was planted with the common reed (*Phragmites australis* (Cav.) Trin. ex Steudel); however, the development of the macrophytes was very poor during the experimentation period because the water level was far below the surface. Thus, in the interpretation of the data, both beds are considered to be unplanted. Design average hydraulic loading rate (HLR) and areal organic loading rate (AOLR) were 29 mm per day and 14.7 g BOD_5/m^2 per day. In this system there is not waste water flowmeter, and therefore for calculation purposes, the flow was estimated assuming that all tap water consumed was transformed in wastewater. During the experiments, air temperature data from a nearby meteorological station were used.

From December 1999 to June 2000, nine influent and effluent grab samples were obtained in order to characterize the performance of the system. These samples were refrigerated and immediately sent to the Technical University of Catalonia Laboratory of Environmental Engineering. TSS and carbonaceous BOD_5 analyses were performed within 12 h of sample collection using conventional methods (APHA-AWWA-WPCF, 1995).

2.2. HFRB in Les Franqueses del Vallès, Barcelona, northeastern Spain (Fig. 1)

This pilot plant was set up in May 2000 and treats in part the urban wastewater from a housing scheme. The plant was built as a demonstration project and also in order to study the influence of HLR, L:W ratio, granular medium size, and water depth on contaminant removal efficiency (García et al., submitted). The climate at the site is Mediterranean, with an average annual temperature and accumulated rainfall of 13.5 °C and 460 mm, respectively (data for 2000). The plant is made up by an Imhoff tank from which the primary effluent is pumped and equally distributed to eight parallel reed beds with a surface area of 54–56 m^2 each. L:W ratio of the beds varies in pairs; for pair A, 1:1, for pair B, 1.5:1, for pair C, 2:1 and for pair D, 2.5:1. The size of the granitic gravel inside each pair also varies; type 1 beds contain a coarse gravel (D_{60} = 10 mm, C_u = 1.6) while type 2 beds contain smaller gravel (D_{60} = 3.5 mm, C_u = 1.7). Type A, B, and C beds were filled to an average depth of 0.55 m, while type D beds were filled to 0.32 m. The porosity of the granular medium is 39% for the coarser medium and 40% for the finer. The absence of significant differences in porosity for the two media is mainly due to the lack of fine material. The water level was maintained approximately 0.05 m below the gravel surface. The sloped bottom (ranging from 0 to 1% in type A, B, and C beds, and 2.5% in type D beds) is lined with an impermeable plastic membrane. All the beds have three perforated tubes (0.1 m in diameter) inserted in the gravel similar to those used at Vilagrassa. All the beds were simultaneously planted with the common reed in March 2001, and the surface was fairly well covered by the end of August 2001. During the investigation the HFRB system was operated with HLR of 45 mm per day (June 2001) or 36 mm per day (July and August 2001, and August 2002). The HLR was controlled via pump operation frequency. During the experiments, air temperature and solar radiation data from a nearby meteorological station were used.

From July to August 2001, five influent and effluent grab samples (from each bed) were obtained in order to characterize the performance of the system. These samples were analyzed for TSS, carbonaceous BOD_5, ammonia, and dissolved reactive phosphorus (DRP) using the methods described in APHA-AWWA-WPCF (1995). For calculations one of the campaigns was not considered because there was a short rainy period.

The aerial and belowground biomass of the reeds and the litter layer were quantified in beds C1 and C2 in September 2002. Two plots of 0.25 m^2 were selected in each bed and the stems were cut just above the soil surface. The litter layer was then carefully removed. The roots and rhizomes were obtained using a square core (0.5 m × 0.5 m) which was inserted into the gravel (the biomass and gravel were removed to allow the device to penetrate). During the extraction of belowground biomass it was observed that most rhizomes only penetrated as far as 10 or 12 cm below the surface. All samples were dried at 105 °C to determine dry weight.

2.3. Vertical temperature and redox potential profiles

Profiles were carried out in March, May, and June 1999 at Vilagrassa (one each month), and in July and August 2001 at Les Franqueses (two each month). They were obtained from all the perforated tubes in all the beds by submerging temperature and E_H probes attached to an arm which descended slowly (less than 5 cm/min). Measurements were taken every 1 or 5 cm depending on the site and water level. Temperature was measured using the thermistor of a YSI 58 oxymeter (accuracy: ±0.5 °C) and E_H using a Crison 506 with a platinum electrode and an Ag/AgCl reference system (accuracy: ±10 mV). Before taking E_H measurements, the electrode was tested using a standard solution provided by the manufacturer (+468 mV at 25 °C). Redox values were corrected for the potential of the reference system (+207 mV at 25 °C). Readings were taken after 2–3 min in order to obtain stable values. In the plant at Les Franqueses, E_H values were only obtained during one July campaign. Vertical profiles were measured for the different tubes over approximately the entire daylight period in order to obtain the diurnal variation in water temperature. Thus, the tubes were treated as replicates that allowed the temperature to be measured at different times. This was necessary due to the possible disturbance of the water in a tube after the profile had been measured. In the system at Les Franqueses, in July 2001 sunlight reached almost the entire surface of the medium in the beds, while in August 2001 the surface was fairly well covered by the reeds (especially during the last campaign).

In addition, water temperature was measured on 3 days (campaigns) in August 2002 in all the perforated tubes in beds C1 and C2 of the system at Les Franqueses. Measurements were carried out over the entire daylight period at depths of 5, 15, and 40 cm using Hanna Checktemp 1 thermometers (accuracy: ±0.3), whose sensors were attached to a rod submerged in the perforated tubes. At that time the reeds covered the entire surface area of the beds, and a conspicuous litter layer was also present.

