Hydraulic behaviour and removal efficiencies of two H-SSF constructed wetlands for wastewater reuse with different operational life

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ABSTRACT

This work focuses on the performance evaluation of two full-scale horizontal suburface flow constructed wetlands (H-SSF CWs) working in parallel, which have an almost equal surface area (about 2,000 m^2) but with different operational lives: 8 and 3 years. Both H-SSF CWs, located in Southern Italy (Sicily), are used for tertiary treatment of the effluent of a conventional wastewater treatment plant. This study evaluates and compares H-SSF CW efficiency both in terms of water quality improvement (removal percentage) and achievement of Italian wastewater discharge and irrigation reuse limits. The mean removal percentage, for the overall operational life, of TSS, COD and BOD (80%, 63%, 58% obtained for H-SSF1 and 67%, 38%, 41% for H-SSF2), confirm the high reliability of CWs for wastewater treatment. However, despite the satisfactory removal of microbial indicators (the mean *E. coli* removal was up to 2.5 log unit for both beds), CWs didn't achieve the Italian limits for wastewater reuse. Information on hydraulic properties of the CWs were extracted from breakthrough curves of a non-reactive tracer (NaCl). By comparing the nominal (τ_n) and actual residence time (τ), hydraulic behaviour was revealed.

Key words | constructed wetlands, horizontal subsurface flow, hydraulic characteristics, salt tracer test

INTRODUCTION

Constructed wetlands (CWs), widely applied for the treatment of wastewater produced by residential settlements and industrial activities (Vymazal 2009), are now standing as potential alternatives or supplementary systems for the treatment of wastewater, especially for small and medium communities where low maintenance and operation needs are essential (Puigagut *et al.* 2007). The removal efficiency of soluble pollutants in CWs is primarily related to the extent of contact between wastewaters and the their reactive surface/volume. Residence time distribution function (RTD) is a characteristic of wetland hydraulic properties as it describes a whole spectrum of time lengths that wastewater spends in the wetland (Małoszewski *et al.* 2006). If a tracer pulse is added to an ideal wetland inlet, all of the tracer will exit at the same time, the residence time. In real wetlands, flow is non-ideal. Non-ideal flow comprises different flow velocities and mechanisms of diffusion, causing a distribution of residence times (Levenspiel 1972). This paper describes the removal performance of CW technologies designed to treat the secondary effluent of municipal wastewater and the methodology followed to acquire and analyse constructed wetland hydraulic behaviour by performing several tracer tests using sodium chloride as tracer. Water quality analyses, flow measurements and tracer tests were carried out in two horizontal subsurface-flow constructed wetlands (H-SSF1 and H-SSF2), one in operation since 2001 and the other since 2006. These wetlands, located in Southern Italy (Sicily), function as the tertiary treatment of the effluent of a conventional treatment plant, work in parallel and have an almost equal surface area (about 2,000 m^2).

METHODS

Description of the wetland system

The research was carried out in a full-scale constructed wetland treatment plant located in San Michele di Ganzaria (Eastern Sicily), a rural community of about 5,000 inhabitants, 90 km South-West of Catania. The experimental plant consists of two horizontal subsurface flow (H-SSF)

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constructed wetlands (CWs) working in parallel: H-SSF1 in operation since 2001 and H-SSF2 since 2006 (Cirelli *et al.* 2007). These CWs are part of an almost completed wastewater reuse project, which included four H-SSF reed beds, working in parallel, followed by three batch stabilization reservoirs also working in parallel. In expectation of the wastewater reuse project being completed, only part of the secondary effluent of a conventional treatment plant, about 4 L/s, is diverted and treated by H-SSF1 and H-SSF2, which have a surface area of about 1,950 m^2 (25×78 m) and 2,080 m^2 (33×63 m) and a design flow rate of about 455 m^3/day. The end section of the H-SSF2 reed bed (i.e. the last 3 m of the bed) functions as a free water surface with an area of about 190 m^2. The filter beds are 0.6 m deep and filled with 8–10 mm gravel. Calcareous gravel (0.38 porosity) was used in the H-SSF1 and volcanic gravel (0.40 porosity) in H-SSF2. Nine piezometers were positioned along each bed to monitor wastewater quality. Both wetlands were planted with *Phragmites australis* at a density of four rhizomes/m^2.

