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Hydrodynamics of horizontal subsurface flow constructed wetlands

Florent Chazarenc, Gérard Merlin*, Yves Gonthier[1]

Ecole Supérieure d'Ingénieurs de Chambéry (ESIGEC), Environmental Biotechnology and Process Engineering, Campus Scientifique, Bâtiment Chartreuse, F 73 376 Le Bourget du Lac, Cedex, France

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Abstract

Constructed wetland hydrodynamics were modeled using mathematical tools generally employed in chemical engineering processes. The hydraulic residence time (HRT) distributions of the subsurface horizontal flow constructed wetland from Curienne (France) were estimated using the impulsion tracer method. A non-ideal flow wetland was first modeled by classical method: the dispersion plug flow model (DPFM), which gives a constant ratio to axial dispersion (the Peclet number *Pe*), and the stirred tanks in series model (STSM), which gives a number of stirred tank in series (NSTS). Six experimental HRTs were monitored to determine flow characteristics. Several periods were monitored to represent different seasons. It was found that evapotranspiration played a major role in summer by improving HRT.

Keywords: Constructed wetlands; Hydraulic residence time distribution; Hydrodynamic performance; Modeling; Evapotranspiration

1. Introduction

The use of constructed wetlands for rural wastewater treatment in France has increased exponentially over the last 10 years. In these facilities, high levels of pollutant removal are due to a good combination of chemical, biological, and physical processes. Several studies have shown the important role played by macrophytes in constructed wetlands (Brix, 1997).

Other studies have shown the importance of evapotranspiration during hot periods in natural wetlands (Herbst and Kappen, 1999; Pauliukonis and Schneider, 2001). Furthermore, plant growth and type, have an important role on the roughness coefficient which conditions flow paths, as shown by Vassilios and Tsihrintzis (2001). Considering the importance of flow paths in wetlands, this paper deals with its influence on the efficiency of wastewater treatment in constructed wetlands.

One of the best methods for determining and analyzing constructed wetland flow paths is using the evaluation of hydraulic residence time (HRT) distribution by the impulsion tracer method, generally used in chemical engineering processes (Gourlia, 1995). This

* Corresponding author. Tel.: +33-4-79-75-88-93; fax: +33-4-79-75-88-90.
E-mail addresses: gerard.merlin@univ-savoie.fr (G. Merlin), yves.gonthier@univ-savoie.fr (Y. Gonthier).
[1] Tel.: +33-4-76-85-15-40; fax: +33-4-76-85-15-26.

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method is usually employed for determining non-ideal flow in chemical reactors. The resulting HRT distribution gives information about mixing and dispersion in a given filter. It is also possible to create more complex models with adapted software to study hydrological behavior in natural wetlands (Mansell et al., 2000), or in constructed wetlands (Somes et al., 1999). Two ideal reactors are commonly used: the plug flow reactor (PFR) and the continuous flow steady-state reactor (CFSTR).

All reactors (including reed beds) can be considered theoretically as a combination of multiple single steady-state flow ideal reactors. Werner and Kadlec (2000) showed that the saturated flow of a constructed wetland has non-ideal flow behavior. Our experiments were monitored using a subsurface horizontal flow wetland. The determination of the practical HRT was established with the classical method of a stimulus-response experiment. The aim was to compare hydraulic behavior variations, due to season, with inflow characteristics. The use of classical models gave a first approach of the dispersion and mixing levels in the reed bed.

2. Material and methods

2.1. Wastewater treatment plant from Curienne

This constructed wetland consists of a three-stage system dimensioned for the equivalent of 500 person equivalent (PE) and situated at Curienne (latitude: 45°34′6″; longitude: 6°0′55″) at an elevation of 720 m. The climate is characterized by an average rainfall of about 1600 mm and an average air temperature of 10 °C (Merlin et al., 2002). Temperature extremes range between −15 and +35 °C. Large stones have been placed in the inlet and outlet zones for effluent distribution. Water levels are set at approximately 5 cm below the bed surface with a swiveling standpipe. The bottom slope ranges from 0.5 to 1.5% and all slide slopes of the wetlands cells were constructed on a 2:1 ratio. Basins were sealed off by compacted clay. The study focused on the second stage filter. The filter studied is 31 m long, 19.5 m wide, 0.72 m deep; this basin has been packed with gravel (6–20 mm) and large stones (20–50 mm) have been placed at the inlet, in the middle of the length and in the outlet zone.

