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ANALYSIS OF HYDRODYNAMIC CHARACTERISTICS OF A HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND

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ABSTRACT

Horizontal subsurface flow (HSSF) constructed wetlands are widely used for wastewater treatment but there's still a lack of information on flow characteristics changes throughout the porous bed over time. The continuous growth of roots, the adsorption, sedimentation and precipitation of wastewater compounds and the biofilm release over operation time leads to the development of stagnated areas, the appearance of hydraulic short-circuiting and variations in dispersion conditions, which affect substrate distribution throughout the bed and, therefore, may worsen the overall performance of the system. In order to enable a better understanding of the transport mechanisms throughout the bed, two series of tracer tests were performed in a laboratory HSSF system at the hydraulic loading of 4.7×10^{-3} m^3 m^{-2} h^{-1}. The first series was executed with the bed without vegetation and the second with the bed already colonized with *Phragmites australis* after an operation period of eight months at an average organic loading of 12 g m^{-2} d^{-1} COD. The magnitude of longitudinal dispersion was estimated both by a curve-fitting technique using the non-linear least square optimization method (LSOM) and using the moment method (MOM) over the *advection-dispersion-reaction* equation. The flow regime and the extension of dead volumes were estimated by the same curve-fitting technique over the *multiple tanks in series* model (MTS). The results showed that the development of plants and biomass did not contribute for a significant amount of longitudinal dispersion in the overall media length. However, the dispersion was very strong in the inlet section, where the dead volumes increased approximately 65% within the colonized bed. The flow regime may be considered as plug flow throughout the overall length and the tracer retention was associated with dispersion and internal recirculation and, additionally, for Series II it was associated with the occurrence of clusters of biomass and roots. The MTS better explain the tracer results for the overall media length. The MOM seems to be inadequate for estimating Pe leading to underestimated values when compared with the ones calculated by LSOM.

Keywords: Hydrodynamic characteristics, HSSF constructed wetland, dispersion

1. INTRODUCTION

Horizontal subsurface flow (HSSF) constructed wetlands are biological porous media systems, colonized with helophyte plants, which use physical, chemical and biological processes (*e.g.* filtration, bio-conversion and uptake by plants) to remove pollutants present in wastewater. They combine high filtration rates with the maintenance of high biomass concentrations, whose capabilities are increased when high porosity and specific surface bed material are used. Therefore, they are considered to be a technically, economically and environmentally sustainable solution, but showing, however, problems of performance decline, which are considered to be associated with porous media clogging. The packing media used as bed, normally gravel, is very useful for plant anchorage and biofilm development, although it may become frequently clogged due to factors whose interrelations are not well known. The migration of pollutants in the bed is, therefore, difficult to study since there are many factors which may affect the transport mechanisms, such as media characteristics (*e.g.* type of material, porosity and number of layers and its depth), the physical properties of the filled material (*e.g.* sorption), excessive biomass growth, the accumulation of solids, the development of rhizomes and roots, the hydraulic and organic loadings, and the chemical and biochemical transformation throughout the bed. As referred by Albuquerque (2003), the interrelationship may stimulate the development of several mechanisms such as dead volumes, hydraulic short-circuiting, internal recirculation and dispersion, leading to changes in the hydrodynamics of the bed and, consequently, to alterations in the system's performance. Therefore, the analysis of flow patterns for different bed characteristics (*e.g.* with and without vegetation) is important for improvements in HSSF design, construction and maintenance practices.