Water quality analyses

At the inlet and outlet of H-SSF1 (from 2001) and H-SSF2 (from 2007), the following physicochemical parameters were evaluated to December 2008 (about twice a month for H-SFF1 and weekly for H-SSF2) according to APHA, AWWA, WEF (1998) methods: total suspended solids (TSS) at 105 °C, BOD_5, COD, total phosphorus (TP) and total nitrogen (TN). Microbiological parameters, such as *E. coli* and *Salmonella* were also evaluated. *E. coli* was counted according to APHA (1998) methods and *Salmonella* was examined according to Barbagallo *et al.* (2003). Wastewater sampling has been done in different days for the two beds. For the physicochemical parameters, the evaluation of treatment performance was based on the removal efficiency percentage. For microbiological parameters, log reductions were calculated. Furthermore, to characterize wetland treatment performance, a graphical display method was adopted. In particular, the input–output concentration (C_i–C_o) graph was used in this research because it extends the idea of treatment ability to a group of wetlands (Kadlec 2009). The multiple data sets are also represented by a linear trend and linear regression coefficient (R^2).

Tracer tests

The salt tracer used to determine the actual residence time (τ) of the two full-scale constructed wetlands was sodium chloride (NaCl) as reported in other studies (e.g. Chazarenc *et al.* 2003; Suliman *et al.* 2006). In particular, three tests were performed at different flow rates in H-SSF1 and two tests in H-SSF2. The salt tracer was injected with a pump after dissolution of 150 kg NaCl in 450 L of wastewater. The injection times, which last about 10 minutes, may be considered practically instantaneous compared to the residence time of several days. The electrical conductivity (EC) was measured and recorded automatically by a probe with a data logger (Delta OHM – HD 2106.2) at the outlet of the bed. The EC values obtained in mS/cm were then converted to chloride concentrations by using calibration curves as suggested by Ronkanen & Kløve (2007). A linear relationship ($R^2 = 0.99$) was found between salt concentration and EC. Before fitting the curve, the initial electrical conductivity was subtracted at each measuring point. A flow meter was installed in the inlet pipe. The flow rate was calculated as the ratio of total volume to the duration of the test and it was assumed constant. From the experimental RTD of each tracer test, actual residence times (τ) and variance (σ^2), were calculated according to Levenspiel (1972). The tail of the RTD curve was extrapolated assuming exponential decay, as suggested by Kadlec & Wallace (2009), since at the end of the tests EC was higher than the background value. In order to characterize the hydraulic performance of a wetland, the hydraulic efficiency (e_v) was calculated as the ratio of the actual (τ) and theoretical retention time (τ_n), this latter calculated on a plug flow (PF) assumption as reported in IWA (2000). By comparing τ and τ_n, hydraulic behaviour was revealed (Kadlec & Wallace 2009):

- $\tau << \tau_n$: fluid follows a preferential path. This is an indicator of short-circuiting;
- $\tau >> \tau_n$: fluid stagnates in the reactor and does not participate in reactions. This phenomenon is due to the presence of dead or stagnant zones.

Finally, the normalized variance of the tracer response curve was calculated to estimate the dispersion number (D), used to characterize the degree of the non-ideal flow conditions of the PF model. The equation for D estimation, by trial and error, was (Levenspiel 1972):

$$\sigma_\theta^2 = 2D - 2D^2\left[1 - \exp\left(-\frac{1}{D}\right)\right] \tag{1}$$

RESULTS AND DISCUSSION

BOD_5 and COD

The inlet and outlet concentrations of BOD_5 and COD for the entire period of record of each wetland are plotted in Figure 1. Each point represents single daily sampling.

