Importance of hydraulic characterisations in waste stabilisation pond research: results from pilot-scale algal, duckweed, rock filter and attached-growth media reactors

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Abstract The specific nature of fluid dynamics within waste stabilisation ponds can have a determining influence on their overall treatment performance. This paper presents the results of hydraulic tracer experiments undertaken to characterise the flow behaviour of several pilot-scale advanced pond reactors (a duckweed-based pond, an algal-based 'open' pond, a rock filter and a novel horizontal-flow attached-growth media reactor) used for polishing of a full-scale pond effluent. Duplicate tracer studies were undertaken for each of the four experimental reactors with the aid of the fluorescent dye rhodamine WT. Results showed flow distribution in all reactors to be relatively well dispersed, consistent with that of a completely mixed tank reactor suffering from the existence of dead space volume. Outcomes of this research highlight the importance of undertaking detailed characterisations of flow hydraulics within experimental pond systems, and emphasise the value of pre-validating the hydraulic design of experimental reactors used for pond research.

Keywords Attached-growth media; duckweed pond; hydraulic behaviour; rhodamine WT tracer; rock filter; waste stabilisation pond

Introduction

Waste stabilisation ponds (WSPs) are a widely accepted, economical and effective wastewater treatment technology that are now regarded as the method of first choice for wastewater treatment in both small- and large-scale communities throughout the world (Mara *et al.*, 2001; Mara and Johnson, 2007). The treatment efficiency of WSP systems depends upon numerous factors, including: the type of wastewater; the organic loading regime; the geometry and configuration of the pond system; and climatological and environmental conditions such as air temperature and the amount of wind and incident sunlight the pond receives (Cauchie *et al.*, 2000). In addition to these influential criteria, the hydraulic behaviour of wastewater within the WSP is also of prime importance in determining pond treatment efficiency, since it controls the hydraulic residence time (HRT) and also the residence time distribution (RTD) which determines the dispersion of waste substrates and chemical and biological entities within the reactor basin (Uhlmann, 1979; Naméche and Vasel, 1996). Performance of the various 'waste stabilisation' processes, for example, may be particularly affected by problems directly related to the HRT arising from anomalies in the hydrodynamic flow pattern, such as short-circuiting or the existence of dead spaces (Ferrara and Harleman 1981; Cauchie *et al.*, 2000). The determination of a pond reactor's RTD (hydraulic flow pattern) and subsequent HRT is thus of major interest regarding the design and characterisation of WSP systems (Baléo *et al.*, 2001).

A good knowledge of hydraulic flow conditions allows for the optimisation of mass transfer processes during the degradation of wastewater pollutants, and more generally, detailed information on flow behaviour is required in order to calculate the yield of various reactions with kinetic parameters (Baléo *et al.*, 2001). Knowledge of a reactor's HRT is important, for example, when attempting to model pathogen die-off during WSP research (e.g., Brissaud *et al*., 2000), since residence time is recognised to be a primary factor governing UV-induced microbial decay in pond environments (Davies-Colley *et al.*, 1999). In terms of the pattern of fluid dynamics within a given reactor vessel, there are two extremes of ideal flow that can exist: plug flow; and completely mixed flow. It has long been recognised, however, that flow conditions rarely conform to ideal flow behaviours in practice (Danckwerts, 1953) and that reactor flow patterns typically lie somewhere in between these two theoretical ideals; something referred to as 'non-ideal' flow. Tracer studies of scale model ponds and smaller full scale WSPs have provided an indication of the extent of deviation from both plug and completely mixed flow behaviour in practice. Field trials, for example, have produced RTDs demonstrating a variety of flow behaviours ranging from almost completely mixed flow (Moreno, 1990; Frederick and Lloyd, 1996) to behaviour approaching plug flow conditions (Arceivala, 1983).