2.2. Hydraulic residence time distribution determination

The protocol used was based on the rapid injection of 120 l of concentrated sodium chloride solution (67 g/l) at the inflow and the measurement of conductivity at the outflow. The observed HRT was then calculated using the answer curve obtained after collecting conductivity data at outflow:

$$E(t) = \frac{C(t) - C_{\mathrm{w}}}{C_{\mathrm{e}}\tau} \tag{1}$$

where $C(t)$ is the conductivity variation at outlet, C_{w} the conductivity due to wastewater composition, C_{e} the equivalent concentration and τ the theoretical residence time distribution ($\tau = V/Q$).

The observed HRT(t_{s}) is determined as follows:

$$t_{\mathrm{s}} = \frac{1}{S}\int_0^{\infty} E(t)t\,\mathrm{d}t \tag{2}$$

where

$$S = \int_0^{\infty} E(t)\,\mathrm{d}t$$

By comparing the theoretical and observed HRT, certain unique hydraulic behavior was revealed:

- $t_{\mathrm{s}} > \tau$: Inflow crosses the reed bed without reacting; this is an indicator of short-circuiting. Fluid follows a preferential path and the first peak is seen at an earlier stage of the curve than in the theoretical curve, which peaks at a later stage.
- $t_{\mathrm{s}} < \tau$: Fluid stagnates in the reactor and does not participate in reactions. This phenomenon is due to the presence of dead or stagnant zones.

The plug flow model is usually used for the horizontal subsurface flow (HSSF) constructed wetlands, but a more realistic model must take into account axial dispersion: the dispersion plug flow model (DPFM). A dimensionless number is thus used, the Péclet number:

$$Pe = \frac{Ul}{D} \tag{3}$$

where U is the flow speed (m s^{-1}), l the flow length (m), and D the diffusion coefficient (m^2 s^{-1}).

The DPFM applies in the case of flow close to plug flow and is based on the superimposition of a simple convective plug flow with an unpredictable dispersion model obeying Fick's law (Levenspiel, 1972). It is also possible to use another type of non-ideal flow model, assuming that a HSSF is a succession of stirred tanks: the stirred tank in series model (STSM). In this model, the flow path in the non-ideal reactor is represented through a series of n equal-size ideal stirred tanks separated by waterfalls. If $n \to 1$, then there is a large dispersion, and if $n > 100$, flow is similar to a plug flow.

2.3. Normalized response, mass conservation

In order to have an idea of the tracer conservation (loss by absorption in the filter), a simple mathematical determination is monitored to show tracer response curves in normalized quantities:

$$N(t) = (C(t) - C_{\mathrm{w}})\frac{1}{\lambda_{\mathrm{Na}^+} + \lambda_{\mathrm{Cl}^-}} M Q_{\mathrm{s}} \frac{1}{\mathrm{MI}} \quad (4)$$

where $C(t)$ and C_{w} correspond, respectively, to conductivity at the outlet and due to wastewater composition, expressed in $\mathrm{S\,m^{-1}}$; $\lambda_{\mathrm{Na}^+} + \lambda_{\mathrm{Cl}^-}$ is the molar conductivity limit; $5.01 \times 10^{-3}\,\mathrm{S\,m^2\,mol^{-1}}$ for Na^+ and $7.63 \times 10^{-3}\,\mathrm{S\,m^2\,mol^{-1}}$ for Cl^-; M the sodium chloride molar weight ($58.5\,\mathrm{g\,mol^{-1}}$); Q_{s} the outflow rate ($\mathrm{m^3\,h^{-1}}$); and MI the total salt mass injected (g).

3. Results and discussion

Six pulse tracer experiments have been set up, using $E(t)$ determination (for analysis with DPF and STS), and theoretical HRT(τ) are employed. This determination assumes that inflow and outflow are equal and constant, but the SSFW of Curienne is built with a direct pseudo-separative network so that inflow and outflow are not constant, due to:

- parasitic contributions of water (rainy periods, pseudo-separate network);
- water volume losses due to evapotranspiration and infiltration.