The H-SSF2 data clouds are mostly over the H-SSF1 data as the central tendency lines of the H-SSF1 are always lower than those of the H-SSF2. This highlights a generally better performance for H-SSF1 in BOD_5 and COD. In fact, the mean organic matter removal, for the overall operation period, was about 60% in H-SSF1 and 40% in H-SSF2 (Tables 1 and 2). This could be explained by alga growth and decomposition occurring in the free water surface area at the end of the H-SSF2, which increase organic concentration in the effluent. Another possible explanation is that starting from the start-up of 2007, the mean influent concentrations detected were generally lower than in previous years, giving overall lower removal efficiency for the two beds. A poor relationship between inflow and outflow BOD_5 concentrations, especially for H-SSF1 ($R^2 = 0.16$), was detected. Vymazal (1999) and Brix (1998) reported a similar poor relationship between inflow and outflow BOD_5 concentrations for vegetated H-SSF CWs located in the Czech Republic ($R^2 = 0.32$) and Denmark ($R^2 = 0.08$). This means, in general, that the effluent concentration is around the background concentration and then the scattering is around it.

TSS and *E. coli*

Figure 2 presents input TSS versus output TSS concentration for both CWs and *E. coli* reduction through reed beds. There is no great difference in the performances for either parameter as the lack of separation of the data clouds show. The central tendency lines are essentially coincidental. Except for a few deviations, both systems produce a final effluent with TSS concentration less than 20 mg/L regardless of input level (up to 120 mg/L for H-SSF1 and 113 mg/L for H-SSF2). This performance was very stable over their entire operational periods (8 years for H-SSF1 and 3 for H-SSF2) and does not show any decrease. The mean TSS removal in H-SSF2 (67% ±20) was lower than that obtained in H-SSF1, but it is noted that the mean TSS concentration detected at the H-SSF2 influent was lower (Tables 1 and 2). There is very little or no difference in the results for H-SSF1 and H-SSF2 for *E. coli* reduction. Similar *E. coli* treatment trends for both wetlands were observed with a mean reduction more than 2.5 log units. In particular, *E. coli*, were reduced to a mean value of 2.7 Ulog (±0.8) (incoming range 4.5–5.3 Ulog) in the effluent of H-SSF1 and a mean value of 2.6 Ulog (±0.8) in H-SSF2 (incoming range 5.3–5.4 Ulog). There is little relationship between input and output *E. coli* concentration in either CW ($R^2 \leq 4$).

TN and TP

Figure 3 presents nitrogen and phosphorus input versus output data for the studied systems. For TP, there is little or no difference between the two beds. The shallower slope of the H-SSF2 regression line highlights the ability of the bed to maintain TN effluent characteristics unchanged despite the variation inlet concentration. This could demonstrate the ability of algae and microphytes to remove TN directly on the open water surface at the end of H-SSF2.

Despite plant uptake of nitrogen and phosphorus generally being non-significant for their removal, a positive effect of the plants was observed. In the first year of H-SSF2 operation, its average removal efficiency of nutrient (60 to 46% for TN and TP) was higher than that in the H-SSF1 bed in 2001 (29 to 31% for TN and TP) (Tables 1 and 2). These

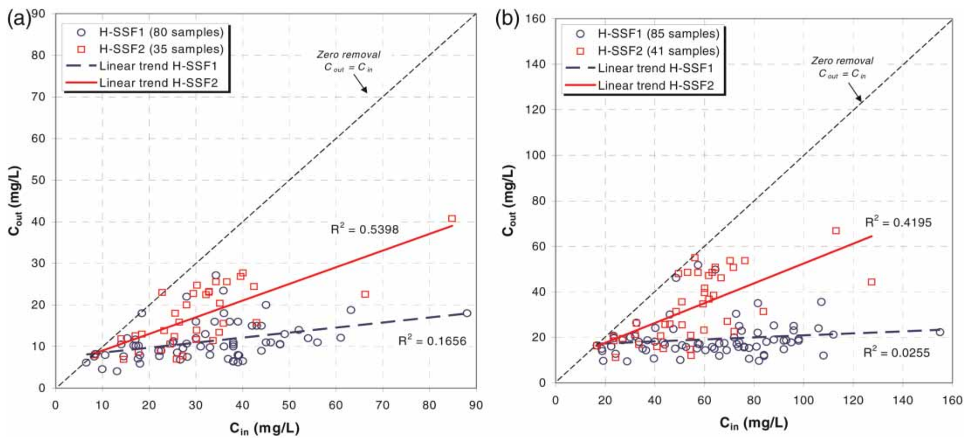

Figure 1 | Performance of H-SSF2 and H-SSF1 for BOD_5 (a) and COD (b) reduction.

