Influence of the media granular size of small pilot subsurface flow wetlands on axial dispersion and the hydraulic behaviour.

Fonder N., Xanthoulis D.

Abstract

The objective of this paper is to evaluate using tracer tests, the role of the granular media size on the hydraulic behaviour of small -scale pilot horizontal subsurface flow (HSSF) gravel beds. The non-ideal flow was modelled by the tank-in-series model (TIS) using the moment analysis and Gamma distribution fitting using the Solver™ routine in Microsoft Excel™; the Plug Flow with Dispersion (PFD) model was also assessed. Tests were performed under a greenhouse in four identical pilot-scale gravel beds of 9:1:1 ratio, which received an equal, inflow of clear water. The influent flow rate was 40 L/day and the surface area of the pilot cells was 0.8 m². The pea gravel media used in the four beds were as follows: 3-5 mm, 6-8 mm, 8-10 mm and 10-12 mm. The tracer used was Potassium Bromide (KBr) with a concentration of 1 g Br^-/L, using a single-shot injection into the inlet distribution tubes. Tests were repeated three times, with identical materials and methods. Statistical differences were observed between replications. Water loss by evaporation of the unplanted gravel beds was of 11% for the smaller media size (3-5 mm) which is significantly different than the 4 to 5% obtained for the other media sizes. Tracer detention time, tracer peak time, volumetric and hydraulic efficiencies show all the same tendency which is a significant reduction with larger particles sizes. The two methods of calculation for the number *N*TIS by moment analysis and Gamma distribution fitting (using Solver™) are significantly different. The Gamma model increases the number of TIS with significantly higher values for smaller media sizes.

Fonder N., Xanthoulis D.
Dept. of Hydrology and Rural Hydraulics, Agricultural University. of Gembloux (FUSAG), Epuvaleau Non-profit Association, Passage des deportes, 2, B-5030 , Gembloux, Belgium (E-mail: fonder.n@fsagx.ac.be)

Keywords

Tracer test, Subsurface Flow gravel bed, media size, Gamma distribution

Theoretical Background

Flow in constructed wetland is non-ideal, and can be attributed to an array of factors, including vertical stratification, preferential flow, dispersion and degree of hydraulic loading. Precipitation and evapotranspiration (ET) impacts flow patterns and water balances. Constructed wetlands (CW) that have been tracer tested exhibit exit curves that cannot be represented by either of the two ideal reactor models: the plug flow (PF) reactor and continuously-stirred tank reactor (CSTR) (Wallace and Knight, 2006). Kadlec, 1999 demonstrated with previous well-documented works that the flow patterns through treatment wetland systems are non-ideal and do not conform to either the PF or CSTR ideals. Rather, results fall somewhere in-between the two extremes, with HSSF systems typically behaving as a mean value of 11 TIS (Kadlec and Wallace, 2008).

The nominal detention time (τ_n) sometimes called theoretical mean residence time is defined as follows (Eq.1). For a FWS wetland, the nominal wetland water volume is defined as the volume enclosed by the upper water surface and the bottom and sides of the impoundment. For a SSF wetland, it is that enclosed volume multiplied by the porosity of the clean (unclogged) bed media.

$$\tau_n = \frac{V_n}{Q} = \frac{\varepsilon(LWh)_n}{Q}$$

(Eq.1), where: τ_n = nominal hydraulic detention time, days; L = wetland length, m;

W = wetland width, m; h = water depth, m; LWh_n = nominal wetland volume, m^3; Q = flow rate, m^3/d; ε = bed media porosity,

unitless.Dimensionless time, θ, can be used instead of the nominal hydraulic detention time, τ_n, when comparing tracer response curves.

Nominal detention time is not necessary indicative of the actual detention time because it assumes that the entire volume of water in the wetland is involved in the flow. In the case of preferential flow pathways and death zones, this assumption may lead to an erroneous estimation of the actual detention time (Kadlec and Knight, 1996).

Residence times in reactors are studied by injecting a tracer according to a specific program, and by recording tracer concentration at the outlet. Recorded data provide a residence time distribution

(RTD. (Edeline, 1998). The RTD represents the time various fractions of fluid (water in the case of wetland) spent in the reactor; hence, it is the contact time distribution for the system (Kadlec and Knight, 1996).