To provide a precise model, these parameters were studied and models created where possible.

3.1. Influence of overloads

As many SSFW are designed for small communities, less than 2000 inhabitants, the flow supply systems are unit or pseudo-separative. This frequently involves hydraulic overloads, particularly during very wet periods or during snow melt. During such periods of high flow intensity, the level of water increases and can lead to a difference of level between inlet and outlet of the treatment cell. As a result, theoretical HRT cannot be determined. A new approach is necessary.

3.1.1. Hypothesis

Considering the filter slope and flow speed as well as the water level in the filter, which can be superior to the gravel level (generally during very wet periods), it is possible to say that the water level changes in spite of the filter surface (Fig. 1).

By definition $q = US$ and $U = -k(\mathrm{d}z/\mathrm{d}x)$ (Darcy's law) with Q the inflow in $\mathrm{m^3}$ per day, U the speed flow

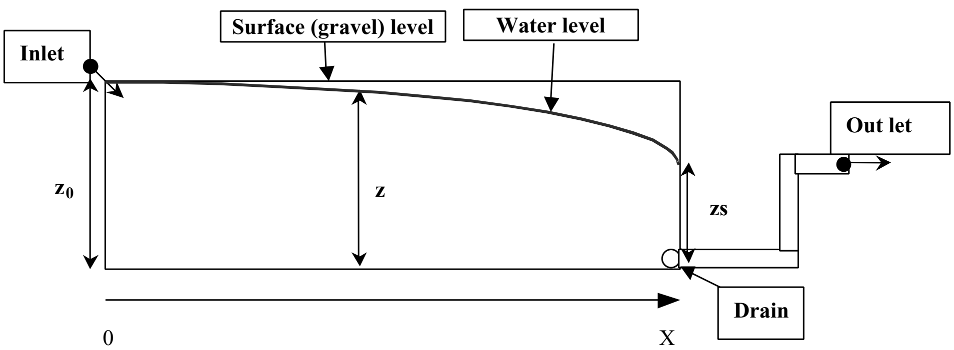

Fig. 1. Water level fluctuation in saturated horizontal flow.

in $\mathrm{m\,s^{-1}}$ and $S = lz$ in $\mathrm{m^2}$:

$$Q = -k\frac{\mathrm{d}z}{\mathrm{d}x}lz \quad \text{and} \quad Q\int_0^x \mathrm{d}x = -kl\int_{z0}^{z} z\,\mathrm{d}z \Rightarrow z_0^2 - z^2 = \frac{2Qx}{kl} \Rightarrow z = \left[z_0^2 - \frac{2Q}{kl}x\right]^{1/2} \tag{5}$$

3.1.2. Determination of hydraulic residence time

Considering inflow and filter porosity constant: $\mathrm{d}\tau = \mathrm{d}V/Q$

$$\tau = \frac{1}{Q}\int_0^x \varepsilon lz\,\mathrm{d}x = \frac{\varepsilon}{Q}\int_0^x l\left(z_0^2 - \frac{2Q}{kl}x\right)^{1/2}\mathrm{d}x \Rightarrow \tau = \frac{\varepsilon l}{Q}\left[\frac{-kl}{3Q}\left[z_0^2 - \frac{2Q}{kl}x\right]^{3/2}\right]_0^X \tag{6}$$

Finally,

$$\tau = \frac{\varepsilon kl^2}{3Q^2}\left[z_0^3 - \left(z_0^2 - \frac{2QX}{kl}\right)^{3/2}\right] \quad \text{or} \quad \tau = \frac{\varepsilon kl^2}{3Q^2}z_0^3\left(1 - \left(1 - \frac{2QX}{klz_0^2}\right)^{3/2}\right) \tag{7}$$

Verification: if $2QX/klz_0^2 \ll 1$ then $\tau \approx (\varepsilon kl^2/3Q^2)z_0^3$, where k is the hydraulic conductivity in $\mathrm{m\,s^{-1}}$; l the width in m; Q the inflow and outflow rate in $\mathrm{m^3\,s^{-1}}$; z_0 the water level at the head of the filter in m; X the length in m; and ε the porosity.