2.4. Daily variations in effluent quality

Daily effluent variations were measured twice (two campaigns of 1 day) in June 2001 for beds A1 and C1 of the Les Franqueses HFRB system using two Sigma 900 automatic samplers. Hourly samples were preserved by the addition of a few drops of H_2SO_4. The number of effluent samples obtained from each campaign and each bed was 24 with the exception of bed A1 during the first campaign when a sampler failure meant that we could only obtain 19 samples. In addition to effluent samples, one influent grab sample was obtained during each campaign in order to characterize the performance of the beds at that time. Filtered COD (to avoid fluctuations due to TSS) and ammonia were selected as representative parameters to evaluate daily variations. Analyses were performed the day after sampling using conventional methods.

2.5. Contaminant variation across the width and along the length of the beds

At the HFRB system at Vilagrassa, representative samples of all water depth of each perforated tube were collected after hand stirring the water content of the tube. These samples were obtained 2 days after each of the three initial campaigns to obtain temperature and E_H profiles. The samples were analyzed for TSS and BOD_5. The same methodology was used for the HFRB system at Les Franqueses to evaluate variation with length. In the latter case, filtered COD from each sample was analyzed.

2.6. Contaminant variation with water depth

Depth variations were evaluated in August 2001 for the system at Les Franqueses using beds C1 and D1 and in August 2002 using C1 and C2. Samples were collected from different perforated tubes at depths of 5, 30, and 50 cm (beds C1 and C2) and 5, 15, and 27 cm (bed D1). Samples were obtained by slow pumping from plastic tubes located at the different depths. These tubes were installed 2 days before the sampling and the initial water extracted was discharged in order to ensure that the samples were representative. Filtered COD and ammonia were chosen as representative parameters in 2001, and only ammonia in 2002.

2.7. Hydraulic behavior of the beds

Tracer studies were conducted in beds C1 and C2 of the system at Les Franqueses in August 2002 by injecting a solution of 200 g KBr/l into the inlet tube for each bed. Water samples were collected from the effluent and from each perforated tube at different depths (5, 30, and 50 cm) using the methods described above. Samples were taken at different intervals, varying in most cases from 4 to 24 h. Ion chromatography was used to determine the bromide concentration (APHA-AWWA-WPCF, 1995). The average tracer retention time (TRT) was calculated at each depth of each perforated tube as a qualitative indicator of water velocity in the beds. Note that the TRT was calculated as when a 50% of the tracer had passed the measurement location, and therefore this parameter depends on the shape of the tracer response curve and not simply on the tracer concentration. The tracer recovery rate from the effluent of bed C1 was 118% and for bed C2, 95%.

2.8. Statistical methods

Statistical operations were carried out using the SYSTAT statistical package. The ANOVA test was used to compare data averages. For all the ANOVA tests it was verified that the dependent variables were normally distributed using the Kolmogorov–Smirnov test; if this was not the case, they were log-transformed. The Tukey method was used to test all pairwise comparisons of the marginal averages as a tool for detecting pairs of averages that differed significantly.

3. Results

3.1. Performance of the HFRB systems

During 2000, in the hotel at Vilagrassa, the average tap water consumption based on 204 daily readings ($12.5 \pm 4.1\,m^3$ per day) was very similar to the wastewater flowrate assumed in the HFRB system design. Beds influent TSS and BOD_5 were 120 ± 40 and 410 ± 90 mg/l, respectively. Note that the BOD_5 was quite high probably due to the considerable activity of the hotel restaurant that serves customers who are nor staying at the hotel as well as guests. From the data, the

Table 1
Averages and standard deviations of the water quality parameters in the effluents from all the beds of the HFRB system at Les Franqueses in July and August 2001

Parameter	A1	A2	B1	B2	C1	C2	D1	D2
BOD_5 (mg/l)	66 ± 18	65 ±17	70 ± 14	63 ± 16	56 ± 18	70 ± 16	43 ± 15	18 ± 3
NH_3 (mg N/l)	50.0 ± 10.1	43.5 ± 8.7	45.6 ± 9.6	43.4 ± 10.0	43.3 ± 7.2	43.1 ± 8.3	40.9 ± 10.3	36.6 ± 13.1
DRP (mg P/l)	11.7 ± 1.1	10.3 ± 0.9	10.7 ± 1.7	10.5 ± 1.6	10.4 ± 0.9	10.2 ± 1.1	11.2 ± 2.2	10.7 ± 1.7

$N = 4$.

estimated average HLR (33 mm per day) and AOLR (13.6 g BOD/m^2 per day) were also very similar to those assumed in the design. The system removed TSS very effectively (average effluent, 9 ± 4 mg/l), but not so BOD_5 (190 ± 60 mg/l).

In July and August 2001, for the system at Les Franqueses, average bed influent BOD_5, ammonia and DRP were 130 ± 23 mg/l, 57.8 ± 6.4 mg N/l, and 11.0 ± 2.0 mg P/l, respectively. The estimated average AOLR was 4.7 g BOD/m^2 per day. Table 1 shows the averages and standard deviations of the water quality parameters measured in the effluent from each bed. Effluent TSS results are not shown in Table 1 because they were under 2 mg/l in all cases. Beds A, B, and C had a clearly lower overall BOD_5 removal (ranging approximately from 46 to 57%) than beds of the type D (with a range of 67–86%). Note that the D beds are shallower than the others. Effluent nutrient concentrations for all beds were similar to influent concentrations, and therefore the removal efficiency was in general very low. Beds D1 and D2 had the highest ammonia removal rate (ranging from 29 to 37%).