Table 1 | Mean influent (±SD) and effluent (±SD) wastewater concentrations and mean (±SD) pollutant removal efficiencies (*R*) throughout the monitoring period in H-SSF1

	TSS		BOD_5		COD		TN		TP		*E. coli*[a]	
2001												
in (mg/L)	66	(18)	35	(10)	76	(21)	26	(3)	6	(<1)	5.3	(0.4)
out (mg/L)	12	(4)	11	(4)	18	(4)	18	(4)	4	(1)	3.1	(0.8)
R (%)	81	(6)	68	(11)	75	(5)	29	(11)	31	(10)	2.2	(0.5)
2002												
in (mg/L)	95	(17)	44	(16)	92	(22)	21	(4)	7	(3)	5.1	(0.4)
out (mg/L)	11	(3)	13	(4)	19	(4)	10	(7)	5	(1)	3.1	(0.9)
R (%)	88	(4)	68	(13)	78	(6)	56	(22)	32	(23)	2.1	(0.8)
2003												
in (mg/L)	82	(15)	42	(8)	84	(14)	23	(5)	7	(2)	5.1	(0.3)
out (mg/L)	12	(3)	11	(3)	17	(5)	12	(5)	4	(1)	3.0	(0.7)
R (%)	85	(4)	72	(8)	79	(5)	50	(16)	37	(15)	2.0	(0.5)
2004												
in (mg/L)	39	(35)	16	(8)	37	(15)	31	(6)	7	(1)	4.5	(0.7)
out (mg/L)	5	(2)	8	(2)	16	(4)	25	(8)	6	(<1)	2.0	(0.7)
R (%)	77	17)	37	(28)	51	(20)	20	(16)	17	(6)	2.5	(0.5)
2005												
in (mg/L)	41	(16)	25	(9)	48	(16)	–	–	–	–	4.8	(0.4)
out (mg/L)	3	(2)	8	(2)	16	(4)	–	–	–	–	1.5	(0.6)
R (%)	92	(5)	63	(13)	63	(15)	–	–	–	–	3.5	(0.5)
2006												
in (mg/L)	69	(8)	54	(13)	87	(18)	–	–	5	(1)	5.0	(0.1)
out (mg/L)	10	(5)	19	(1)	34	(3)	–	–	3	(1)	2.6	(0.6)
R (%)	86	(7)	63	(10)	61	(5)	–	–	31	(12)	2.4	(0.5)
2007												
in (mg/L)	36	(12)	24	(7)	44	(9)	31	(7)	7	(1)	5.1	(0.4)
out (mg/L)	14	(6)	16	(5)	29	(10)	25	(10)	6	(<1)	2.4	(0.1)
R (%)	84	(15)	50	(27)	59	(21)	49	(19)	16	(6)	2.6	(0.4)
2008												
in (mg/L)	34	(26)	21	(9)	36	(14)	20	(7)	8	(3)	5.2	(1.1)
out (mg/L)	13	(7)	15	(7)	27	(14)	9	(4)	7	(2)	2.6	(1.1)
R (%)	54	(24)	29	(19)	26	(18)	56	(16)	12	(8)	2.4	(0.9)
Overall period												
in (mg/L)	62	(31)	32	(15)	64	(28)	23	(6)	7	(2)	5.0	(0.5)
out (mg/L)	10	(5)	11	(4)	20	(8)	13	(7)	5	(2)	2.7	(0.8)
R (%)	80	(17)	58	(22)	63	(22)	45	(20)	27	(16)	2.5	(0.8)

[a]Concentration and removal values in Ulog.

differences in removal efficiency during the start-up of the plants, is probably related to the sampling period. Samples were collected at the beginning of plant growth in H-SSF1, while the sampling survey began when the plants were already fully developed in H-SSF2.