For example, during the impulsion tracer assay of March 2001 (a hydraulic overload period) with an inflow of $4.66\,\mathrm{m^3\,h^{-1}}$ ($Q = 1.29 \times 10^{-3}\,\mathrm{m^3\,s^{-1}}$), HRT was between 27.1 and 34 h (Table 1). This model for experimental HRT determination supposes that infiltration, as well as hydraulic conductivity, is constant along the surface filter. This is not strictly true because of the presence of large stones in certain areas of the bed. This represents a first approach to characterizing the influence of hydraulic overloads.

Table 1
Determination of hydraulic residence time taking into account water level and hydraulic conductivity

Classical τ determination (=V/Q)	Parameters	Determination according to Eq. (10)
30.8 h	$z_0 = 0.92$ and $k = 0.01$	34.1 h
30.8 h	$z_0 = 0.82$ and $k = 0.008$	27.1 h

Table 2
Sensitivity analysis for the hydraulic residence time model

Parameters variation (%)	Model response variation (%)		
	Q (inflow)	z_0 (water level)	k (hydraulic conductivity)
−100	–	–	–
−75	−364	–	–
−50	−122	–	–
−25	−41	–	9
+25	25	−35	−5
+50	42	−68	−8
+75	–	−100	−10
−100	–	−132	−11

3.1.3. Sensitivity analysis

The most sensitive parameter is observed to be the inflow value (Table 2). This model therefore needs very precise measurements of inflow. Sensitivity to hydraulic conductivity is lower than inflow.

3.2. Influence of evapotranspiration

Evapotranspiration occurs in constructed wetlands but this phenomenon has not yet been greatly studied. A recent study showed that evapotranspiration in a natural reed bed (*Phragmites australis*) situated in a north German lake was between 800 and 1300 mm per year. Under certain conditions a reed canopy can reach a transpiration rate as high as 10 mm per day as mentioned by Herbst and Kappen (1999). Other studies show that in a lysimeter planted with *Typha latifolia*, for a period of 2 months over the summer season in eastern United Sates, evapotranspiration rates are commonly above 5 mm per day as studied by Pauliukonis and Schneider (2001).

3.2.1. Hypothesis

The evapotranspiration rate is equal on the entire filter surface; reaction volume and filter porosity are constant.

Focusing on a small part of the filter length dx:

entry + creation = exit + accumulation + disappear

$$Q = Q + \mathrm{d}Q + \varphi\,\mathrm{d}S$$

Table 3
Evapotranspiration estimated using a 1 m^2 pilot

Month (in year 2000)	ETP (mm)	Percentage of inflow estimated
May	165.0	17
June	378.2	40
July	127.5	13
August	281.5	30

$$0 = \mathrm{d}q + \varphi l\,\mathrm{d}x \Rightarrow \int_{q_0}^{q} \mathrm{d}q = -\varphi l \int_0^x \mathrm{d}x \Rightarrow Q_\mathrm{s} = Q_0 - \varphi l x \quad (8)$$

Hydraulic residence time in a small part of the filter:

$$\mathrm{d}\tau \approx \varepsilon \frac{hl\,\mathrm{d}x}{Q} \Rightarrow \tau = \int_0^L \varepsilon \frac{hl}{Q_0 - \varphi l x}\,\mathrm{d}x = \frac{hl\varepsilon}{-\varphi l L} \ln \left| Q_0 - \frac{\varphi l L}{Q_0} \right| \quad (9)$$

Finally,

$$\tau = \frac{\varepsilon h l L}{-\varphi l L} \ln\left(\frac{Q_\mathrm{s}}{Q_0}\right) = \frac{\varepsilon V}{Q_0 - Q_\mathrm{s}} \ln\left(\frac{Q_0}{Q_\mathrm{s}}\right) \quad (10)$$

where Q_0 and Q_s is, respectively, inflow and outflow rates in $m^3\,h^{-1}$.

Evapotranspiration was measured directly on pilot-scale during summer 2000. The set-up consisted of a tank (1.48 m long, 0.7 m wide and 0.55 m deep), filled with the same gravel used in the filter (6–20 mm) and planted with common reeds (*P. australis*). The tank was kept full of water to recreate the filter's hydraulic conditions (saturated flow), and the evapotranspiration was estimated by measuring the water level between each filling. During the month of June, temperatures averaged 30 °C and water loss by evapotranspiration represented 40% of inflow (Table 3).