A reliable means for studying the importance and extension of these mechanisms is to carry out tracer tests throughout the bed and analyse the exit concentration curves with time, commonly known as breakthrough curve. This curve may be normalized to obtain a residence time density function E(t), commonly known as dimensional residential distribution time curve (RTD curve). Salt tracer experiments are a convenient and widespread method used for hydrodynamics studies in wetland systems (Chazarenc *et al.*, 2003). One way to analyse the RTD curves is to determine the distribution moments (Albuquerque and Bandeiras, 2005), which allows obtaining information concerning the presence of dead volumes, short-circuiting or internal recirculation, namely by performing consistency tests on experimental data. The bed's hydrodynamic behaviour, in terms of flow regime and longitudinal dispersion, may be analysed by estimating model parameters through curve-fitting techniques such as the non-linear least square optimization method (LSOM). The *advection-dispersion-reaction* model (ADR) has been used to study longitudinal dispersion in porous media systems (Chazarenc *et al.*, 2003; Albuquerque and Santana, 2004). Application of the ADR equation to porous media for event prediction and forecasting of solute concentration is normally made by estimating the the Peclet number (Pe). The *multiple tanks in series model* (MTS) for non-ideal flow has also been used also for estimating yhe flow regime (Albuquerque, 2003) and the extension of dead volumes (Kadlec and Knight, 1996; Chazarenc *et al.*, 2003).

The objective of this paper is to study the flow regime and to identify the main mechanisms that can interfere with the transport of pollutants through a HSSF constructed wetland for wastewater treatment using a set of tracer tests.

2. TECHNIQUES FOR EVALUATING POLLUTANT TRANSPORT IN THE BED

An accurate method to study the transport of pollutants in saturated porous media is to conduct a tracer test using a slag injection (Santamaria *et al.*, 1999; Albuquerque, 2003). The tracer is inserted at the entry, evaluating the system's response at the exit through sample collection and plotting the exit concentration-time curves. The normalised E(t) curves may be calculated through numerical integration of the respective areas (Eq. (1) of Table 1). The first moment about the origin μ_m (mean residence time) and the second moment about the measuring point σ^2 (variance) of the E(t) curve may be computed by applying Eq. (2) and (3), respectively. In order to better compare the results of different experiments it is usually computed the reduced variance (σ_θ^2) and the dimensionless curves E(θ) through Eq. (4) and (5), respectively.

Table 1. Parameters used to obtain RTD curves for slag inputs (Albuquerque and Bandeiras, 2005)

Name	Parameter	Expression
Dimensional RTD curve (T^{-1})	E(t)	$C(t) \Big/ \int_0^\infty C(t)\,dt$ (1)
Mean residence time (T)	μ_m	$\int_0^\infty t \bullet E(t)\,dt$ (2)
Variance in (T^2)	σ^2	$\int_0^\infty (t-\mu_m)^2 \bullet E(t)\,dt$ (3)
Reduced variance	σ_θ^2	σ^2/μ_m^2 (4)
Dimensionless RTD curve	E(θ)	$\mu_m \bullet E(t)$ (5)
Reduced mean residence time	$\mu_{(m,\theta)}$	μ_m/τ (6)
Mass recovery (M)	M_s	$\int_0^\infty Q \bullet C(t)\,dt$ (7)

Legend: τ is the theoretical hydraulic retention time (T), calculated taking in account the porous volume and the flow rate.

As referred by Albuquerque (2003), the identification of mechanisms responsible for flow and substrate maldistribution may be achieved through consistency tests on experimental data such as the estimation of the reduced mean residence time ($\mu_{(m,\theta)}$) and the tracer mass recovery rate (M_s), using expressions (6) and (7) respectively. The magnitude of dispersion and the extension of zones that can interfere with the flow patterns (*e.g.* dead volumes) may be better understood through the estimative of parameters of the ADR equation and the MDS model using the LSOM.