3.2. Temperature variations

At Vilagrassa, in general there were no significant differences ($P > 0.05$) between the average water temperature profiles obtained from the perforated tubes in a given location. Only nine averages (from a total of 54) were found to be statistically different, and as a result the temperature values corresponding to these nine profiles have not been considered in Fig. 2. Average water temperature was very similar in the morning (9 a.m.–1 p.m.) and in the afternoon (3 p.m.–7

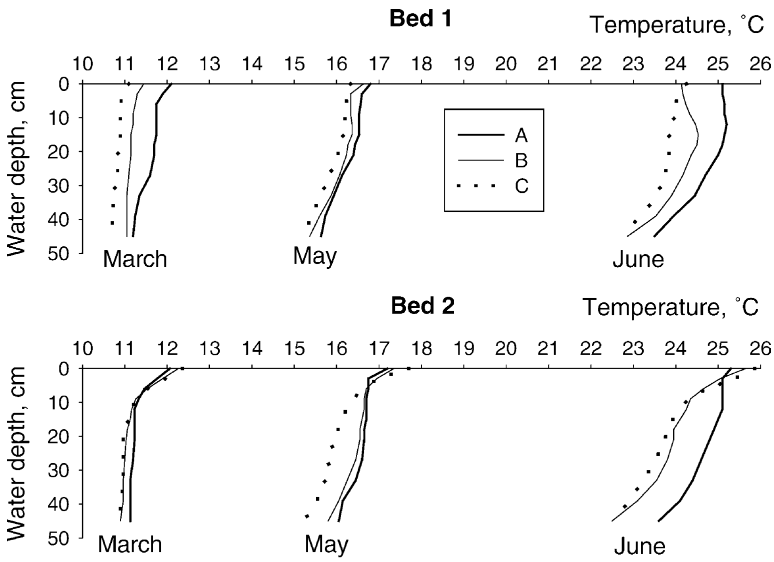

Fig. 2. Temperature variation with water depth for the HFRB system at Vilagrassa during the three campaigns. Each profile corresponds to the average temperatures obtained for the perforated tubes of a given location (A, B, or C). Note that profiles for bed 1 were obtained in the morning, while those for bed 2 were obtained in the afternoon.

p.m.) (11.2 ± 0.3 and 11.3 ± 0.4 °C for the first campaign, 16.1 ± 0.4 and 16.5 ± 0.5 °C for the second, and 24.2 ± 0.7 and 24.3 ± 0.8 °C for the third). Minimum and maximum temperature variations between the surface and the bottom were 0.4 and 1.5 °C in March, 1.1 and 2.4 °C in May, and 1.3 and 3.3 °C in June. Minimum variations correspond to the morning (bed 1) while the maximums correspond to the afternoon (bed 2). Water temperature was systematically warmer near the inlet (location A) than it was near the outlet (location C). However, only the average morning temperature for the three locations during the March campaign, and those during June (morning and afternoon) are statistically different ($P < 0.05$).

At Les Franqueses the average temperature was clearly lower in the morning than in the afternoon: 24.8 ± 1.2 and 25.8 ± 1.9; 21.8 ± 0.9 and 23.1 ± 1.4; 23.2 ± 1.0 and 23.9 ± 1.3; and 22.7 ± 0.9 and 23.0 ± 0.8 for the first to the fourth sampling campaigns, respectively. All these pairs of averages were statistically different ($P < 0.05$). Thus, the temperature variations at Les Franqueses showed a clearer daily trend than those at Vilagrassa, and as a result these variations are shown in Fig. 3. This figure was compiled using