4. Modeling

4.1. Normalized answer curve

During dry periods, December and July, the curve shows a significant dispersion. This is in contrast to humid periods, March 2001 and May 2000, where filter flow behavior approaches plug flow (Fig. 2). Using Eq. (4), normalized response curves have been determined. These curves were integrated to obtain the tracer ratio obtained at the outlet (percentage of injected mass). Despite using the same experimental protocol for all six experiments, response curves are different, and this is principally due to the weather conditions during experimentation.

Tracer conservation is confirmed in Table 4, the maximum tracer loss is 20%, and this can be attributed to biological assimilation, retention, or absorption.

4.2. Results of DPFM and STSM

Global evapotranspiration (including evaporation and transpiration from macrophytes) plays a major rule in the July experiments (Fig. 2 and Table 5). This phenomenon increases the HRT (up to 80 h), and improves the Péclet number in the DPFM ($Pe = 28$–30) and the number of CSTRs ($n = 14$) in the STSM. This seems to reduce dispersion. Assays carried out during periods of precipitation show the reduction of the observed HRT (34 and 28 h the two lowest values obtained) due to inflow increases (Fig. 2). Furthermore, with the same inflow, the two experiments have different hydraulic characteristics.

During March 2001, the Péclet number was equal to 22 (Table 5), which means that there is a greater dispersion than in May 2000, when its value was equal to 37. This difference can be attributed to plant presence in May, which enhances hydrodynamic and reduces dispersion. In December, plants were cut and activity was lower. The Péclet number and the number of CSTRs are very low compared to warmer seasons. This confirms the hypothesis that plant presence reduces dispersion and enhances plug flow. Most of the results in Table 4 indicate the presence of dead zones except for the two periods of heavy rain. Filter structural design can partly account for this: inflow arrives in the corner of the basin and outflow is at the opposite corner. This design is favorable to the development of preferential flow paths which also give rise to dead or stagnant zones. Obviously for high rainy period simulations, short cut appears. With in situ observations, we can give some responses elements to explain this phenomenon. For such periods, filter is saturated, and as percolation is very low, a free water surface level appears. In this water surface layer, hydraulic resistance is lower than in media layers and a short cut is creating.