Obtaining a detailed understanding of the *in situ* hydraulic flow pattern within a WSP reactor—ignoring the possibility of applying computational fluid dynamics—implies the need to undertake chemical tracer experiments. Despite the importance of hydraulic flow pattern on WSP performance, tracer studies are rarely conducted by WSP researchers; most likely because of the significant time, expense and often specialist analytical equipment required to carry out these assessments (Shilton and Harrison, 2003). The same is also true for pilot-scale WSP research, where one finds few reports of detailed hydraulic characterisations in the literature (e.g., Zimmo, 2003). This paper presents the results of hydraulic tracer experiments aimed at characterising the hydraulic flow patterns of pilot-scale reactors used in a previously reported advanced WSP effluent upgrade study (Short *et al*., 2007). It was not the specific aim of this work to investigate the potential impact(s) of flow hydraulics on treatment performance; rather, hydraulic flow patterns were characterised as part of the general description of the pilot plant itself, and also to provide insights into reactor flow patterns so as to facilitate more detailed interpretation of experimental performance assessments. This paper provides insights into the hydraulic behaviour of pilot-scale algal- and duckweed-based pond systems as well as characterising flow conditions within pilot-scale rock filters and novel horizontal-flow attached-growth media reactors operated as part of a research project on advanced in-pond effluent upgrades for *in situ* polishing of WSP effluent.

Materials and Methods

Pilot plant description

An experimental pilot plant was constructed and operated at the Bolivar wastewater treatment plant north of Adelaide, South Australia. The pilot plant was operated as part of a study investigating different in-pond WSP upgrade methodologies for final polishing of pond effluent—primarily for algal solids removal. A detailed description of the pilot plant, its hydraulic configuration and experimental operation was provided in Short *et al*. (2007). Briefly, the pilot plant consisted of nine above-ground 2.8 m^3 inert polyethylene reactors arranged in three parallel series. In an attempt to optimise *in situ* flow conditions, hydraulic inlets and outlets for each pilot-scale reactor were fitted with perforated PVC manifolds (Figure 1) rather than being operated as 'single point' inlets and outlets. Each of the three parallel reactor trains was operated over a 12 month period from July 2005 to August 2006. During the 12 month monitoring duration, the pilot plant was operated under a staggered configuration using a combination of four experimental treatments: duckweed (DW); open pond (OP); rock filter (RF); and a novel horizontal-flow attached-growth media (HF-AGM). Given that the DW, OP and RF treatments have been described elsewhere (Short *et al.*, 2007), only the HF-AGM treatment will be described in detail here.

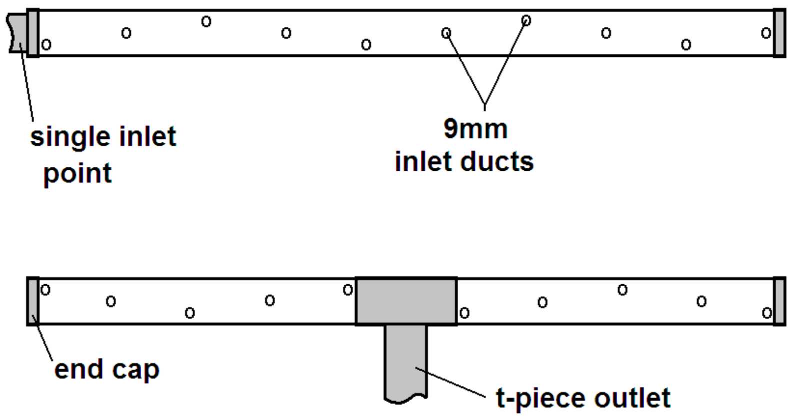

Figure 1. Schematic representation of an individual pond inlet (top) and outlet (bottom) manifolds showing arrangement of the inlet and outlet hydraulic ducts along the manifold length.

The HF-AGM treatment consisted of conventional polypropylene fill media (TKP-319; 2H Plastics, Victoria Australia) configured in a 'horizontal-flow' arrangement. The polypropylene media is traditionally used in vertical-flow configurations (e.g., cooling towers and trickling filters) and so the use of this media on a horizontal flow plane is considered novel for wastewater treatment applications. The HF-AGM has a 19 mm void channel width and a specific surface area of 150 m^2 m^{-3}; giving each pilot-scale HF-AGM reactor an available media surface area in the order of 340 m^2. The media consists of numerous layers of 0.3 mm thick corrugated polypropylene sheets, each welded together to form a 'honeycomb-like' matrix of flow-through channels. The media itself is lightweight, rigid and self-supporting, with a very high void space volume (95% v/v).