The RTD is a probability function for residence times in the wetland. This time function is characterized by several F(t)Δt fractions which stays in the wetland for a length of time equal to t + Δt. For an impulse of tracer (injection: t=0), this density function is (Kadlec and Knight, 1996):

$$F(t) = \frac{QC(t)}{\int_0^\infty QC(t)dt} \quad \text{(Eq.2)}$$

where, F = RTD function [d-1]; C(t) = exit tracer concentration [g/m³]; t = time [d]

The RTD is a distribution and it is possible to calculate the different central moments which define the key parameters that are actual detention time and dispersion of a pulse due to mixing (Edeline, 1998; Kadlec and Knight, 1996). The *zeroth moment* corresponds to the sum of all F(t)Δt fractions which, by definition, is equal to unity.

The *first moment* represents the average time spent by a particle in the wetland which is nothing else than the actual residence time (τ, in days). This value defines the centroid of the exit tracer concentration distribution:

$$M_1 = \int_0^\infty tF(t)dt = \tau \quad \text{(Eq.3)}$$

The *second moment* corresponds to σ² (in days²) which is the variance of the distribution and is calculated from the actual residence time. It characterizes the spread of the tracer response curve about the mean of the distribution. Thus, t² must be replaced by (t-τ)² to characterize the dispersion of the tracer response curve about the mean of the distribution (Edeline, 1998; Kadlec and Knight, 1996):

$$M_2 = \int_0^\infty (t-\tau)^2 F(t)dt = \sigma^2 \quad \text{(Eq.4)}$$

This measure of dispersion may be rendered dimensionless by dividing by τ² (Kadlec and Knight, 1996). The variance of the RTD is created by mixing of water during passage, or equivalently by a distribution of velocities of passage. This can be lateral, longitudinal or vertical mixing. The variance-to-square-mean ratio is called the dimensionless variance (σ_θ^2) of the tracer pulse. This new parameter (σ_θ^2) has an important relationship with the number (*N*) of equivalent tanks in series in a TIS model and with the Peclet number (*Pe*) of a plug flow with dispersion (PFD) model (see Eq 6).

The volumetric efficiency e_v, which evaluates the effective volume utilisation of the tracer response curve, may be defined as the tracer detention time (τ, in days) divided by nominal detention time (τ_n, in days).

Tank-in-series Model (TIS): The series of completely stirred reactor (tank-in-series, TIS) is used to model the flow regime that exists between the hydraulic flow patterns of CST and PF reactors. The TIS model is defined as a number (*N*) of equally-sized, perfectly mixed reactors (R_1, R_2, .. R_N) arranged in series. The number of tanks can be any integral number between 1 and ∞. The response of this series of tanks is calculated from the dynamic tracer mass balance equations for the reactors. Levenspiel (1972) demonstrates that the RTD curve for the TIS model can be represented by:

$$C(t) = \frac{N^N t^{N-1}}{\tau^N (N-1)!} \exp\left[\frac{-Nt}{\tau}\right] \quad \text{(Eq.5)}$$

For the TIS model, it is possible to define simple relations between the parameters of the distribution and the moments. For instance, the TIS conceptual model (which produces a gamma distribution) has a dimensionless variance given by:

$$\sigma_\theta^2 = \frac{1}{N} \quad \text{(Eq.6)}$$

A series composed of 1 reactor (*N*=1) corresponds to the ideal flow of a CSTR. While, a series composed of an infinity of reactors (*N*=∞) corresponds to the PF model. When *N* increases, the distribution becomes narrower and the hydraulic behaviour of a system tends toward the PF reactor.

Gamma distribution fitting : A serious failure of the moment methods of parameter estimation is that it emphasizes the tail of the response curve much more than the central portion, including the peak area. A more recent procedure is to utilize a robust parameter determination routine, with a search to minimize the sum of the squared errors between the selected detention time distribution function (TIS in this case) and the data (Kadlec and Wallace, 2008). The SOLVER™ application from Microsoft Excel™ can be used to simultaneously solve the variables *N* and τ to minimize the differences between the observed TIS detention time distribution and the predicted one.