Wastewater discharge and reuse limits

It could be deceptive to evaluate constructed wetland performance just according to removal efficiency. Constructed wetlands, and in general all wastewater treatment

Table 2 | Mean influent (±SD) and effluent (±SD) wastewater concentrations and mean (±SD) pollutant removal efficiencies (*R*) throughout the monitoring period in H-SSF2

	TSS		BOD_5		COD		TN		TP		*E. coli*[a]	
2007												
in (mg/L)	27	(24)	35	(5)	63	(9)	23	(5)	4	(<1)	5.3	(0.7)
out (mg/L)	7	(3)	18	(7)	37	(13)	9	(3)	2	(1)	2.7	(1.0)
R (%)	68	(17)	42	(22)	41	(23)	60	(19)	46	(20)	2.6	(0.7)
2008												
in (mg/L)	41	(27)	30	(18)	50	(26)	34	(17)	7	(2)	5.4	(1.0)
out (mg/L)	11	(7)	17	(8)	30	(15)	13	(7)	5	(3)	3.0	(0.8)
R (%)	67	(23)	41	(16)	37	(19)	58	(15)	35	(31)	2.4	(0.7)
Overall period												
in (mg/L)	35	(26)	31	(14)	55	(22)	29	(14)	6	(2)	5.4	(0.7)
out (mg/L)	9	(6)	17	(8)	33	(15)	11	(6)	4	(3)	2.6	(0.8)
R (%)	67	(20)	41	(19)	38	(20)	59	(16)	40	(27)	2.6	(0.8)

[a]Concentration and removal values in Ulog.

plants, are designed to meet discharge limits. For this reason, samples expressed as percentages below the wastewater Italian limits for discharge into surface waters (D. Lgs. 152/2006) and for agriculture reuse (DM 185/2003) have been calculated. World Health Organization guidelines (WHO 2006) for wastewater reuse have been also taken in account.

In both effluents, COD and TSS concentrations were always below the Italian discharge concentration (35 and 125 mg/L, respectively). Furthermore, the two wetlands always reduced COD to acceptable concentrations for irrigation (100 mg/L). Just a few samples (1 out of 80 for H-SSF1 and 5 out of 35 for H-SSF2) didn't comply with the BOD_5 limit of 25 mg/L for discharge into surface water. Both effluent nitrogen concentrations met the legal requirements for irrigation (35 mg/L) while the phosphorus limit (10 mg/L) was only exceeded by 3% (H-SSF1) and 5% (H-SSF2) of the samples. Despite constructed wetlands having shown good removal of microbial indicators (more than 2.5 log unit) did not show the ability to produce effluent with *E. coli* levels matching the Italian wastewater reuse standard (50 UFC/100 ml [Maximum value to be detected in 80% samples for natural treatment systems.]). Only 35 and 27% of samples collected at the outlets of H-SSF1 and H-SSF2, were below the maximum *E. coli* value limit imposed by the law. This result highlights the need for further treatment to achieve the Italian limits required for irrigation reuse.

On the other hand, the numbers of *E. coli* in the H-SSF1 and H-SSF2 effluent (always $\leq 10^3$ *E. coli* per 100 ml) ensure that health-based targets proposed by the WHO (2006) are