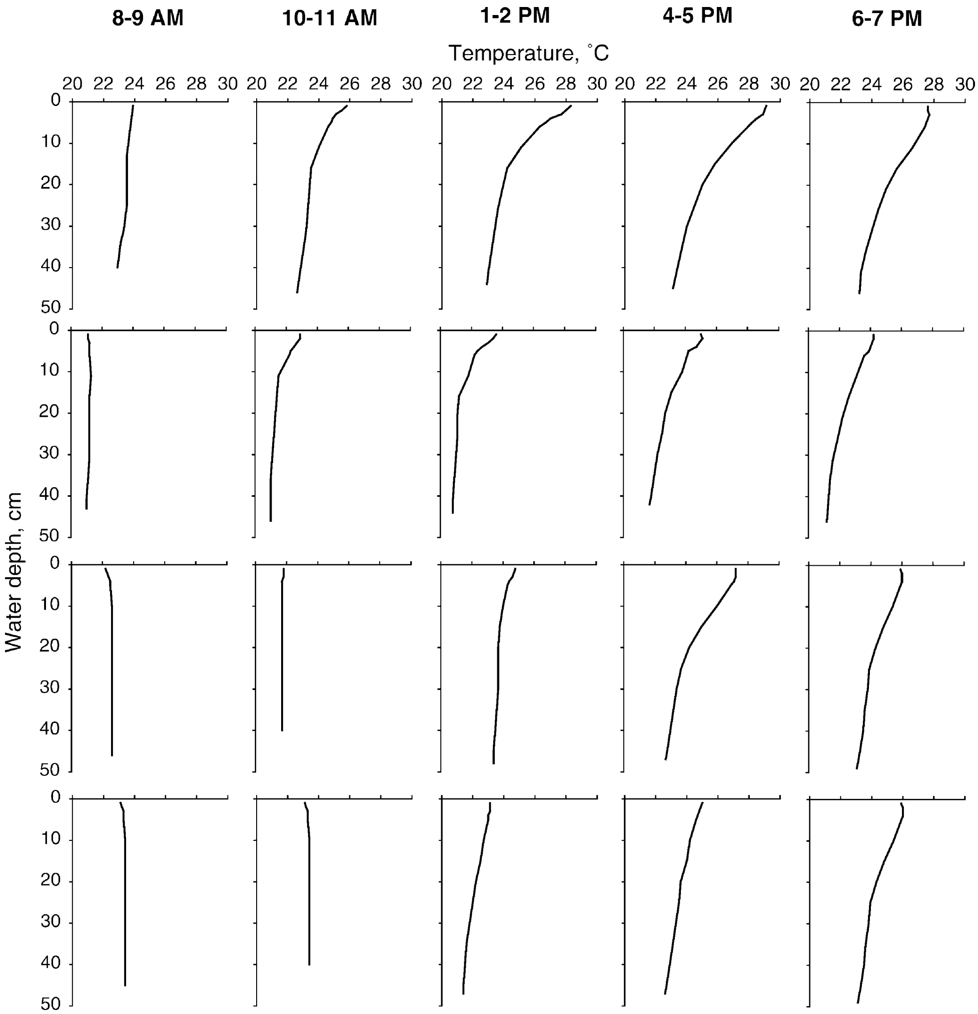

Fig. 3. Daily temperature variations with water depth for the HFRB system at Les Franqueses during the four campaigns (5 and 24 July; 9 and 30 August). Note that the profiles come from different beds and perforated tubes. The first row of graphs corresponds to the first sampling campaign, and so on.

data from different beds (with the exception of D type beds because of their lower depth) and independently of whether the measurements were taken in tubes near the inlet or the outlet, because warmer water temperatures near the inlet were not observed. Water temperature variation with depth showed the same hourly pattern: early in the morning (8 a.m.–9 a.m.) water temperature was very similar throughout the whole depth, and as solar radiation and air temperature increased, the surface water temperature became clearly higher than that of the water at the bottom. The maximum temperature variation with depth was systematically observed in the afternoon: 6.0, 3.3, 4.5, and 2.8 °C for the first to the fourth campaigns, respectively. Taking into account that the average air temperature was very similar for all campaigns (25.8 ± 2.6, 24.7 ± 5.0, 25.6 ± 2.9, and 25.0 ± 1.9 °C for the first to the fourth, respectively), that the solar radiation was very similar during the first and the third (21.1 and 18.9 MJ/m^2 per day, respectively) and during the second and the fourth (13.6 and 13.8 MJ/m^2 per day, respectively), and that the reeds were more developed during the third and fourth campaigns, the differences observed in the maximum temperature variations between the first and the third (1.5 °C) and the second and the fourth (0.5 °C) campaigns are probably mainly due to the shading provided by the plant cover.

In August 2002, in beds C1 and C2 of the HFRB system at Les Franqueses, the maximum temperature variation with depth was also observed in the afternoon in the three campaigns: 1.4, 1.7, and 1.6 °C for C1 and 0.9, 1.3, and 0.7 °C for C2. Note that these variations were lower than the lowest (maximum variation) observed in 2001 (2.8 °C), although solar radiation and the average daily air temperature were very similar. These differences between the 2 years are due to both the higher density of reed stems (540 and 1800 g/m^2 in C1 and C2, respectively) and the presence of a conspicuous layer of litter in 2002 (660 and 310 g/m^2 in C1 and C2, respectively) which in 2001 was non-existent. The larger temperature variations measured in 2002 in bed C1 are related to the lower reed biomass, both aerial and belowground (which was 270 g/m^2 in C1 compared to 600 g/m^2 in C2). All these results show the effect that plant cover has in reducing vertical temperature variations.

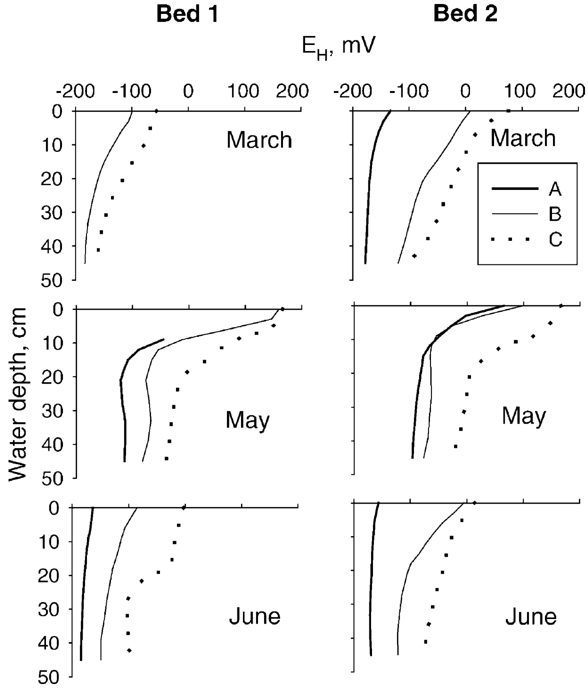

Fig. 4. E_H variations with water depth for the HFRB system at Vilagrassa during the three campaigns (March, May, and June). Each profile corresponds to the average E_H obtained for the perforated tubes located at a given location (A, B, and C). Note that for bed 1 in March, E_H variations at location A are not shown because of significant statistical differences between averages for the three tubes.