Plug Flow with Dispersion model : Another model uses a dispersion process superimposed on a plug flow model (PFD). Mixing is presumed to follow a convective diffusion equation. The dispersion coefficient describes eddy transport of water elements both upstream and downstream. If the dispersion is infinite, the system will behave as a CSTR. While if the dispersion equals to zero, then the system will behave as an ideal PFR. Different PF models with dispersion can be obtained by varying the boundary conditions for solving the advection–diffusion equation of the tracer in one dimension (Levenspiel, 1999). Horizontal SSF systems have a significant degree of deviation from the PF model (*D*> 0.01) as the tracer response is clearly asymmetrical (Chazarenc *et al*., 2003). Within this context the appropriate boundary conditions are those of closed–closed vessels and there are no analytical solutions. In this case the curve can be constructed by numerical methods. For open–open boundary conditions there is an analytical solution given by Garcia *et al* (2004) :

$$C(t) = \frac{1}{2\sqrt{\theta D}} \exp\left[-\frac{(1-\theta^2)}{4\theta D} \right] \qquad \text{(Eq.7)}$$

where the dispersion number is estimated by the equation: $\sigma_\theta^2 = 2D + 8D^2$

The PFD model may be characterized by one dimensionless number which is called the Peclet number (*Pe*) and which corresponds to the inverse of a dimensionless dispersion coefficient (*D*):

$$Pe = \frac{vL}{D_L} = \frac{1}{D} \qquad \text{(Eq.8)}$$

Where v = interstitial water velocity [m]; L = length [m]; D_L = axial dispersion [m²/d]

When analysing RTDs, the dimensionless variance allows a comparison between the PFD and TIS models. A simple solution approach may also be used to correlate *N* and *Pe* (Thonart, 2003):

$$Pe = 2.(N-1) \text{ for } Pe \le 30 \qquad \text{(Eq.10)}$$

$$Pe = 2N \text{ for } Pe > 30 \qquad \text{(Eq.11)}$$

Materials and Methods

The four pilot wetland cells, built in March 2006, are a trench installed under a greenhouse in Gembloux, Belgium. The trenches have a metal frame with glass sides and bottom (previously used for irrigation in open channel flow tests). The dimensions are: L: 2,8 m, W: 0,3 m, D:0,3 m, with a Length to Width ratio of 9:1. They were initially covered with a plastic liner, and then filled with pea- and non-limestone gravels. The frames are inclined to create a 1% bottom slope. The height of the adjustable outlet regulates the water level to 1cm below the surface of the gravel. Inlets and outlets have distribution and collection zones of 15 cm with larger gravels (12-16mm). Inside the bed the gravel diameter has been separated into (3,5-5) mm (5-8 mm), (8-10 mm) and (10-12,5 mm) – using ASTM (American Society for Testing and Materials Standards) screens

Two head tanks of 100 L each, load the pilots with drinking water from the public network through a Watson-Marlow 205S peristaltic pump, equipped with 8 marprene manifold tubing of 2,79 mm in diameter. Each tube delivers a flow rate of 20 L/d at 57 rpm. A pair of tubes is used for a flow rate of 40 L/d per pilot.

Potassium bromide was used as the tracer. One litre is injected through the tubes of the peristaltic pump at the concentration of 1 g Br^-/L. Single-shot injections lasted 35 min and may be considered as nearly instantaneous impulses as they lasted less than 2% of the nominal residence time. Background conductivity was assessed during two days prior to the test start.

Samples were taken manually every hour. Outflow was collected in buckets at the bottom end of the pilots. The water volume was measured and a sample was taken for analyses in laboratory. The measuring instrument was a WTW Br 800 bromide combination electrode connected to a WTW pH/Ion 340i ion meter. Effluent samples were analyzed up to five times the nominal hydraulic retention time, and tracer experiments were replicated three times.

Results and Discussion

Figure 1 and Table 1 presents the major results of the three replicated tracer tests.

As the first test was performed without measures of the outflow, the tracer mass recovery for Test 1 was estimated taking into account the evaporation rate measured by the two next tests. The first test was done on late summer, the second at fall and the third one during the summer.

A significant difference in evaporation rate was observed within the four media sizes during all the tests, with the largest difference observed during the third test (summer): the smallest media size of 3-5 mm had a significantly different rate of water loss on a daily basis than the three other media sizes. For the smallest media size, the mean value was 11% of water loss/ day, whereas it was 4 to 5 % for the larger media sizes.