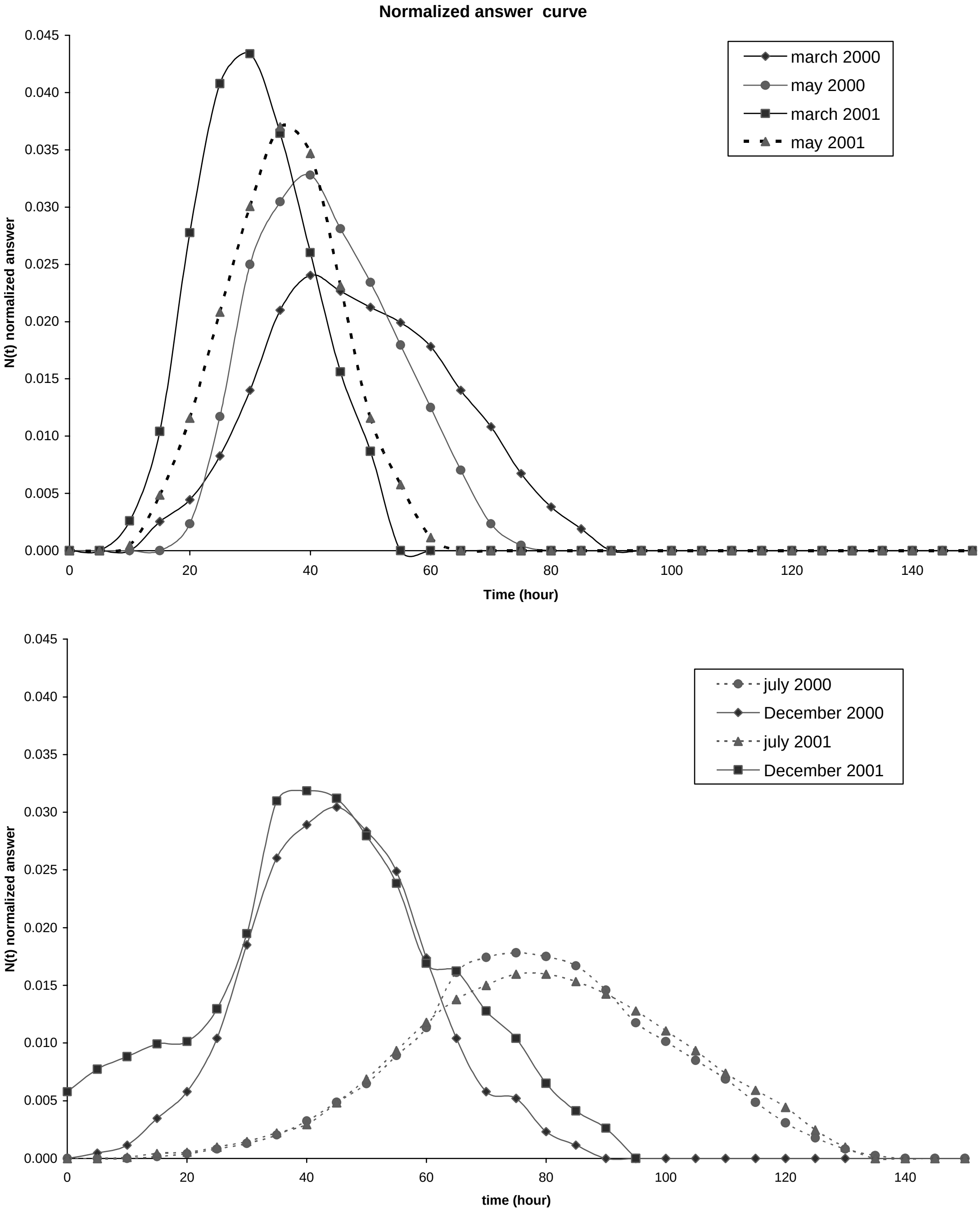

Fig. 2. Normalized response curves.

Table 4
Modeling results

	DPF model		STS model		Visim® simulation	
	Péclet number	τ	Number of CFSTR	τ	Entry gain	Exit time delay
March 2000	18	43	10	45	0	0
May 2000	37	34	16	37	1.5	0
July 2000	28	74	14	77	0.55	35
December 2000	12	45	7	50	0.8	4.5
March 2001	22	28	11	31	nd	nd
May 2001	13	36	9	40	1	0
July 2001	30	73	14	76	0.55	34
December 2001	13	46	7	50	0.7	6

DPF: dispersion plug flow; STS: stirred tanks in series; CFSTR: continuous flow steady-state reactor.

Table 5
Second stage hydrodynamic parameters

Date	Inflow ($m^3\,h^{-1}$)	Outflow ($m^3\,h^{-1}$)	Reaction volume (m^3)	τ (h)	t_s (h)	Short cut of inflow (%)	Dead volume (%)	Recovery of tracer (%)
March 2000	2.1	1.9	143.8	71.9	48	0	33	96
May 2000	4.0	4.1	143.8	35.5	43	17	0	82
July 2000	1.7	1.1	143.8	104.2	79	0	24	87
December 2000	2.0	2.0	143.8	71.8	45	0	37	78
March 2001	4.7	4.7	143.8	30.8	31	0	0	91
May 2001	2.1	1.9	143.8	72.6	36	0	51	93
July 2001	2.0	1.0	143.8	99.8	80	0	20	79
December 2001	1.8	1.8	143.8	79.8	44	0	45	92