Hydraulic characterisation

Hydraulic loading rates during tracer experiments for each of the pilot-scale treatment reactors are provided in Table 1. According to Levenspiel (1999) the operational flow pattern within the pilot plant reactors was classified as 'steady state' flow, meaning that the influent flow rate was constant with time. In order to characterise the patterns of flow within the experimental reactors, hydraulic tracer experiments were performed. These tracer studies were done with using the fluorescent dye rhodamine WT in conjunction with a calibrated SCUFA® submersible fluorometer–data logger (Turner Designs, Inc., Sunnyvale, CA) equipped with an opaque flow-through cap and associated software (SCUFAsoft™ v.2.1). Rhodamine WT has been developed specifically for hydraulic tracer studies (Smart and Laidlaw, 1977) and the SCUFA® fluorometer—with its in-built temperature compensation capabilities and a rhodamine WT detection limit of 0.04 ppb—is also well suited for field-based tracer experiments. Rhodamine WT has previously been the tracer of choice for numerous other research investigations into the hydraulics of WSPs (e.g., Pedahzur *et al.*, 1993; Naméche and Vasel, 1996; Cauchie *et al.*, 2000; Shilton *et al.*, 2000; Barter, 2003).

Initial rhodamine WT pulse injection dosage was calculated so as to allow for sufficient fluorescence peak height in the outflow according to Kilpatrick (1970). The 'impulse stimulation' method (Naméche and Vasel, 1996) was adopted for all tracer studies, during which pulse injections (commonly ≈30 ml) of a 10^{-2} dilution of the 20% active rhodamine WT stock solution were used. Tracer pulses were further diluted to ≈150 ml and slowly injected into the influent manifold feed line (prior to 90º elbows to further aid dye mixing) using a 60 ml syringe, and the data logger simultaneously started. Rhodamine WT fluorescence was then measured and recorded, commonly at one minute intervals, using the SCUFA® fluorometer–data logger for a sufficient length of time to allow for a minimum of four reactor volume turnovers. Following the cessation of each individual tracer run, the data was downloaded and exported directly into Microsoft® Office Excel XP (Microsoft Corporation, Washington, USA) for analysis.

Hydraulic flow rates were recorded at the commencement and cessation of individual tracer runs using both rotameter flow meter readouts of reactor influent and also volume-based reactor effluent flow measurements taken with the aid of a graduated measuring cylinder and a stopwatch. The average of these two flow rates was then used for calculating the theoretical HRT of the pilot pond. The theoretical HRT (τ_{th}) for each pilot pond was calculated simply by dividing the reactor's hydraulic volume (V_p; m^3) by the hydraulic flow rate entering the pond (Q_0; $m^3\ h^{-1}$). Hydraulic residence time distribution (RTD) curves—also known as C_{pulse} curves—were compiled based on the fluorescence–time data from the tracer studies, and were then used to characterise the flow patterns within each pilot-scale reactor vessel. RTD curves were compiled using PRISM 4.03 (GraphPad Software, San Diego, CA, USA). Actual mean HRT (τ) was calculated based on the raw tracer data from the fluorescence–time RTD curves according to the method of Levenspiel (1999) given by:

$$\tau = \frac{\sum_i t_i C_i \Delta t_i}{\sum_i C_i \Delta t_i}$$

where τ = the mean HRT (hours)
t_i = the elapsed time (minutes)
C_i = the tracer fluorescence at each logged time interval
Δt_i = the elapsed time interval between each measurement of C_i

The theoretical HRT can then be compared with the mean HRT as determined form the tracer data in order to provide some information about the magnitude of dead volume or the extent of short-circuiting within the pond reactor (Baléo *et al.*, 2001). The existence of dead volume is indicated by $\tau < \tau_{th}$ whereas short-circuiting is said to occur if $\tau > \tau_{th}$ (Cauchie *et al.*, 2000; Baléo *et al.*, 2001). In the present case, short-circuiting did not apply and so dead volume (V_d; m^3) was calculated according to the following equation:

$$V_d = V_p \cdot \left(1 - \left(\frac{\tau}{\tau_{th}}\right)\right)$$

where V_p = hydraulic volume (m^3)
τ and τ_{th} are the calculated mean and theoretical HRT respectively (hours)

Commonly, duplicate hydraulic tracer experiments were performed on individual pilot reactors in order to assess the consistency of the observed flow pattern. To allow for direct comparisons between duplicate tracer runs with differing flow rates, RTD curves were normalised so that the area under the curves of duplicate runs were equal to unity. This was done according to the method of Levenspiel (1999), whereby the measured tracer fluorescence at each logged time interval was divided by the area under the raw RTD curve (calculated using PRISM 4.03) giving the resultant normalised RTD curves a uniform area of 1.