The mean value tracer mass recoveries of tests two and three (including all media sizes) was 96%, which is considered an excellent rate of tracer recovery. Test one was excluded (as the mass of the tracer does not result from direct measurements). Statistics attest that the set of data (concentration of tracer versus time) were homogenous and acceptable for statistical analysis for all three tests and media sizes. Statistics are normal and performed with t-distribution tests with confidence intervals of 0.05.

The first surprising result is coming from the differences observed within replications on the same media sizes. The tracer detention time varies significantly within replications; from 2.0 to 2.5 days for media size 3-5 mm; from 2.0 to 2.6 days for media size 6-8 mm; from 1.7 to 2.4 days for media size 8-10 mm and from 1.5 to 2.4 days for the largest media size of 10-12 mm. It can be noted that the relative spread of the tracer detention time increases as the media size increases.

As no reference of replicated tracer tests under the same experimental conditions has been found in literature to explain the phenomena, the following hypothesis were speculated : (i) tests were not performed during the same season of the year, which has induced variable evaporation of the gravel beds; (ii) repairs of leaks has been done to the beds in-between tests which necessitated removal and replacement of the gravels, this could have induced changes in preferential flow paths for the different tests, and (iii) the pilots were not set under the exact same flush conditions before starting the test. For example, the first experiment did not adequately flush the gravel beds before starting the test, which is demonstrated by a systematically lower volumetric efficiency.

However, the mean values of tracer detention time are not significantly different, even if τ decreases from 2.3 to 2.1 with the increase of media size from 3 to 12 mm.

The volumetric efficiency reflects ineffective volume within a wetland, compared to presumed nominal conditions. The reported mean value for porosity of a clean sand or gravel media ranges from 0.30 to 0.45 (Kadlec, Wallace, 2008). The observed porosity of the tested pilots ranges from 0.35 to 0.39. The mean value of volume efficiencies of HSSF is 83% (Chazarenc et al, 2003; Garcia, 200'; Bavor et al, 1988). Detailed data of tracer studies in Kadlec and Wallace, 2008 point out that non-planted HSSF, or gravel beds, often present a volumetric efficiency higher than 100%. The current study observed the same phenomena, with volumetric efficiencies ranking from 109 to 136 %. No significant differences are observed according the calculation methods, but a significant difference is observed for the media sizes. The volumetric efficiency decreases with the increase of media size. The mean value obtained by Gamma distribution fitting is 137% for the smallest media size of 3-5 mm; 134% for media size 6-8mm; 123 % for media size 8-10 mm and 110 % for the largest media size of 10-12 mm.

The tracer peak time is also varying significantly within replicated tests and between mean values of media sizes. In accordance with the tracer detention time and volumetric efficiency previously discussed, the tracer peak time is smaller for larger media size and ranged from 2.2 for media size 3-5mm down to 1.8 for media size 10-12 mm.

The hydraulic efficiency λ presents the ratio of tracer peak time divided by nominal detention time and provides the same information as volumetric efficiency. Garcia *et al* (2004) report that hydraulic efficiency can be categorised as "good hydraulic efficiency" when λ is > 0.75, which is the case for the tests reported in this paper. Thus, the pilots can be considered as having a good hydraulic behaviour. According to the same authors, the good hydraulic efficiency is attained at the same time as the normalised variance and the dispersion number are approximately lower than 0.15 and 0.08 respectively, which is also the case of data sets reported in this paper.

The second significant effect resulted from the analysis methods used to calculate the number of tanks-in-series (*N*).

Figure 1 illustrates the differences observed within replications, but also the differences between the media sizes and the models applied. Kadlec and Wallace (2008) refers to a mean value *N* of 11 TIS for HSSF systems (mainly assessed by moment analysis). Figure 1 shows that the tail portions of the curves are taken too much into account compared to the central portions and peak areas when the moment method is used. This leads to bell-shaped curves that are much too flat (grey doted lines). In order to reduce this effect, data taken into account for these calculations considers that after 5 times the nominal hydraulic retention time, the tail curves are forced back to background concentration for the tracer.

The gamma distribution fitting represented a significant improvement over moment analysis, as explained by Kadlec and Wallace (2008). The SOLVER™ application allows the modeller to simultaneously solve for the variables *N* and τ to minimize the differences between the observed RTD and the predicted RTD. The graphs show that Gamma distribution model, as fitted according to the Sum of Squared Errors (SSQE), fits the peak area of the response whereas moment calculation better fits the tail.

