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HYDRAULIC TRACER STUDIES IN A PILOT SCALE SUBSURFACE FLOW CONSTRUCTED WETLAND

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ABSTRACT

Current design procedures for Subsurface Flow (SSF) Wetlands are based on the simplifying assumptions of plug flow and first order decay of pollutants. These design procedures do yield functional wetlands but result in over-design and inadequate descriptions of the pollutant removal mechanisms which occur within them. Even though these deficiencies are often noted, few authors have attempted to improve modelling of either flow or pollutant removal in such systems.

Consequently the Oxley Creek Wetland, a pilot scale SSF wetland designed to enable rigorous monitoring, has recently been constructed in Brisbane, Australia. Tracer studies have been carried out in order to determine the hydraulics of this wetland prior to commissioning it with settled sewage. The tracer studies will continue during the wetland's commissioning and operational phases. These studies will improve our understanding of the hydraulics of newly built SSF wetlands and the changes brought on by operational factors such as biological films and wetland plant root structures.

Results to date indicate that the flow through the gravel beds is not uniform and cannot be adequately modelled by a single parameter, plug flow with dispersion, model. We have developed a multiparameter model, incorporating four plug flow reactors, which provides a better approximation of our experimental data. With further development this model will allow improvements to current SSF wetland design procedures and operational strategies, and will underpin investigations into the pollutant removal mechanisms at the Oxley Creek Wetland. © 1997 IAWQ. Published by Elsevier Science Ltd

KEYWORDS

Artificial wetlands; constructed wetlands; gravel beds; hydraulics; pilot scale; submerged flow wetlands; subsurface flow wetlands; tracer studies.

INTRODUCTION

Current design procedures for Subsurface Flow (SSF) wetlands are based on the simplifying assumptions of plug flow and first order decay of pollutants (eg USEPA, 1993). These design procedures do yield functional wetlands (Reed and Brown, 1995), but also result in over-design and have been shown to inadequately describe the pollutant removal mechanisms which occur within them. The plug flow design assumption is used even though a number of researchers have found that plug flow does not adequately describe the water flow through SSF wetlands eg. Bowmer (1987), Bavor *et al.* (1988) and Kadlec (1993). Perhaps this is because attempts to model the flow through SSF wetlands have met with varying degrees of success, Pilgrim *et al.* (1992) noted variation of dispersivity with distance travelled and Waters *et al* (1993) suggest a random or probabilistic element in observed flow patterns. Kadlec (1994) has used single parameter models such as plug flow reactors with dispersion or equally sized stirred tanks in series to "adequately" describe the outlet tracer responses for SSF wetlands although little data has been published. In fact Kadlec (1994) notes that there have been few attempts to quantify dispersion by modelling. Kadlec (1993) and Kadlec and Knight (1996) also describe multiparameter models for flow through SSF wetlands, these models more closely fit internal tracer data but there is still limited information on which to calibrate them. There is a need for more experimental data to further define spatial and temporal variations in flow patterns and to develop existing models.

Furthermore, much of the operational data available for SSF wetlands is presented on a concentration basis only. Thus, one of the imperatives in wetlands research is a rigorous mass balance based study of the performance of an SSF wetland over its operational lifetime.

Consequently a pilot scale SSF wetland specifically designed to enable rigorous monitoring has recently been built at the Brisbane City Council's Oxley Creek Wastewater Treatment Plant. We agree with Pilgrim's (1992) assertion that the only way to assess the hydraulics of a specific bed is to do field studies. Therefore the first stage of experimental work at this wetland involves creating a solid baseline of hydraulic data on which to build a mass balance model of the wetland's performance.

The aims of this stage are:

- to conduct tracer studies to determine the hydraulic behaviour of the wetland under various operational and environmental conditions; and
- to model the hydraulic behaviour of the wetland.

Fulfilling these aims would:

- allow improvements to current SSF design procedures and operational strategies; and
- provide a solid foundation for the next stage of the Oxley Creek experimental program - investigations into SSF wetland pollutant removal mechanisms.

Oxley Creek wetland design

The wetland contains 4 equally sized beds. The base of each bed is 3 metres wide, 25 metres long and has a one percent slope from inlet to outlet. The beds are of earthen construction, and the walls slope outwards at about 45°. Each bed is lined with a single sheet of high density polyethylene.