3. MODELS FOR ESTIMATING HYDRODYNAMIC CHARACTERISTICS

3.1. Advection-dispersion-reaction equation (ADR)

In porous media systems where the ratio length/width is too large (Albuquerque, 2003), such as HSSF constructed wetlands, the effects of liquid flow in the vertical direction (*z* direction) are considered as unimportant when compared to the flux in the horizontal direction (*x* direction) and, therefore, the ADR 1-D equation (Eq. (1)) is usually utilized to describe advection, dispersion and reaction (van Genuchten and Alves, 1982; Santamaria *et al.*, 1999):

$$R \bullet \frac{\partial C}{\partial t} = D \bullet \frac{\partial^2 C}{\partial x^2} - v \bullet \frac{\partial C}{\partial x} \tag{8}$$

where C is the solute concentration (ML^{-3}), D is the effective dispersion coefficient (L^2T^{-1}), v is the average interstitial velocity (LT^{-1}), x is the distance (L) and R the sum of reactions. Eq. (1) assumes that adsorption or exchange reactions are always instantaneous (equilibrium adsorption). In order to better compare the results of different assays it is usual to transform Eq. (8) in a dimensionless form (Eq. (9)), assuming the dimensionless variables $\theta_i = {}^{t_i}\!/\!_{\tau}$ and $\zeta_i = {}^{x_i}\!/\!_{L}$ (van Genuchten and Alves, 1982):

$$R \bullet \frac{\partial C}{\partial \theta} = \left(\frac{D}{vL}\right) \bullet \frac{\partial^2 C}{\partial \zeta^2} - \frac{\partial C}{\partial \zeta} \tag{9}$$

where θ is the dimensionless hydraulic retention time, ζ the dimensionless horizontal distance and L the bed length (L). The $\left({}^{D}\!/\!_{vL}\right)$ ratio is also called the dimensionless dispersion number, it is equal to the inverse of the Peclet number (Pe) and describes the relative influence of the effects characterised by advection-dispersion problems. A large value of Pe means the presence of plug flow regime. Values above 500 would mean a small amount of dispersion, from 40 to 500 it indicates an intermediate dispersion, from 5 to 40 it points to a large amount of dispersion and for values approaching zero it denotes the presence of mixed flow (Santamaria *et al.*, 1999; Albuquerque, 2003).

3.2. Multiple tanks in series model with dead volumes (MTS)

The MTS model simulates the flow as it flows through N tanks in series of equal volumes and equally mixed, admitting that solute concentration in the end compartment is given by Eq. (1). The concentration C (LT^{-1}) at each instant and in each tank is given by the mass balance in each unit, leading to the following expression (Santamaria *et al.*, 1999; Albuquerque, 2003):

$$QC_1 = V_1 \bullet \frac{dC_1}{dt}, \left(QC_1 - QC_2\right) = V_2 \bullet \frac{dC_2}{dt}, \ldots, \left(QC_{(N-1)} - QC_N\right) = V_N \bullet \frac{dC_N}{dt} \tag{10}$$

Values of N below 4 indicate that mixing conditions are important in the bed, whilst high values of N indicate that the regime is plug flow (Kadlec and Knight, 1996).

4. MATERIAL AND METHODS

In order to enable a better understanding of the transport mechanisms throughout the bed, two series of tracer tests were performed in a laboratory HSSF system (dimensions of 2.0 m x 0.80 m x 0.50 m) at the hydraulic loading of 4.7×10^{-3} m^3 m^{-2} h^{-1} (approximately 11.3 cm d^{-1}). The first series (Series I) was executed with the bed without vegetation and the second (Series II) with the bed already colonized with *Phragmites austraulis* after an operation period of eight months at organic loads ranging from 10 to 33 g m^{-2} d^{-1} COD (roots were well developed and spread over the bed). The submerged media was composed by 0.20 m in depth of gravel (average of 70 mm in diameter and porosity of 0.4). Both Series included three assays with tap water and sodium chloride (NaCl) as tracer for three bed length: Inlet – IP2 (0.33 m), Inlet – IP5 (1.00 m) and Inlet – IP8 (1.93 m) as it can be seen in Figure 1. The tracer test procedure included a slag injection of 500 mL of a NaCl concentrated solution (Co = 100 g L^{-1}). The response was evaluated by online measurement of conductivity at equal time periods of 1 minute through a conductivity

TetraCon 325 probe and a multiparametric WTW MultiLine P4 equipment. The time duration of each assay was up to 15 times the theoretical hydraulic retention time until no significant conductivity were observed at the sampling point. An adsorption batch test was carried out to evaluate the existence of NaCl adsorption into the gravel according to the procedure presented in Albuquerque (2003).