Results and discussion

Pilot plant flow hydraulics

It is well understood that WSP efficiency is a function of both the biochemical transformations as well as the hydraulic transport processes occurring within the reactor basin (Polprasert and Bhattarai, 1985). Therefore, the hydraulic operation of each pilot treatment series was probed and characterised with the aid of the fluorescent dye rhodamine WT and an online fluorometer. It is reiterated that it was not the specific aim of this work to investigate the potential impact(s) of flow hydraulics on treatment performance; rather, hydraulic flow pattern was assessed in order to most accurately describe each of the advanced pond upgrade systems and to identify possible differences in fluid dynamics between the four pilot-scale treatment trains. Duplicate normalised RTD curves from corresponding hydraulic tracer experiments for individual pilot-scale DW; OP; RF; and HF-AGM treatment reactors are given in Figures 1 and 2 respectively.

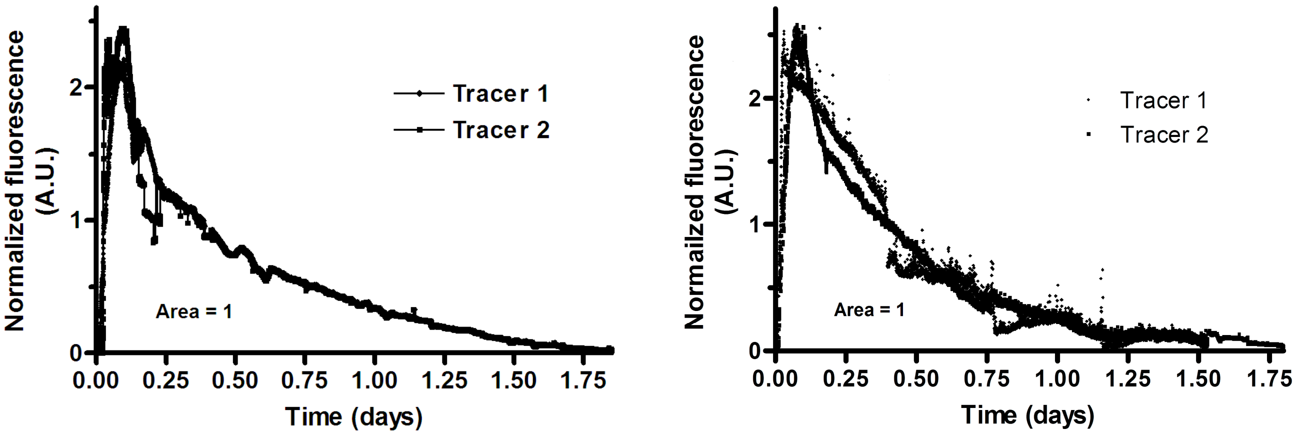

Figure 1. Duplicate normalised residence time distribution curves for DW treatment reactor (left) and OP treatment reactor (right) showing normalised rhodamine WT fluorescence (A.U.; *y*-axis) and time (days; *x*-axis). Tracer experiments for DW reactor were performed under a standing duckweed plant standing biomass density of no less than 2 kg m^{-2} (wet weight).