3.3. Redox potential variations

Fig. 4 shows the E_H variation with water depth for the three campaigns and the two beds at Vilagrassa. The ANOVA test indicated that, in general, at Vilagrassa, there were no significant differences ($P > 0.05$) between the average E_H profiles for the perforated tubes located at the same location (or distance from water inlet). Only eight averages (from a total of 54) were found to be statistically different from the averages for the same location, and as a result, E_H values corresponding to these eight profiles have not been included in Fig. 4. E_H has two clear types of variations, the first one being the increase in length, and the second the decrease in depth. As can be observed, the shape of the E_H profiles is quite similar in the first and the third campaigns, while in the second it follows a different pattern, with a sudden decrease over the top 10–20 cm of the water. This is due to the fact that the system had not received wastewater during the days previous to that campaign due to an electrical failure at the pump. In this second campaign the E_H values of the top 20 cm of water were clearly higher than those observed further down, and also the lowest effluent BOD_5 concentration was observed. The E_H gradients over depth were higher near the outlet than the inlet (average -0.7 ± 0.4, -2.4 ± 0.7, and -2.8 ± 0.6 mV/cm for locations A, B, and C, using data from the first and the third campaigns).

The general trends observed in E_H values at the Vilagrassa system were also observed at Les Franqueses. In this system, it is interesting to note that the E_H values were higher in the shallower beds (type D, on average -131 ± 22 to -144 ± 8 mV) than in the deeper beds (types A, B, and C, on average -151 ± 38 to -183 ± 44 mV), and also there was less E_H variation with depth in shallower beds (note the lower values of the standard deviation with respect to the averages). The variations of E_H with respect to distance from the point of wastewater inlet were clearer in deeper beds.

3.4. Daily variations of effluent quality

These variations were studied in beds A1 and C1 of the HFRB system at Les Franqueses. As can be observed in Fig. 5, filtered effluent COD and ammonia did not show any clear daily trend in either campaign or in either bed. Average effluent concentrations were higher during the first campaign (COD: 45 ± 11 and 65 ± 9 mg/l, and ammonia: 53.5 ± 2.4 and 50.7 ± 2.4 mg N/l, for beds A1 and C1, respectively) than during the second (COD: 27 ± 10 and 30 ± 10 mg/l, and ammonia: 29.5 ± 1.1 and 28.8 ± 2.0 mg N/l, for A1 and C1, respectively). This was due to the short rainy period reported in the second campaign. An analysis of one influent grab sample taken during both campaigns gave a filtered COD concentration of 96 and 42 mg/l and an ammonia concentration of 52.0 and 27.4 m N/l for the first and second campaigns, respectively. The variation in the effluent concentrations was in general low resulting in a low standard deviation with respect to the average. An exception was the COD concentration during the second campaign, but this may be related to the fact that the concentrations measured were low and near the detection limit of the COD assay. Note that in these experiments, filtered COD removal efficiency was low for both beds and in the case of ammonia there was no removal. With the exception of COD in the first campaign, both beds produced a very similar quality effluent in terms of COD and ammonia.

3.5. Contaminant variations across the width and along the length of the beds

Contaminant variation with width was studied in the HFRB system at Vilagrassa. According to the ANOVA method, the TSS and BOD_5 averages obtained for different tubes at the same location were not statistically different ($P > 0.05$). Contaminant variation along the length was studied in both HFRB systems. As can be seen in Fig. 6, in the system at Vilagrassa the average

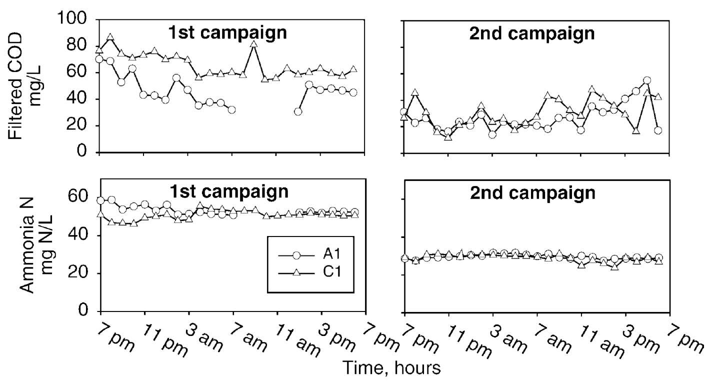

Fig. 5. Daily variations of filtered COD and ammonia in the effluents from beds A1 and C1 of the HFRB system at Les Franqueses. Influent filtered COD was 96 and 42 mg/l and ammonia of 52.0 and 27.4 m N/l for the first and second campaigns, respectively. These data were obtained in June 2001.

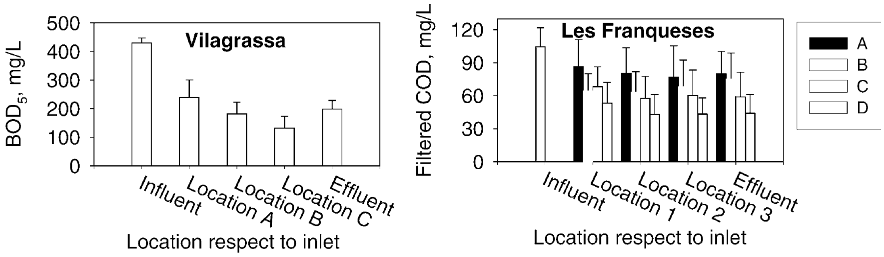

Fig. 6. Changes in BOD_5 and filtered COD concentrations along the length of the beds in the HFRB systems at Vilagrassa and Les Franqueses, respectively. The values displayed for Vilagrassa are the averages of three campaigns and the two beds. The values for Les Franqueses are the averages obtained for each pair of beds with the same length to width ratio (types A, B, C, and D) over four campaigns.