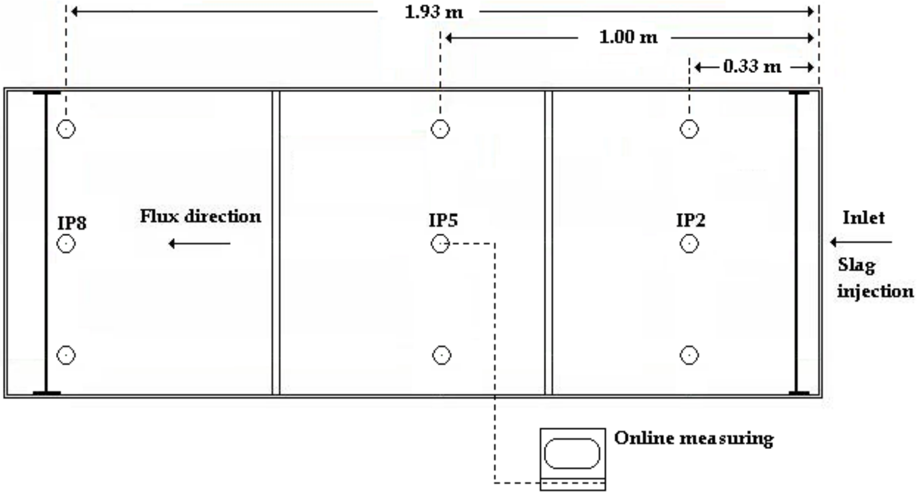

Figure 1. Schematic representation of the SSHF bed (pant)

5. RESULTS AND DISCUSSION

5.1. Residential time distribution curves analysis

The two Series of trials yielded six conductivity over time curves which were converted into C(t) curves over time curves through an accurate calibration equation. The C(t) curves were normalized in E(*t*) curves through numerical integration of the respective areas using Eq. (1). A programme developed in Matlab was used to calculate the parameters presented in Table 2 through the expressions presented in Table 1. The E(t) curves are presented in Figure 2.

Table 2. Characteristics of the RTD curve for Series I and II

Assay	Section	τ (d)	$\mu_{(m,\theta)}$	s_θ^2	Ms/Mo
I.P2	Inlet - IP2	0,26	2,70	0,40	0,61
I.P5	Inlet - IP5	0,76	3,78	0,34	0,43
I.P8	Inlet - IP8	1,51	3,49	0,27	0,21
II.P2	Inlet - IP2	0,26	4,09	0,26	0,72
II.P5	Inlet - IP5	0,76	3,66	0,10	0,37
II.P8	Inlet - IP8	1,51	3,42	0,41	0,25