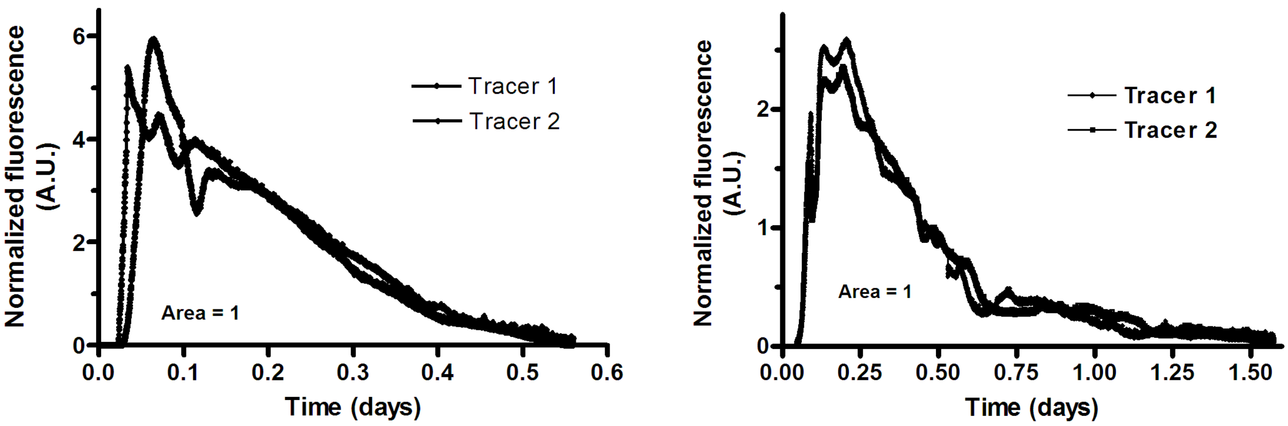

Figure 2. Duplicate normalised residence time distribution curves for RF treatment reactor (left) and HF-AGM treatment reactor (right) showing normalised rhodamine WT fluorescence (A.U.; *y*-axis) and time (days; *x*-axis).

Individual RTD curves for the four discrete treatment reactors (Figures 1 and 2) all show a relatively well dispersed hydraulic flow pattern consistent with that of a completely mixed tank reactor; with a maximum asymmetric fluorescence peak near to the *y*-axis followed by a slow and steady fluorescence decrease within a pronounced tail (Levenspiel, 1999). The long tails in Figures 1 and 2 represent the tracer dye quickly becoming well mixed and then slowly being diluted and washed out of the pond reactor as the entire pond volume is gradually turned over. As shown in Figures 1 and 2, maximum tracer fluorescence was observed in the outflow after only a fraction of the theoretical HRT, suggesting that the flow pattern is more mixed than plug; something that reflects common *in situ* WSP hydraulics (Uhlmann, 1980; Naméche and Vasel, 1996; Torres *et al.*, 1999). The initial fluorescence peak seen in Figures 1 and 2, whilst being representative of a completely mixed tank reactor, is also indicative of a combination of short-circuiting and the existence of dead spaces within all pilot ponds (Bischoff and McCracken, 1966; Uhlmann, 1979; Levenspiel, 1999; Torres *et al.*, 1999). The presence of small-scale accessory peaks within the tail of the RTD curves is also indicative of some degree of localised recirculation within the pilot-scale reactors.

As evident in Figures 1 and 2, there was relatively good consistency in hydraulic distribution between duplicate tracer experiments. Data from within-treatment duplicate tracer runs were averaged in order to yield one value for both theoretical (τ_{th}) and actual mean residence time (τ). Calculated τ_{th} for individual treatment reactors varied according to variations in the precise flow rate at which individual tracer experiments were conducted (see Table 1). Quantitative analysis of the tracer data from Figures 1 and 2 also revealed differing τ values for each treatment based on individual reactor void volumes and tracer experiment flow rates (Table 1). Duplicate mean residence times under the respective experimental flow rates for individual DW, OP, RF and HF-AGM reactors were averaged at 0.96, 0.78, 0.37 and 0.85 days respectively. As is shown in Table 1, $\tau < \tau_{th}$ for all treatment reactors, indicating the existence of dead space volume within all of the pilot-scale pond series. Average dead volumes (V_d) within each pilot-scale reactor were in the order of 13.2, 13.6, 27.9 and 8.5% for DW, OP, RF and HF-AGM treatments respectively (Table 1).

Table 1. Hydraulic characterisation of individual pilot pond reactors for the four experimental treatment systems: duckweed (DW); open pond (OP); rock filter (RF); and horizontal-flow attached-growth media (HF-AGM). Individual parameter values represent the mean of duplicate tracer determinations.

Hydraulic parameter	Experimental treatment			
	DW	OP	RF	HF-AGM
Gross reactor volume (m^3)	2.56	2.56	2.56	2.56
Hydraulic inflow rate (m^3 day^{-1})	2.21	2.76	2.76	2.76
Void space volume (V_p; m^3)	2.56	2.56	1.43	2.45
Void space volume (% total)	100	100	55.86	95.7
Theoretical residence time (τ_{th}; days)†	1.16	0.93	0.52	0.89
Actual mean residence time (τ; days)	0.96	0.78	0.37	0.85
Dead volume (% V_p)	13.16	13.63	27.86	8.50