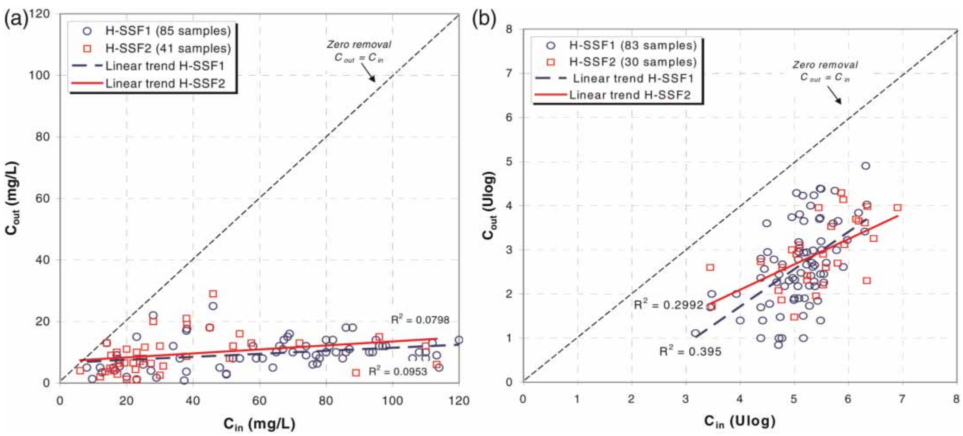

Figure 2 | Performance of H-SSF2 and H-SSF1 wetland for TSS (a) and E. coli (b) reduction.

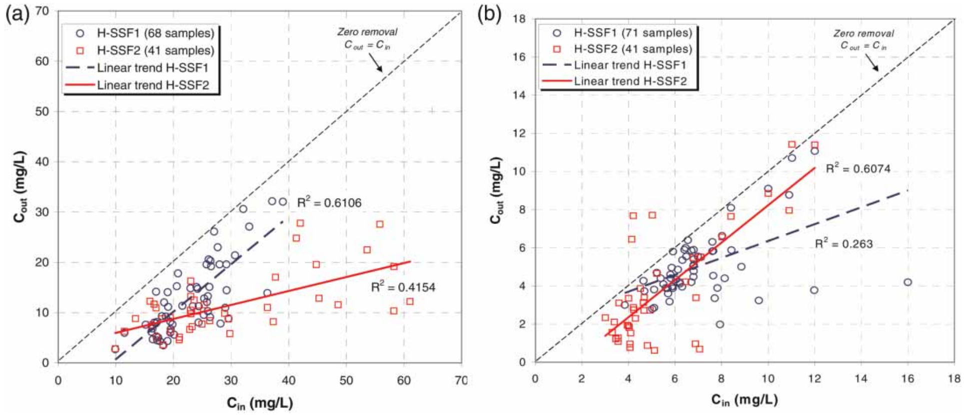

Figure 3 | Performance of H-SSF2 and H-SSF1 wetland for TN (a) and TP (b) reduction.

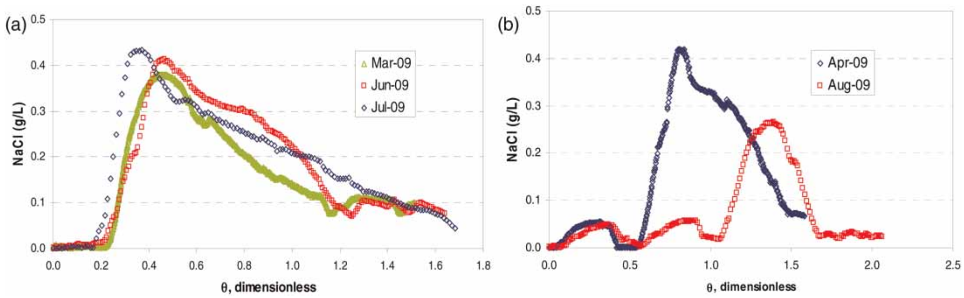

Figure 4 | Changes of the H-SSF1 (a) and H-SSF2 (b) effluent tracer concentration over time in tracer tests.

met, particularly if drip irrigation is used. The performance was good for *Salmonella* removal, which was never detected in the effluent of CWs, despite always being revealed in the influent.

Tracer experiments

The concentration curves versus normalized time ($\theta = \tau/\tau_n$) obtained in all the tests conducted in H-SSF1 have nearly identical shapes (Figure 4(a)). All three curves displayed a sharp rise to a peak, followed by an exponential decrease with a long tail. In March 2009, the total sampling period for the tracer test conducted in H-SSF1 was approximately 254 h. The June and July tests in H-SSF1, concluded at 143 and 163 h. The high mass tracer recovery both in the March (97%) and July (80%) test indicates that the tracer experiments were carried out well in H-SSF1. The mass recovery in June was lower (70%) probably due to a shorter test duration. In H-SSF1 the nominal residence time, assuming unchanged nominal porosity (0.38), was always higher than τ (Table 3). The e_v values agree with the values reported in U.S. EPA (2000) indicating that τ in many horizontal SSF systems is frequently 40–80% less than τ_n, because of loss of pore volume, dead volume or preferential flow. The dispersion numbers (D) obtained in tracer tests performed in March and June in H-SSF1 fit well with the range of 0.07–0.35 quoted by King *et al.* (1997) and Simi & Mitchell (1999) for other H-SSF CWs. None of the tests had a dispersion number lower than 0.025, which is indicative of near PF conditions (U.S. EPA 2000).