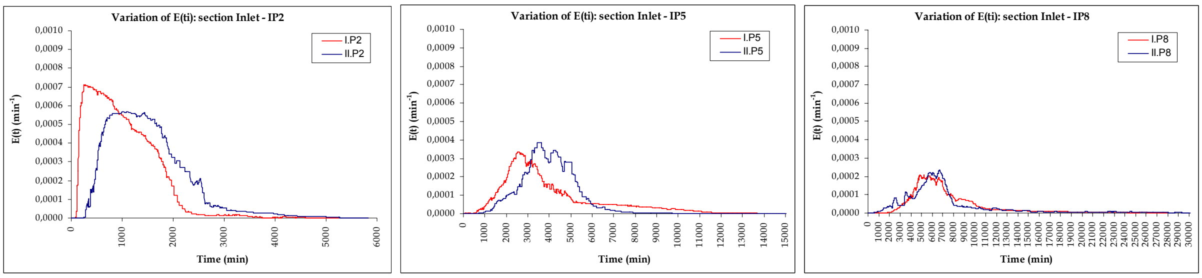

Figure 2. E(t) curves in time for Series I and II

The analysis of variance in E(θ) curves showed a slight decrease in data dispersion with an increase of the bed depth, especially when the bed was poor colonized with plants and no biofilm was present (Series II). It can be observed that the reduced mean residence time is above the unit in all the assays, revealing that the mass centre of impulse was late relatively to the expected and, consequently, indicates tracer retention in the system. Nevertheless, the results of the adsorption test showed that there was no significant adsorption of the NaCl into the gravel for the mass concentration range utilized. Therefore, the observed tracer retention could be associated with mechanical dispersion and molecular diffusion mechanisms associated with internal recirculation rather than due to adsorption phenomena.

In the assays of Series II, since roots, rhizomes and biofilm were well developed the tracer retention could occur into these zones. This circumstance, seemed to be more likely in the initial section (Inlet – IP2) were $\mu_{(m,\ \theta)}$ increased approximately 34% from Series I to Series II and it was observed an important development of biofilm. In the remaining sections the values of $\mu_{(m,\ \theta)}$ were closer and, thus, dispersion and internal recirculation could be the main responsible for retention. The prolonged tail observed in the second part of the curves confirms that dispersion is already an important mechanism in the overall bed. The observed hydraulic retention times strongly increased relatively to the theoretical ones in all sections, ranging from 63% to 76% with higher values in Series II, thus suggesting that channelling was also occurring within the bed.

Although the occurrence of an arbitrary regime is visible by comparing the RTD curves with the typical standard ones for plug and completely mixed flows (presented in Santamaria *et al.*, 1999), the shape of them suggests that the regime in all bed's sections was closer to plug flow with a certain degree of dispersion. The recovered tracer mass was always lower than the introduced mass, decreasing with the bed length and indicating a similar mass conservation along the overall media independently of the operating conditions. These values are lower than the ones obtained by Chazarenc *et al.* (2003). During the course of the tracer impulse through these clusters, as observed by Albuquerque (1993), there might have been created concentration gradients of tracer molecules transported into its interior. When the disturbance abandoned these points, the tracer concentration must have been higher in the interior of the stagnated areas than in its exterior, which may have provoked a gradient inversion, with the consequent diffusion of NaCl into the exterior space. These tracer fractions consequently presented residence times higher than those of the fractions that accompany the impulse front, which may help to explain the tracer retention, as well as the tails observed in all the experiments (Figure 2).

5.2. Estimation of the longitudinal dispersion and flow regime

Since there was some uncertainty concerning the experimental procedure at the upstream boundary (near the tracer injection point) it was decided to evaluate the magnitude of dispersion for two cases:

1. Estimating Pe for the *open* case as described by Santamaria *et al.* (1999), assuming that there is no variation of the dispersion coefficient across boundaries.

Boundary conditions:

$C(x, 0) = 0$ Initial

$$\left[-D\frac{\partial C}{\partial x}+vC\right]\Bigg|_{x=0^+}=\left[-D\frac{\partial C}{\partial x}+vC\right]\Bigg|_{x=0^-} \quad \text{Upper}$$

$$\left[-D\frac{\partial C}{\partial x}+vC\right]\Bigg|_{x=L^-}=\left[-D\frac{\partial C}{\partial x}+vC\right]\Bigg|_{x=L^+} \quad \text{Lower}$$

Solution for Eq. (9) (Santamaria *et al.*, 1999):

$$E(\theta)=\frac{1}{2\sqrt{\pi\bullet\left(1/_{Pe}\right)\bullet\theta}}\,e^{\left(-\frac{(1-\theta)^2}{4\theta\bullet\left(1/_{Pe}\right)}\right)} \qquad (11)$$

The Pe number was estimated through the LSOM by curve-fitting Eq. (11) to $E(\theta)$ in θ curves, adjusting θ_i to t_i/μ_m. The adjustment quality was evaluated by determining the correlation coefficient between the expected residuals in the normal Model and the ones calculated through the model, having also tested the hypothesis of constant variance (homoscedasticity) and null average.