Masonry block walls, built from blocks with open centres so that water can pass through them, divide each bed laterally into alternating open water and gravel sections. The four open water sections promote even water distribution at the inlet and outlet of each of the three gravel sections. The bulk of the treatment occurs in the gravel sections which are each 6.9m long and 0.5m deep. Separating the gravel sections gives us the flexibility to control operating conditions such as aeration, recycle and bypass flows. A combination of masonry block walls and polypropylene sheets divide each bed down its longitudinal centre into two "sides".

To allow comparative experiments, each bed contains a particular size and shape of gravel. The beds are operated in parallel and each receives an independently controlled flow of settled sewage from the wastewater treatment plant. The flow rate to each bed is variable (500-10 000 L/d which corresponds to residence times of about 1.5 to 30 d). Flows are metered using tipping buckets.

Breen and Chick (1995) noted vertical stratification of flows within a mature wetland and Bavor *et al.* (1988) found channelling within planted wetlands. To attempt to account for such practical flow anomalies the hydraulic and mass balance models will be developed by integrating the study results around a number of small elements within the beds. Each bed is notionally divided into elements by a three dimensional rectangular grid and sample points have been located accordingly. Figure 1 shows a plan view of one gravel section, the adjacent open water sections and the sample group locations. Figure 2, a cross sectional view of the south side of a gravel section, shows the notional elements (numbered 0 to 9) which occur at each sample group and the in-situ sampling apparatus. Sampling apparatus is installed in four of the ten elements at each sample group and named according to its associated group and element. The positions of the sampling apparatus vary between sample groups. Samples are only taken from one point in each side of the open water sections as previous studies have shown these sections to behave as well mixed tanks.

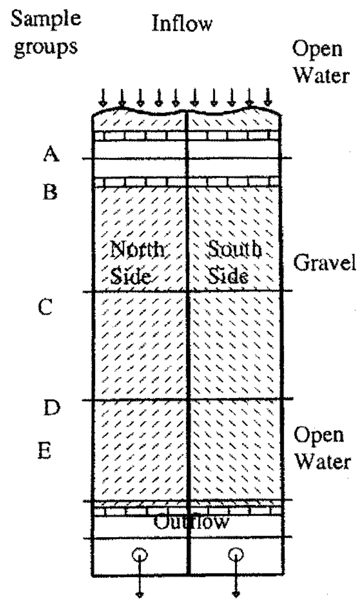

Figure 1. Plan view of the 3rd gravel section of a bed.

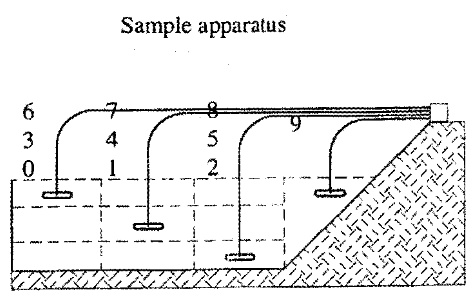

Figure 2. Cross sectional view of the south side of a gravel section showing notional elements (0 to 9) and typical sample apparatus locations.

METHODS

Experimental

Operating conditions. At this stage we are interested in the hydraulics of "new" beds prior to biological film development, so disinfected secondary effluent is used for the tracer studies. We recognise that the complete absence of a biofilm is unlikely, given the available nutrients, but we assume that biofilm growth is limited.

This study was performed across the third gravel section of the bed containing 20mm crushed rock. During the tracer study the operating water level was 0.5m at the bed outlet and the inlet flowrate was 434 ± 100 L/h. Submersible pumps were used to individually mix each side of the open water sections.

Tracer injection. Tracer solution (134g of Lithium Chloride in 2L of water) was prepared. To start the study one litre of tracer solution was mixed into each side of the open water section immediately upstream of the gravel section being studied.

Sample collection and analysis. Water samples were collected from each of the 28 sample points at hourly intervals for the first 30 hours of the study. In addition, more frequent sampling from the upstream open water section occurred during the first three hours of the trial. Furthermore, extra samples were taken from the downstream open water section (two hourly for 90 hours), to allow us to better define tracer response curves. Atomic absorption spectrophotometry was used to determine the lithium ion concentration in the samples (limit of detection = 0.02ppm).