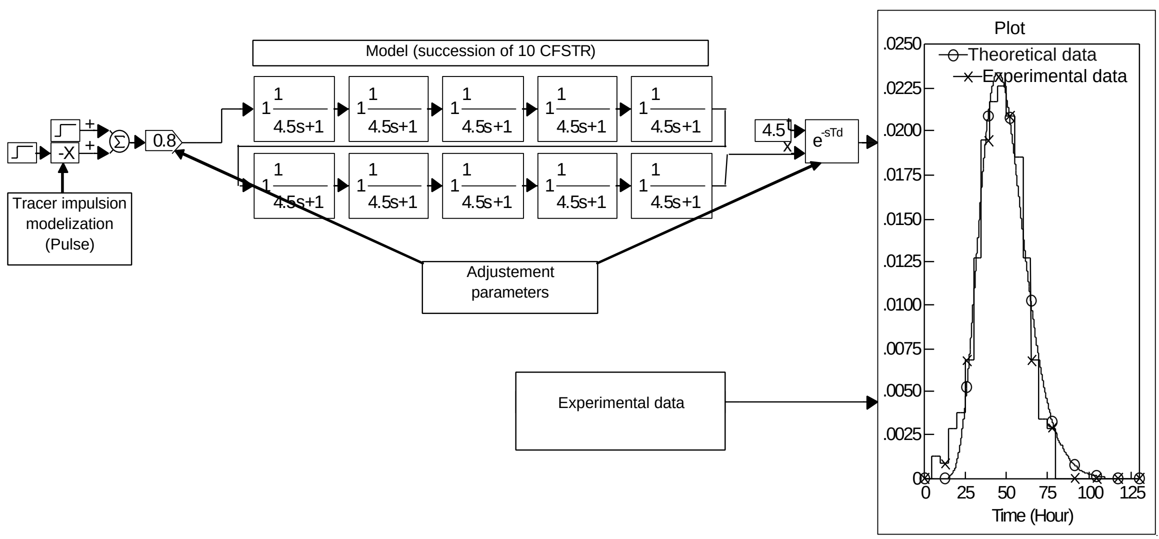

Fig. 3. Visim® simulation for second stage flow.

4.3. Proposed Visim® model

A conceptual model created by Visim® software (including Laplace transforms) fits all response curves by modifying two parameters. The model chosen is simple and is inspired from STSM simulation. It consists of 10 CSTR each with a HRT of 4.5 h (Fig. 3). At the model influent, a function is added to allow for the increase (during rainy periods) or decrease (during high evapotranspiration periods) of the amplitude of the curve. A time delay was added and this provides the real HRT. All the response curves have been fitted with this model except for March 2001. This model enables good fitting between observed and modeled data (Table 5). Moreover, this model confirms effects of evapotranspiration or precipitation on hydrodynamic in HSSF.

5. Simulation limits

5.1. Hydraulic perturbations due to injection

An injection of about 120 l takes less than 5 min to carry out. The inflow average is generally above 2.5 $m^3 h^{-1}$. During the experiment inflow increase from 1.44 $m^3 h^{-1}$ and even if this period is quite short it causes little perturbation in the filter.

5.2. High density of the tracer solution

The tracer solution is made with sodium chloride (66.7 g/l) in water. Final density of the injection tracer is heavier than the wastewater volume mass (1.034 kg/l). During injection, tracer solutions can sink to the bottom of the filter before being dispersed. Such a phenomenon can act as a source of error when determining hydraulic residence time distribution and general flow of the filter. Several experiments have been monitored to observe this. The principle was to take samples at different depths to measure conductivity during experiment. During low flow periods, the tracer arrives initially in the major zones (60 cm depth) before being detected on the surface, which confirms the preceding assumption. In the summer (especially during periods with flow is less than 2 $m^3 h^{-1}$) the tracer tends to sink to the bottom of the basin, the total dead volume is therefore over estimated. During medium flow period (for example, in winter with flow ranging from 2 to 3.5 $m^3 h^{-1}$), distribution of the tracer is good at all levels, and all along periods of hydraulic overload (more than 3.5 $m^3 h^{-1}$).

6. Conclusions

The presence of plants seems to improve flow by creating connection between the surface and rhizosphere. Plant growth may enable better contact between effluent and roots zone. Influence of abiotic factors like precipitation or snow melt have a direct influence on treatment performances and general flow paths. Evapotranspiration is more beneficial and seems to improve all performances. Finally, this study has confirmed the architectural design limits of horizontal flow. At the filter inlet, mixing zones and a wide centered effluent injection is recommended (in a filter more than 10 m wide) to prevent dead volumes from occurring.

Future studies will be based on vertical flow constructed wetlands behavior, the relationship between general hydraulic behavior and the type of catabolism generated in the filter biofilm.

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