2. Estimating Pe for the *close-open* case as described by Santamaria *et al.* (1999) and Albuquerque (2003), assuming that there is variation of the dispersion coefficient across the upper boundaries.

Boundary conditions:

$C(x, 0) = 0$ Initial

$$\left[-D\frac{\partial C}{\partial x}+vC\right]\Bigg|_{x=0^+}=\begin{cases} vC_0, & (0<t\le t_{sl}) \\ 0, & (t>t_{sl}) \end{cases} \quad \text{Upper}$$

$$\left[-D\frac{\partial C}{\partial x}+vC\right]\Bigg|_{x=L^-}=\left[-D\frac{\partial C}{\partial x}+vC\right]\Bigg|_{x=L^+} \quad \text{Lower}$$

where t_{sl} is the pulse time duration (T)

Since there is no analytical solution of Eq. (9) for this set of conditions the value of Pe may be estimated using the MOM method through Eq. (12) (Santamaria *et al.*, 1999):

$$\sigma_\theta^2=\frac{\sigma^2}{\mu_m^2}=2\bullet\left(1/_{Pe}\right)+3\bullet\left(1/_{Pe}\right)^2 \qquad (12)$$

Although Eq. (11) and (12) may give enough information concerning the flow regime and the magnitude of dispersion in the bed, they do not give information concerning the extension of dead volumes, which is an important aspect for a better understanding of the bed's behavior. As referred by Kadlec and Knight (1996) and Chazarenc *et al.* (2003) the MTS model may be used for this purpose. Admitting $\tau_i = V_i/Q$ and the conditions $C_{(N+1)} = 0$, $t = 0$ and m as the ratio of active volume over total useful volume (i.e. the dead volume (Vm) = 1-m), integrating Eq. (10) in time and including the dimensionless variable θ, the following expression is obtained (Santamaria *et al.*, 1999; Dabaliz, 2002):

$$E(\theta)=\frac{1}{m^{N}}\bullet\frac{N^{N}}{(N-1)!}\bullet\theta^{(N-1)}\bullet e^{(-\frac{N\bullet\theta}{m})} \tag{13}$$

Since the Reynolds number (R_e) was approximately 0.1, according to Lencastre (1996), the regime was laminar, hence the Darcy law is valid and any solution of Eq. (9) may be applied. Since the adsorption of NaCl into the gravel was considered negligible, the value of the retention factor (R) is equal to one and Eq. (11) may be applied to experimental data.

The E(t) curves were, therefore, transformed in the dimensionless RTD ones (E(θ) curves) through the application of Eq. (5). The Pe estimated for each assay, using the LSOM through curve-fitting Eq. (11) and using the MOM through Eq. (12), and the estimates of N and Vm using the LSOM through curve-fitting Eq. (13) are presented in Table 3. The software NLREG (Sherrod, 2001) was used for this purpose. For a better comparison of the results of all adjustments it was computed the quadratic error (ξ_{MD}) as described in Albuquerque (2003).

Table 3. Characteristics of the RTD curve for Series I and II

Assay	**Section**	**Eq. (11)**		**Eq. (12)**	**Eq. (13)**		
		Pe	**ξ_{MD}**	**Pe**	**N**	**Vm (%)**	**ξ_{MD}**
I.P2	Inlet - IP2	4,0	0,420	6,2	2,0	2,87	0,193
I.P5	Inlet - IP5	22,2	0,784	7,2	10,0	6,38	0,543
I.P8	Inlet - IP8	29,4	0,649	8,5	10,0	15,12	0,204
II.P2	Inlet - IP2	8,7	0,335	9,1	3,0	8,27	0,226
II.P5	Inlet - IP5	28,6	0,207	21,7	12,0	4,54	0,240
II.P8	Inlet - IP8	33,3	0,699	6,0	11,0	17,89	0,444