In both tracer tests carried out in the H-SSF2, the mass recovery was very low (about 24%) probably due to further dilution of the tracer in the free water surface at the end of the bed. This affected the calculation of hydraulic

Table 3 | Values of the parameters that define the hydraulic behaviour of the H-SSF1 and H-SSF2

	Test	Q (L/s)	τ_n (h)	τ (h)	e_v (%)	t_p (h)	D (dim)
H-SSF1	March 2009	1	82.2	59.2	72	37	0.35
	June 2009	1.3	64.7	48.6	75	31	0.28
	July 2009	1.9	41.6	33.2	80	15	0.59
H-SSF2	April 2009	1.6	59.1	58.2	98	48	0.10
	August 2009	2	46.1	56.7	122	64	0.03

'dim' means dimensionless.

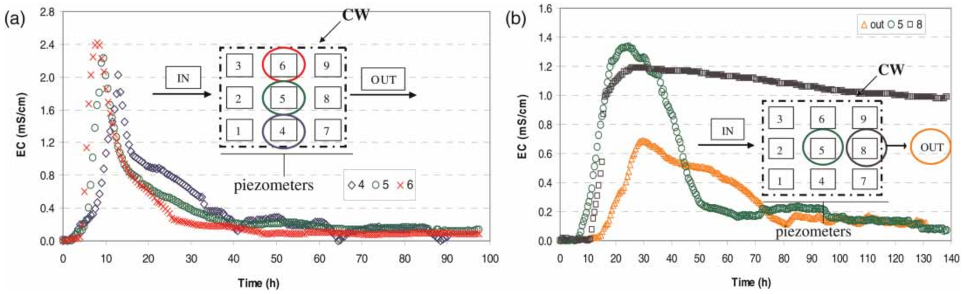

Figure 5 | Breakthrough curves measured in piezometers of H-SSF1 in parallel (a) and in series (b).

parameters, which can be considered poorly representative. For example, tracer peak time (t_p) in the August test was recorded later than the April test, despite having a higher flow rate (Table 3). The peaks, observed in both tests carried out in H-SSF2, indicate the presence of separate flow paths (Figure 4(b)).

Two other salt tracer tests were carried out in H-SSF1 by measuring the EC variation (mS/cm) in the piezometers (sampling locations) where the probes were places in parallel (Figure 5(a)) in the first experiment and in series (Figure 5(b)), during the second one. Breakthrough curves measured in three parallel piezometers (4, 5 and 6, see upper part of Figure 5(a)) confirm that channelling was occurring since the three breakthroughs exhibit different times of arrival. The RTDs measured in the piezometers placed in series (Figure 5(b)), support the presence of zones with stagnant (immobile) water which do not participate in reactions, as it is possible to see in piezometer number 8, where the EC values remained almost unchanged.

CONCLUSIONS

The analysis of RTDs across different flow rates, showed a mean actual residence time always lower than the nominal hydraulic residence time. This was probably due to the presence of dead volumes or preferential flow paths, confirmed by breakthrough curves measured in piezometers inside the H-SSF1. Despite the flow conditions being far from the PF model, the constructed wetlands located in San Michele di Ganzaria (Sicily), have proved to be efficient in removing the main chemical and physical pollutants from the secondary effluent of urban wastewater treatment plants. The *E. coli* removal was up to 2.5 log units for both beds and the average effluent concentrations were 2.6 log units (H-SSF2) and 2.7 log units (H-SSF1); this microbiological indicator didn't respect the Italian standard for wastewater reuse but complied with the WHO guidelines. In any case, the results of this study confirm the high reliability of CWs for tertiary wastewater treatment given that the H-SSF1 treatment capacity remained largely unchanged after eight years of operation.