Modelling

Initial modelling (model 1) followed the work of Levenspiel (1972); each side of the gravel section was modelled as a plug flow reactor with axial dispersion (PFDR) and each side of the open water sections was modelled as a continuous stirred tank reactor CSTR.

Kadlec and Knight (1996) used a multiparameter model based on a plug flow reactor with no axial dispersion and a series of equally sized CSTRs to describe flow through a SSF wetland. We are currently developing a multiparameter model based on four plug flow reactors (model 2). An initial plug flow reactor, with no axial dispersion, through which all the flow passes is used to account for the observed lag times between tracer input and response. The flow then passes to three parallel PFDRs, each with variable volume, flow and dispersion characteristics, to simulate channelling within the gravel sections.

RESULTS AND DISCUSSION

Mass balances

The water and lithium balances closed to within experimental error (Table 1), it is essential that these balances close if meaningful interpretation of the tracer study data is to be made.

Table 1. Overall water and lithium balances

	Water - average flowrates		Lithium - total quantity	
Stream	(L/h)	(%)	(g)	(%)
Inlet	434	100	21.9	100
Outlet	422	97	21	96
Evaporation	12	3	0	0
Accumulation	5	1	0	0

Variability of the inlet water flowrate was due to variations in water supply pressure - this is a very real phenomenon in operating systems and as such needs to be considered when modelling, particularly as the flowrates have a significant impact on the calculated lithium mass balance and on the dispersion coefficients used in the plug flow with dispersion model.

Pan evaporation was approximated from weather data, collected from an on-site weather station, using the Penman equation. Bavor *et al.* (1988) reported a linear relationship between evaporation from SSF gravel beds and Pan Evaporation but the correlation coefficient is very low, so further work is required to clarify this. Consequently we have applied a factor of 0.8, as is commonly used for SF wetlands, to estimate evaporation from within our gravel beds.

Overall lithium recovery was calculated by integrating hourly flowrate and concentration data for each side of the downstream open water section.

Open water section tracer response curves

Upstream open water section. This section performs as designed - it provides a well mixed tank at the inlet of the gravel section. Each side behaves similarly and can be adequately modelled as a CSTR (Figure 3). The data show 100% recovery of lithium at this sample group demonstrating that the CSTR model is conceptually sound.

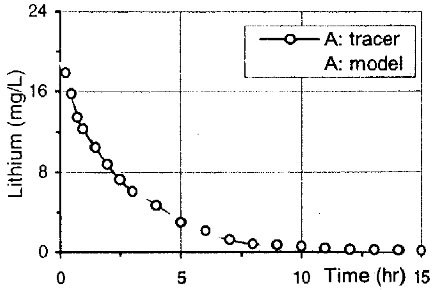

Figure 3. Average tracer response curve in the upstream open water section.

Downstream open water section. Kadlec and Knight (1996) characterise the single parameter, plug flow with dispersion model using the dimensionless, wetland dispersion number, ***D***, and quote typical values ranging from 0.07 to 0.33 for SF and SSF wetlands, where:

$\boldsymbol{D} = D/uL$

and: D = dispersion constant m^2/d
u = velocity, m/d
L = length of the wetland, m

A least squares fit of the single parameter dispersion model to experimental data results in a wetland dispersion number of 0.07. This is of the same order of magnitude as the dispersion number of 0.11 reported by Bavor *et al.* (1988) for a planted gravel bed. A dispersion number of 0.07 implies a moderate to large amount of dispersion within the gravel section (Levenspiel, 1972). For an operating system this means reduced pollutant concentration peaks and reduced pollutant removal rates in comparison with pure plug flow.

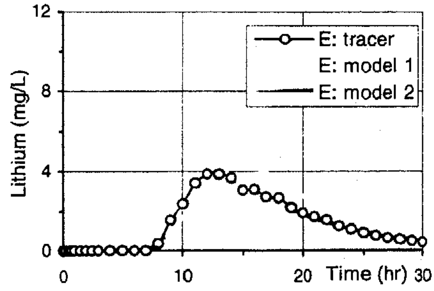

Figure 4. Average tracer response curve in the downstream open water section.