The analytical solution of the MTS model with dead volumes (Eq. (13)) allows a closer representation of the RTD curves for almost all the assays realized as it can be observed by the lower values of ξ_{MD} obtained and by the closer adjustment showed in Figure 3. The results obtained for MTS showed normality in residual distribution, which, associated with the fact that residuals had presented a null average and homoscedasticity (constant variance), allows considering the adjustment with Eq. (13) as being adequate. In the initial section the values of N are below 4, thus suggesting that a certain degree of mixing was present. Nevertheless, for higher length sections the dispersion seemed to be reduced and plug flow was the dominant regime (N ranging from 10 to 12).

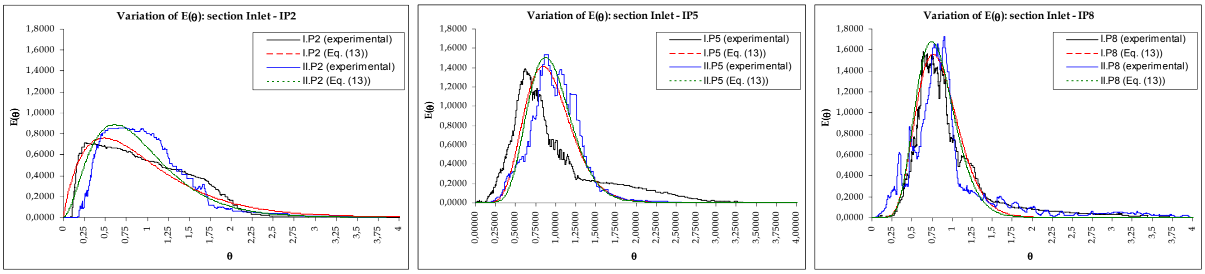

Figure 3. Best curve fitting to RDT data for Series I and II

The range of Pe values obtained through LSOM is more heterogeneous than the ones obtained through MOM and increase with the depth of the bed. The values of Pe estimated by LSOM suggested for the initial section the occurrence of plug flow regime with large amount of dispersion, which were reduced as the tracer flowed for longer bed lengths. This circumstance is convergent with the discussion had above and, therefore, the estimates of Pe through the MOM did not seem to be adequate. The results also showed that the dead volumes increased for longer bed lengths, however, not showing significant changes between the two Series for the overall length. Nevertheless, the variation of Vm was significant in the initial section, especially when the bed was well colonized, having increased approximately 65% from Series I to Series II, which seemed to be related to the intense microbiological activity occurred at the inlet and to the installation of biomass clusters.

6. CONCLUSIONS

For the hydraulic loading applied in this study, which is similar to the ones observed in real HSSF constructed wetlands, and for the different bed characteristics observed in the two Series of assays, the development of roots, rhizomes, biofilm and algae did not seem to influence the hydrodynamic characteristics of the overall bed. However, for the initial section, the use of the bed during eight months for wastewater treatment led to changes in the media characteristics and to the increase of areas with dead volumes. The flow regime may be considered as plug flow throughout the overall bed presenting a strong dispersion in the inlet section (first 33 cm). Dispersion (both mechanical dispersion and molecular diffusion) and internal recirculation seemed to be the main important mechanisms responsible for the response delay. Nevertheless, the development of clusters of biofilm and algae and of roots and rhizomes seemed to have been an important factor in the tracer retention in the assays of Series II. The MTS solution represented in Eq. (13) satisfactorily described the DTR curves obtained in all the assays. The results of Pe calculated by using the MOM are lower than the ones estimated by LSOM, thus suggesting that, for the operating conditions used in this study, the first method leads to underestimated values, especially for long bed lengths.

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