The number *N* TIS is significantly increased in comparison to moment analysis and presents a significant higher *N* for the lowest media size of 3-5 mm. It can be observed that *N*TIS resulting from the Gamma distribution model almost multiplied by 4 the *N*TIS from moment analysis for the lowest particle size (3-5 mm) with *N*TIS values of 9.9 and 35 for moment and Gamma model results. This order of magnitude is by 3 for the granulometry of 6-8 mm (with 7.4 *N*TIS moment method and 23.8 *N*TIS Gamma model). It is multiplied by 2 for the two last media sizes of 8-10 mm and 10-12 mm (with 11.5 *N*TIS moment and 22 *N*TIS Gamma fit, and 10.2 *N*TIS moment and 19 *N*TIS Gamma fit, respectively). The higher *N* obtained with lower granulometry attests that with smaller media sizes, hydraulic behaviour approaches the PF model.

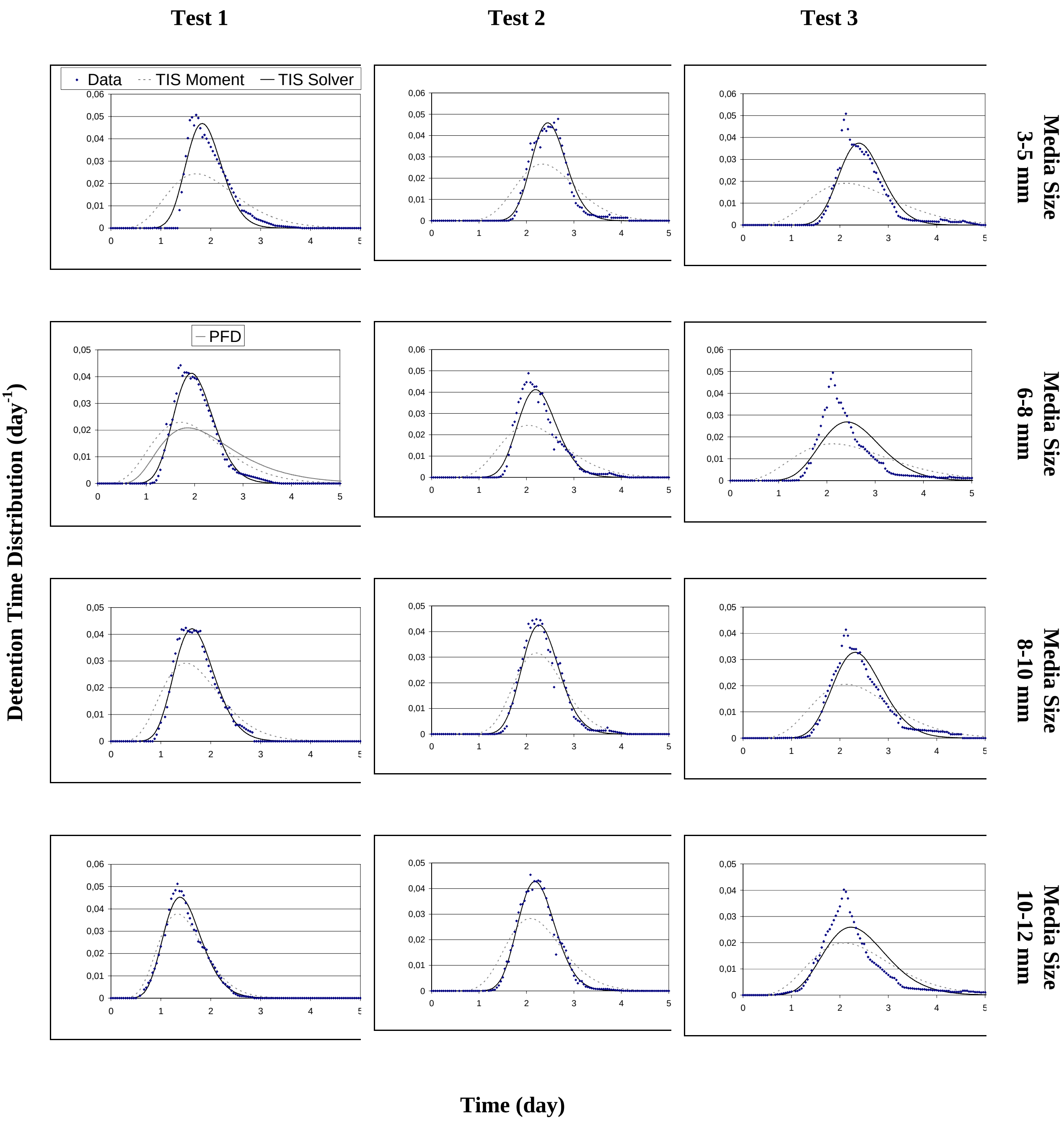
The PFD model was also tested. As the moment analysis was used as part of the PFD calculation method, the poorness of fit is relatively the same as the moment-based TIS model. Peclet numbers (*Pe*) and Dispersion (*D*) numbers are provided for comparison. The Dispersion number is almost constant at 0.05 to 0.07. High variations are observed with the Peclet number within replications.