BOD_5 concentration decreased with length, but it was clearly higher in the effluent than in the previous perforated tube. This trend was systematically observed in the two beds of this system and it does not seem to be related to stagnant conditions in the tubes. The perforated tubes had only a minor impact on the flow field because of their small diameter with respect to the width of the beds. On the other hand, TSS concentration did not show this trend as the concentration was systematically higher in the last perforated tube (17 ± 14 mg/l on average) than in the effluent (8 ± 1 mg/l). In the system at Les Franqueses, most of the filtered COD was removed before the first perforated tube in all beds (Fig. 6), and remained quite steady along the rest of the length. The filtered COD concentration was in general very slightly higher in the effluent than in the previous perforated tube (the differences were on average: 3, 7, 1, and 1 mg/l for beds A, B, C, and D, respectively). This trend was not as systematic as that observed for BOD_5 at Vilagrassa because it occurred in 20 out of 32 tests.

3.6. Contaminant variation with water depth

This was studied at the Les Franqueses system and the results are shown in Table 2. As can be observed, the concentrations of filtered COD and ammonia nitrogen systematically increased slightly with depth in the campaigns during both years. Note that this trend is clear even in the case of bed D1, which is shallower. This pattern also occurs in different tubes of the same bed, regardless of how close they are to the inlet. All these results are in accordance with the depth variations observed for E_H.

3.7. Hydraulic behavior of the beds

The variations in tracer concentration over time in each perforated tube at different depths and in the effluent from beds C1 and C2 of the HFRB system at Les Franqueses are shown in Fig. 7. The TRT and the dimensionless variance of the tracer response curve in the effluent were 117 and 130 h, and 0.13 and 0.08

Table 2
Filtered COD and ammonia nitrogen concentrations at different depths and in different perforated tubes in the HFRB system at Les Franqueses

Campaign	Bed	Depth (cm)	Filtered COD (mg/l)	Ammonia (mg N/l)
Fourth (2001), location 3	C1	5–25–50	51–56–63	45.2–46.4–47.0
Fourth (2001), location 3	D1	5–15–27	36–36–41	51.8–53.0–54.4
Second (2002), location 1	C1	5–25–50	–	39.2–48.8–51.2
Third (2002), location 2	C1	5–25–50	–	33.6–44.4–50.6
Third (2002), location 3	C1	5–25–50	–	30.6–41.0–48.0
Second (2002), location 1	C2	5–25–50	–	45.8–42.6–49.5
Third (2002), location 2	C2	5–25–50	–	28.8–40.6–44.2
Third (2002), location 3	C2	5–25–50	–	32.0–46.4–52.6

Each COD and ammonia value (separated by dashes) corresponds to the value of one analysis of a sample taken at a depth as indicated in the corresponding column.

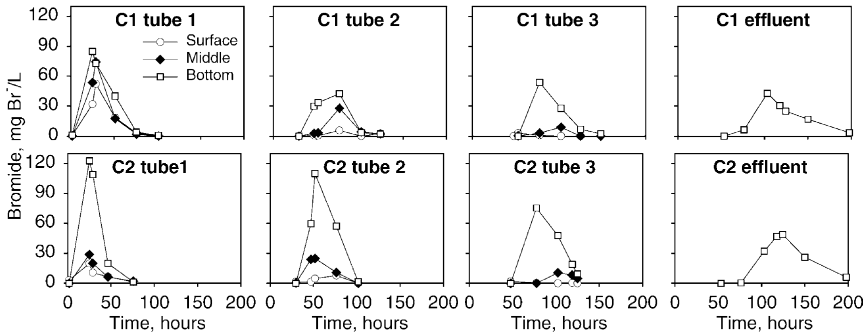

Fig. 7. Variation with time of tracer concentration in each perforated tube at different depths and in the effluent from beds C1 and C2 of the HFRB system at Les Franqueses.

Table 3
Average tracer retention time (TRT) in hours at each perforated tube depth in beds C1 and C2 of the HFRB system at Les Franqueses

Depth (cm)	Tube 1		Tube 2		Tube 3	
	C1 ($N = 6$)	C2 ($N = 5$)	C1 ($N = 6$)	C2 ($N = 5$)	C1 ($N = 5$)	C2 ($N = 5$)
5	36	32	–[a]	67	–[a]	–[a]
25	33	32	78	58	118	108
50	36	30	67	61	89	89

TRT is defined as when 50% of the tracer has passed the measurement location.
[a] Data not shown because the tracer concentration was very low in order to achieve an accurate estimation of the TRT.

for beds C1 and C2, respectively. Note that the TRT was slightly higher for bed C2, while the variance was lower. Also note that the nominal residence time during experimentation was 132 and 139 h for beds C1 and C2, respectively; thus, the effluent TRT was quite similar to the nominal retention time and therefore we can conclude that there are no significant major differential flow paths or dead zones and no short-circuiting. These results also indicate that there was no significant trend for the tracer to sink as it moved along the beds. Table 3 shows the average TRT values measured at different depths and in different perforated tubes. The data indicate that there were no major differences between the upper and lower zones in the tubes at locations 1 and 2. However, at tube 3 the average TRT was slightly non-synchronous with a difference between medium and lower zones of about 20–30 h. This characteristic indicates that the water moves faster in the lower zones than in the upper zones, from some point located between the second and third tubes, and on as far as the outlet. This statement is in agreement with the fact that the average TRT measured in the effluent was slightly lower than the nominal retention time. As has been stated in the explanation of contaminant variations along the length, none of these results seems to be related to stagnant conditions in the tubes.