† Based on corresponding reactor void space volume

Analysis of reactor RTD curve data and corresponding values of τ and τ_{th} for each pilot treatment series showed that hydraulic flow conditions within the HF-AGM pond series were more ideal than those in the parallel DW, OP and RF reactors—evidenced by the closer reflection of τ_{th} in τ. Hydraulic distribution within the DW and OP treatment reactors was found to be similar (13.2 and 13.6% V_d respectively). Although there have been reports of improved hydraulic conditions under a duckweed surface cover compared with uncovered open ponds (Benjawan and Koottatep, 2007), tracer data suggested that flow patterns were very similar in both duckweed-covered and uncovered ponds; an observation in line with that of Zimmo (2003) for similar scale pilot pond systems. It is possible that the relatively small scale of the pond reactors used in this research did not allow for full expression of potential differences in flow pattern between the DW and OP treatments (e.g., improved flow conditions resulting from a wind-shielding duckweed cover); however, this assertion remains speculative. Flow conditions were also more ideal in the DW and OP reactors than the rock filters, with the presence of large volumes of rock media apparently degrading the flow conditions and increasing the reactor's dead volume to around 28%. Poor patterns of flow distribution and hydraulic short-circuiting have been reported for rock filters elsewhere (Swanson and Williamson, 1980).

Dead volumes of the orders seen in Table 1 were likely to have had a measurable impact on the hydraulic efficiency and subsequent treatment performance of each of the pilot-scale advanced pond systems; however, this was not investigated here. Whilst not ideal, dead volume magnitudes recorded for the current pilot pond reactors were significantly lower than the approximate 60% dead spaces reported by Zimmo (2003) following hydraulic characterisations of similar pilot-scale duckweed and open (algal-based) ponds. Although it must be recognised that there is no truly ‘dead’ space in real systems (since even in a completely non-moving region, transport of matter eventually occurs by molecular diffusion), regions of the reactor vessel with fluid retention times of 5–10 times more than that of the bulk of the fluid are for practical purposes referred to as “dead” and are essentially viewed as wasted volumetric space (Bischoff and McCracken, 1966). Despite the initial design of the pilot pond systems adhering to several recognised elements of good hydraulic design, such as the use of rectangular reactors, positioning the inlets and outlets as far from each other as possible and the use of multiple inlet and outlet ‘ducts’ (Moreno, 1990), the observed flow conditions were found to be far from optimal.

Improving our understanding of waste stabilisation pond hydraulics offers the potential for improving the treatment performance of these systems (Shilton *et al*., 2000). According to Shilton *et al*. (2000), any change to the hydraulic operation of a pond (e.g., by baffling or modifying the inlet/outlet configuration) that can effectively delay the arrival of the tracer peak at the outlet, has the potential to significantly improve the overall pond reactor performance. Characterisation of the hydraulic behaviour for each advanced treatment system showed that the HF-AGM reactors displayed the most optimal flow regime of the four pilot treatments. It is possible that the uniform media configuration of the synthetic HF-AGM (as opposed to the random media arrangement for the rock filters) served to more evenly distribute influent wastewater within the HF-AGM reactors, such that they functioned effectively as ‘multi-baffled’ systems. The use of this particular novel HF-AGM may serve to improve the *in situ* hydraulic performance of WSP systems and hence improve overall treatment performance.

Conclusions

Flow behaviour within a number of pilot-scale advanced pond upgrade reactors was shown to reflect that of a completely mixed tank reactor with some short-circuiting and varying degrees of dead space volume. It has been suggested elsewhere that, in spite of the sub-optimal HRT, optimal WSP performance may be achieved under a completely mixed flow regime (Sweeney *et al*., 2003); however, the impacts of different hydraulic regimes on treatment performance were not investigated here. Considering that flow conditions within the experimental reactors were found to be sub-optimal, particularly for the rock filters, this work illustrates the importance of sound hydraulic design in experimental WSP research and highlights the importance of tracer studies during the *design* phase of research. Given the recognised importance of hydraulic behaviour on pond treatment performance, it is also suggested that future reporting of pilot-scale WSP research incorporates detail of hydraulic flow conditions within experimental reactors. More comprehensive reporting of wastewater hydraulics within pilot-scale (and indeed other smaller and larger scale) systems would add another dimension to the interpretation of results, and would also allow for more precise and meaningful performance comparisons between different pond systems operated by different researchers around the world.

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