Table 1 : Results of major parameters for the four media sizes and three replication tests.

Media Size / Tests Parameters	Nom.	Form.	Unit	3-5 mm				6-8 mm				8-10 mm				10-12 mm			
				Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean	Test 1	Test 2	Test 3	Mean
Length	L	Measure	m		2.5				2.5				2.5				2.5		
Width	W	Measure	m		0.28				0.28				0.28				0.28		
Depth	D	Measure	m		0.28				0.28				0.28				0.28		
Volume	V	L*W*D	L		196				196				196				196		
Porosity	ε	Measure	-		0.35				0.36				0.38				0.39		
Nominal Volume	V_n	V*ε	L		68.60				70.56				74.48				76.44		
Inflow rate	Q	Measure	L/day	40	41.34	40.62	**40.65**	40	41.34	40.66	**40.67**	40	42.82	40.68	**41.17**	40	41.76	40.32	**40.69**
DATA																			
Nominal Det. Time	τ_n	V_n/Q	day	1.7	1.7	1.7	**1.7**	1.8	1.7	1.7	**1.7**	1.9	1.7	1.8	**1.8**	1.9	1.8	1.9	**1.9**
Tracer Mass Rec.			%	115	94	99	**103**	115	94	95	**101**	102	95	101	**99**	92	92	96	**93**
Variance	σ^2	2nd mom.	day²	0.16	0.15	0.28	**0.20**	0.18	0.18	0.86	**0.41**	0.15	0.16	0.33	**0.21**	0.14	0.16	0.90	**0.40**
Dim.-less Variance	σ_Θ^2	σ^2/τ^2		0.042	0.025	0.046	**0.038**	0.043	0.036	0.130	**0.070**	0.051	0.030	0.056	**0.046**	0.065	0.031	0.154	**0.083**
MOMENT ANALYSIS																			
Tracer Det.Time	τ	1st mom.	day	2.0	2.5	2.5	**2.3**	2.0	2.3	2.6	**2.3**	1.7	2.3	2.4	**2.2**	1.5	2.3	2.4	**2.1**
Tracer peak Time	τ_p		day	1.7	2.6	2.1	**2.2**	1.7	2.0	2.1	**2.0**	1.5	2.2	2.1	**1.9**	1.3	2.1	2.1	**1.8**
Volum. efficiency	e_V	τ/τ_n	%	115	151	147	**138**	115	133	148	**132**	92	134	133	**120**	78	123	127	**109**
Hydraulic efficiency	λ	τ_p/τ_n	-	1.00	1.58	1.26	**1.28**	0.97	1.20	1.22	**1.13**	0.81	1.27	1.16	**1.08**	0.70	1.14	1.10	**0.98**
Nr of Tank in Series	N	$1/\sigma_\Theta^2$	-	7.2	15.1	7.3	**9.9**	6.5	10.1	5.7	**7.4**	7.8	18.8	8.0	**11.5**	9.7	13.7	7.3	**10.2**
SOLVER™ fit using Gamma distribution																			
Tracer Det.Time	τ	Solver™	day	1.9	2.5	2.5	**2.3**	2.0	2.5	2.6	**2.4**	2.0	2.3	2.4	**2.3**	1.5	2.3	2.4	**2.1**
Volum. Efficiency	e_V	τ/τ_n	%	111	151	147	**136**	115	146	148	**136**	108	134	133	**125**	78	127	127	**111**
Number of TIS	N	Solver™		27.7	47.1	30.2	**35.0**	24.2	30.7	16.4	**23.8**	17.8	34.9	22.0	**24.9**	14.6	32.6	13.2	**20.1**