4. Discussion

The Vilagrassa HFRB system was not very efficient for removing BOD_5 (54% on average), although the system operated with a very similar HLR and AOLR to those assumed in the design. This may be related to four sinergic characteristics: (1) the fact that the data were obtained during the first year of operation of the plant with little development of the biofilm responsible for degradation of organic matter; (2) underdesign; (3) the use of large quantities of disinfectants (NaOCl) in the hotel; and (4) short-circuiting because of preferential bottom water flow. Recent studies in HFRB systems indicate that to achieve a BOD_5 effluent concentration lower than 25–30 mg/l the AOLR should be under 6 g BOD/m^2 per day (García et al., submitted; US EPA, 2000), and that of the Vilagrassa system was 13.6 g BOD/m^2 per day. The effect of disinfectants was detected in a parallel study in the same plant evaluating the removal of faecal microorganisms (Graus, 2000). In this study, it was observed that faecal bacteria were absent from most of the influent samples despite the presence of the two septic tanks in series (where the disinfectants could have been diluted or reacted). Thus, it is highly probable that the disinfectants also affected the development of the microbial biofilm. Indirect evidence of preferential bottom water flow is related to the fact that the BOD_5 concentration was higher in the effluent than in the previous perforated tubes (Fig. 6, location C). In the absence of direct measurements of BOD_5 at different depths in this system, it is very probably that the BOD_5 increases with depth in agreement with the results for the E_H profiles and the direct measurements of the system at Les Franqueses. If the outlet pipe takes an equal mixture of the water column, the effluent organic matter concentration should not be higher than that observed in a sample of the water column.

Les Franqueses HFRB system also showed a low efficiency for removing BOD_5 and the other contaminants tested; D type beds (the shallowest) had the highest efficiencies. In this case, the AOLR cannot be a reason for low removal efficiency because during experimentation it was estimated to be on average 4.7 g BOD/m^2 per day, which is well under the limit of 6 g BOD/m^2 per day stated before. On the other hand, the probable effect of disinfectants was not noticed as it occurred at Vilagrassa. Microbial analyses of the influent detected significant amounts of faecal bacteria in all cases tested (data not shown). Thus, it is very likely that the low removal efficiency was due to experiments being carried out during the start-up period. This HFRB system started up in May, and the samples were taken in July and August, so it is very likely that there was not enough time for the biofilm to develop. Indirect evidence of preferential bottom water flow in this system is also noted and is related to the same characteristics reported in the previous paragraph for the Vilagrassa system. The better performance of D type beds is related to their lower depth, which improves oxygen diffusion at the top of the beds and/or the capacity for the reeds to supply oxygen to the root zone (García et al., submitted).

The results obtained at Vilagrassa indicate that water temperature profiles do not vary significantly across the width of unplanted HFRBs. This trend should also be true for mature HFRBs, but local variations in plant cover and the development of the litter layer, for example, may cause small differences. Also, in this system we have observed that the water was warmer near the inlet than at the outlet (the temperature of the influent being 1.2–1.8 °C warmer than the average temperature of the beds). In the HFRB system at Les Franqueses, the temperature profiles did not vary significantly along the length of the beds in conjunction with the fact that the influent water temperature was almost equal to, or as much as 1.8 °C lower than, the average temperature of the beds. Differences in the behavior of the temperature along the length of the two HFRB systems tested seem therefore to be related to the period in which the experiments were carried out, since this determines the relationship between influent temperature and the bed water temperature, which is highly dependant on environmental conditions. Obviously, other physical factors such as medium heat capacity and thermal conductivity are also involved in these differences.

In the system at Les Franqueses, the differences in temperature gradients between the summer 2001 campaigns were mainly attributed to the degree to which the plant cover had developed. During the first campaign, when the system had little vegetation, the maximum temperature gradient was 12 °C/m, while during the fourth, with a quite significant plant cover, it was 5.6 °C/m. In the summer of 2002, with complete plant development and a conspicuous litter layer, the maximum temperature gradient was 3.4 °C/m. Thus, it is clear that the plants and the litter layer reduce the inordinate temperature gradients that occur in unplanted beds, especially in summer. Under these conditions, the daily trend of temperature variation with depth is smoothed. All of these findings are in agreement with the works of Brix (1990) and Kadlec (2001), who have reported little temperature variation with depth in mature beds. They are also in agreement with the results of Tanner et al. (1995), which showed that plant shading resulted in 2–4 °C cooler surface water temperatures.

The results of this study indicate that vertical E_H gradients vary in response to distance from the point of influent loading. Kadlec and Knight (1996) have described the same trend. On the other hand, we found that E_H gradients did not vary significantly across the width of the HFRBs at Vilagrassa and as a result they can be used as a tool for detecting preferential lateral water circulation. E_H decreases with depth because oxygen diffusion and oxygen plant supply occur mainly at the top of the gravel beds. It increases with length because of the progressive oxidation of organic matter, resulting in a less reducing environment. E_H variations with length and depth are related to the changes observed in contaminant concentrations.

In both the Vilagrassa and the Les Franqueses HFRB systems, the organic matter, measured as BOD_5 or filtered COD, decreased with length, while it did not vary (Vilagrassa) with width. In the Les Franqueses system, it was observed that filtered COD and ammonia nitrogen increased with depth. Chemical changes in the vertical profile of reed beds have been related to plant activity and the interaction of plants with the system hydraulics (Breen and Chick, 1995). Nevertheless, in the Vilagrassa system, macrophytes were not present during the whole study and at Les Franqueses they were not significant at the beginning of the trials, but vertical variations of E_H and contaminants were systematically observed. Thus, plant density may contribute to the vertical distribution of the contaminants but is not a necessary condition.