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REFERENCES

APHA, AWWA, WEF 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edition. APHA, AWWA, WEF, Washington, DC, USA.

Barbagallo, S., Cirelli, G. L., Consoli, S., Toscano, A. & Zimbone, S. M. 2003 Performances and Hydraulics of a H-SSF constructed wetland for municipal wastewater reuse. In *Proceedings of 4th IWA International Symposium on Wastewater Reclamation and Reuse, 12–14 November*, Mexico City, Mexico.

Brix, H. 1998 Denmark. In: *Constructed Wetlands for Wastewater Treatment in Europe* (J. Vymazal, H. Brix, P. F. Cooper, M. B. Green & R. Haberl, eds.). Backhuys Publishers, Leiden, The Netherlands, pp. 123–152.

Chazarenc, F., Merlin, G. & Yves, G. 2003 Hydrodynamics of horizontal subsurface flow constructed wetlands. *Ecological Engineering* **21** (2–3), 165–173.

Cirelli, G. L., Consoli, S., Di Grande, V., Milani, M. & Toscano, A. 2007 Subsurface constructed wetlands for wastewater treatment and reuse in agriculture: five years of experiences in Sicily, Italy. *Water Science and Technology* **56** (3), 183–191.

IWA 2000 *Constructed Wetlands for Pollution Control*. Scientific and Technical Report No. 8, IWA Publishing, London, England, 164pp.

Kadlec, R. H. 2009 Comparison of free water and horizontal subsurface treatment wetlands. *Ecological Engineering* **35** (2), 159–174.

Kadlec, R. H. & Wallace, S. 2009 *Treatment Wetlands*, 2nd edition. CRC Press, New York, USA.

King, A. C., Mitchell, C. A. & Howes, T. 1997 Hydraulic tracer studies in a pilot scale subsurface flow constructed wetland. *Water Science and Technology* **35** (5), 189–196.

Levenspiel, O. 1972 *Chemical Reaction Engineering*, 2nd edition. Wiley, New York, USA.

Małoszewski, P., Wachniew, P. & Czuprynski, P. 2006 Study of hydraulic parameters in heterogeneous gravel beds: constructed wetland in Nowa Słupia (Poland). *Journal of Hydrology* **331** (3–4), 630–642.

Puigagut, J., Villaseñor, J., Salas, J. J., Bécares, E. & García, J. 2007 Subsurface-flow constructed wetlands in Spain for the sanitation of small communities: a comparatives study. *Ecological Engineering* **30** (4), 312–319.

Ronkanen, A.-K. & Kløve, B. 2007 Use of stabile isotopes and tracers to detect preferential flow patterns in a peatland treating municipal wastewater. *Journal of Hydrology* **347** (3–4), 418–429.

Simi, A. L. & Mitchell, C. A. 1999 Design and hydraulic performance of a constructed wetland treating oil refinery wastewater. *Water Science and Technology* **40** (3), 301–308.

Suliman, F., Futsaether, C., Oxaal, U., Haugen, L. E. & Jenssen, P. 2006 Effect of the inlet outlet positions on the hydraulic performance of horizontal subsurface-flow wetlands constructed with heterogeneous porous media. *Journal of Contaminant Hydrology* **87** (1–2), 22–36.

U.S. EPA 2000 *Constructed Wetlands Treatment of Municipal Wastewaters*. EPA 625/R-99/010, Office of Research and Development, United States Environmental Protection Agency, Washington, DC, USA.

Vymazal, J. 1999 Removal of BOD_5 in constructed wetlands with horizontal subsurface flow: Czech experience. *Water Science and Technology* **40** (3), 133–138.

Vymazal, J. 2009 The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. *Ecological Engineering* **35** (1), 1–17.

WHO 2006 *Guidelines for the Safe Use of Wastewater, Excreta and Greywater*, Volume 2, Wastewater Use in Agriculture. World Health Organization, Geneva, Switzerland.

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