Sum of Squ. Errors	SSQE	Solver™		0.0014	0.0006	0.0024	**0.0015**	0.0005	0.0013	0.0047	**0.0022**	0.0003	0.0005	0.0008	**0.0005**	0.0027	0.0027	0.0024	**0.0026**
PLUG FLOW with Dispersion																			
Peclet Number	P_e	2N-1	-	13	29	13	**18**	12	19	11	**14**	15	37	15	**22**	18	26	14	**19**
Dispersion number	D	$1/P_e$	-	0.07	0.03	0.08	**0.06**	0.08	0.05	0.10	**0.0767**	0.07	0.03	0.07	**0.0567**	0.05	0.04	0.07	**0.0547**

Figure 1 : Graphs of tested models, according to media sizes and replications.
Graphs present the Detention Time Distribution function (f(t) in day^{-1}), versus Time (day) with different TIS fits. Plot squares are the data of the experimental function; the doted grey line is the DTD function obtained by TIS moment analysis; the black line is the DTD function obtained by gamma distribution fitting and the PFD curve is only shown by the grey line for the test 1, media size of 6-8mm.



Conclusions

The tracer tests were replicated three times on four identical non-vegetated pilot gravel beds to assess the influence of media size on hydraulic behaviour. Replications have shown significant differences about the tracer detention time; and, the differences increased with the size of the particles tested. Tracer detention time, tracer peak time, volumetric and

hydraulic efficiencies show all the same tendency which is to decrease significantly with larger particles sizes. The two methods of calculation for the number *N*TIS by moment analysis and Gamma distribution fitting are significantly different. The Gamma model (fitted using the Solver™ routine in Microsoft Excel™) significantly increases the number of TIS with significantly higher values with the decrease for the media size. These experiments report a better hydraulic behaviour and efficiency for a lower granulometry of 3-5 mm compared to 10-12 mm with other media sizes showing an intermediate range of behaviour.

Future planned works

In order to check the real impact of evaporation, future results will be analyzed based on tracer mass and no longer on concentration.

Gravel beds have been planted with *Phragmites* and future experiments will be repeated with the same methods in order to assess the impact of plants on HSSF hydraulics.

A similar tracer test will be performed on an operating site and to compare against pilots in a greenhouse under maximum controlled conditions.

References

Bavor H.J., Roser D., McKersie S.A., Breen P.F. (1988) *Treatment of secondary effluent.*, Report to Sydney Water Board, Sydney, NSW, Australia.

Chazarenc, F., Merlin, G., Gonthier, Y., 2003. *Hydrodynamics of horizontal subsurface flow constructed wetlands*. Ecological. Engineering. 20, 165–173.

Garcia J., Chiva J., Aguirre P., Alavarez E., Sierra J.P. And Mujeriego R. 2004. *Hydraulic behaviour of horizontal subsurface flow constructed wetlands with different aspect ratio and granular medium size*. Ecological Engineering 23, pp177-187.

Edeline F. (1998). *L'épuration physico-chimique des eaux : théorie et technologie. 4^{ième} édition*. Liège : CEBEDOC, 288p.

Kadlec H.R., Knight R.L. 1996. *Treatment Wetlands*. Lewis

Publishers. ISBN 0-87371-930-1. 893p.
Kadlec H.R. 1999. *The inadequacy of first-order treatment wetland models*. Ecological Engineering 15, pp 105-119.

Kadlec H.R, Wallace S.D. 2008. *Treatment wetlands 2nd Edition*. CRC Press. Boca Raton. Florida. 1016p.
Levenspiel O., Turner J.C.R. (1972) The interpremation of residence time experiments. *Chemical Engineering Science* **25** 1605-1609.
Levenspiel, O., 1999. *Chemical Reaction Engineering*. Wiley, New York, NY, 668 pp.
Thonart Ph. (2003). Liquid-gaz transfers in reactors. Curriculum delivered for Master in sanitation Engineering. Gembloux Agriculturl University Press. 163p.
Wallace S.D, Knight R.L. (2006). *Small Scale Constructed Wetland Treatment systems, feasibility, design criteria, and O&M requirements*. Water Environment Research Foundation 2006.