Tracer experiments performed on the HFRB system at Les Franqueses indicate that water velocity in HFRBs increases with depth; however, the changes in average TRT with depth were only significant in the perforated tube near the outlet. This pattern indicates that water moves with approximately the same velocity as far as a point located somewhere between the tubes at locations 2 and 3 in the beds studied (C1 and C2), where preferential bottom water flow starts. The movement of water in HFRBs is a very complex phenomenon affected by many characteristics (Blazejewski and Murat-Blazejewska, 1997; Platzer and Mauch, 1997). One reason that has been described is the preferential penetration of roots and rhizomes into the surface layers of the medium (Breen and Chick, 1995). Another reason that has been reported is changes in porosity with depth as a result of excessive traffic on the beds during construction, in conjunction with the presence of the macrophytes (Marsteiner et al., 1996). In our case, because water flow with depth is only different near the outlet, it suggests that preferential bottom water flow is related with the location of the outlet drainage pipe. This statement opposes the results of Marsteiner et al. (1996), which compared subsurface (using a drainage pipe located at mid-depth) versus bottom drainage of beds and found that the vertical location of the pipe was not an important factor influencing the hydrodynamics of the system. However, the results of Marsteiner et al. (1996) and our results are not strictly comparable because the flow tests were carried out under very different conditions in terms of HLR, hydraulic retention time and type of medium contained in the beds.

In addition to tracer tests, a property indicating preferential bottom water flow near the outlet is the higher effluent contaminant concentration than in perforated tubes near the outlet, in conjunction with the increase of contaminant concentration with depth. If the outlet pipe takes an equal mixture from the water column, then the effluent contaminant concentration will be equal to, or lower than, that obtained from a representative (mixed) sample from the perforated tube near the outlet.

5. Conclusions

The presence of a fully developed plant cover in HFRBs greatly reduces the vertical temperature gradients that are observed in unplanted (or poorly vegetated) systems in temperate climates, especially during warmer months. Temperature profiles do not vary significantly across the width of the beds, while they can vary with length depending how fast the system arrives at an equilibrium temperature. Daily variations of temperature gradients do not produce significant changes in effluent quality, at least not within the conditions tested in the present study.

The E_H, organic matter (measured as BOD_5 or COD), and ammonia do not vary significantly across the width, whereas they do change with length and depth. E_H decreases with increasing depth, while the other parameters increase because the mechanisms involved in water oxygenation (diffusion and/or plant supply) occur mainly at the top of the gravel beds. Changes in length include the increases of E_H and the decreases of the other parameters due to progressive oxidation.

The location of the effluent drainage pipe on the bottom of the beds seems to promote preferential bottom water flow which has been detected by means of a tracer test. This pattern cannot be generalized because the factors that determine hydrodynamics in the beds depend on each particular case and on the operation strategy.

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References

APHA-AWWA-WPCF, 1995. Standard Methods for the Examination of Water and Wastewater, 19th ed. American Public Health Association, Washington, DC.

Blazejewski, R., Murat-Blazejewska, S., 1997. Soil clogging phenomena in constructed wetlands with subsurface flow. Wat. Sci. Tech. 35 (5), 183–188.

Bowmer, K.H., 1987. Nutrient removal from effluents by an artificial wetland: influence of rizosphere aeration and preferential flow studied using bromide and dye tracers. Wat. Res. 21 (5), 591–599.

Breen, P.F., Chick, A.J., 1995. Rootzone dynamics in constructed wetlands receiving wastewater: a comparison of vertical and horizontal flow systems. Wat. Sci. Tech. 32 (3), 281–290.

Brix, H., 1990. Gas exchange through the soil-atmosphere interphase and through dead culms of *Phragmites australis* in a constructed reed bed receiving domestic sewage. Wat. Res. 24 (2), 259–266.

Brix, H., 1994. Functions of macrophytes in constructed wetlands. Wat. Sci. Tech. 29 (4), 71–78.

Brix, H., 1997. Do macrophytes play a role in constructed treatment wetlands. Wat. Sci. Tech. 35 (5), 11–17.

García, J., Aguirre, P., Mujeriego, R., Huang, Y., Ortiz, L., Bayona, J.M., 2004, Initial contaminant removal performance factors in horizontal flow reed beds used for treating urban waste water, submitted for publication.

Graus, S., 2000. Desinfecció en Aiguamolls de Flux Subsuperficial. Undergraduate Thesis. School of Civil Engineering, Technical University of Catalonia, 77 pp.

Kadlec, R.H., 2001. Thermal environments of subsurface flow treatment wetlands. Wat. Sci. Tech. 44 (11–12), 251–258.

Kadlec, R.H., Knight, R.L., 1996. Treatment Wetlands. CRC Press, Boca Ratón, FL, 893 pp.

Marsteiner, E.L., Collins, A.G., Theis, T.L., Young, T.C., 1996. The influence of macrophytes on subsurface flow wetland (SSFW) hydraulics. In: Proceedings of the Fifth International Conference on Wetland Systems for Water Pollution Control. Paper II/2. September, Vienna.

Platzer, C., Mauch, K., 1997. Soil clogging in vertical flow reed beds-mechanisms, parameters, consequences and . . . solutions? Wat. Sci. Tech. 35 (5), 175–181.

Rash, J.K., Liehr, S.K., 1999. Flow pattern analysis of constructed wetlands treating landfill leachate. Wat. Sci. Tech. 40 (3), 309–315.

Smith, I.D., Bis, G.N., Lemon, E.R., Rozema, L.R., 1997. A thermal analysis of a sub-surface, vertical flow constructed wetland. Wat. Sci. Tech. 35 (5), 55–62.

Tanner, C.C., Clayton, J.S., Upsdell, M.P., 1995. Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands. Part I. Removal of oxygen demand, suspended solids and faecal coliforms. Wat. Res. 29 (1), 17–26.

US EPA, 2000. Constructed Wetlands Treatment of Municipal Wastewaters. EPA/625/R-99/010, United States Environmental Protection Agency, Office of Research and Development, Cincinnati, OH, 165 pp.