Even though these estimates of dispersion agree with other reports, Figure 4 shows that it was not possible to match the shapes of the single parameter dispersion model (model 1) and experimental curves (Figure 4). The experimental peak concentration occurred earlier than the model peak concentration and adjusting model parameters to match the 'experimental peak concentration time' resulted in overprediction of the peak concentration and underprediction of the lag time.

However, the multiparameter model (model 2) gave a better fit with experimental data (Figure 4).

Gravel section tracer response curves

Sample points. Flow through the gravel beds is not uniform. Other authors, e.g. Bavor *et al.* (1988) and Pilgrim *et al.* (1992) have attributed such non-uniformities to features associated with bed development, such as excessive solids loading or biofilm growth, leading to clogging and/or preferential flow paths. We agree that these mechanisms do affect flow patterns. However, here we show that some channelling exists from construction, despite stringent efforts to avoid this by;

- Careful construction of the beds - paying particular attention to uniformity in the slope of the base.
- Placement of the sampling apparatus within the gravel beds during construction.
- Grading and washing the gravel.
- Careful placement of the gravel within each bed, especially around sampling apparatus.

There is no apparent pattern to the channelling, it is not associated with edge effects and does not appear to follow single, continuous hydraulic lines through the length of the gravel section. Figure 5 shows the range of tracer responses through the cross section of the bed at sample group C. The range of responses in each side of the bed are different and the individual responses vary considerably, peak tracer concentrations vary from 4 to 10 mg/L and peak response times vary from 5 to 9 hours.

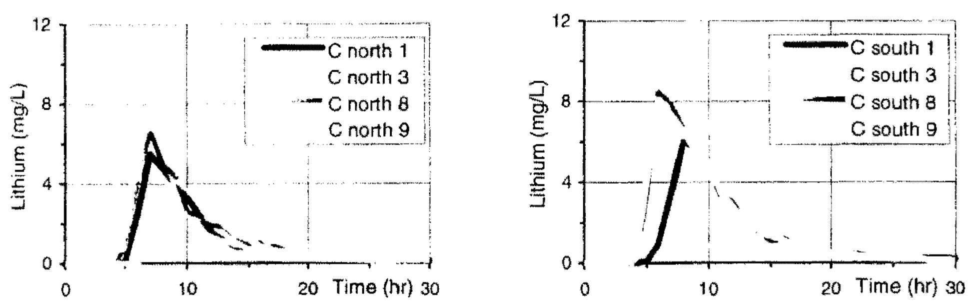

Figure 5. Tracer response curves for individual sample points in the gravel section at samplr group C.

Observations of channelling in this carefully constructed, pilot scale wetland have important implications for the operation of full scale wetlands, particularly where they are used as a low technology, low cost form of wastewater treatment, as greater irregularities in gravel size, shape and placement are inevitable.

Channelling of flows makes data interpretation difficult because the proportion of cross sectional area perpendicular to channelling flow is unknown, and not able to be estimated with any degree of accuracy. Thus water and tracer balances become quite complex, and simplifying and averaging assumptions are necessary to calculate them. At this stage we have chosen to equally weight the flows past each sample point in order to calculate internal lithium balances. This approach gives mixed results, at sample groups B, C and D it predicts 95%, 85% and 97% lithium recovery respectively. More work is needed to determine if there is a better method of proportioning the flows.

The difficulty in data interpretation also affects our ability to meaningfully optimise the fit of the models to experimental data taken from individual points within the bed.

The issues of channelling and proportioning flowrates to calculate internal mass balances are probably exacerbated by variations in the inlet flowrate to the bed and will become more complex as the beds mature.

Sample groups. A single water sample taken from an open water section will provide a true representation of the average tracer concentration at that location in the bed. For this reason we have used tracer concentration data collected from the open water sections to optimise our models. If the models are conceptually correct, optimising them in this way should produce a set of parameters that will adequately describe the tracer response for any section of the bed. Figure 6 shows that if we maintain the model parameters used to optimise the models for sample group E, neither model 1 or model 2 give an excellent fit to the average experimental data at sample groups B and C. However, model 2 seems to provide a better approximation of the average tracer response shapes, especially if we consider the fact that the tracer curves are based on 95% and 85% tracer recovery respectively.

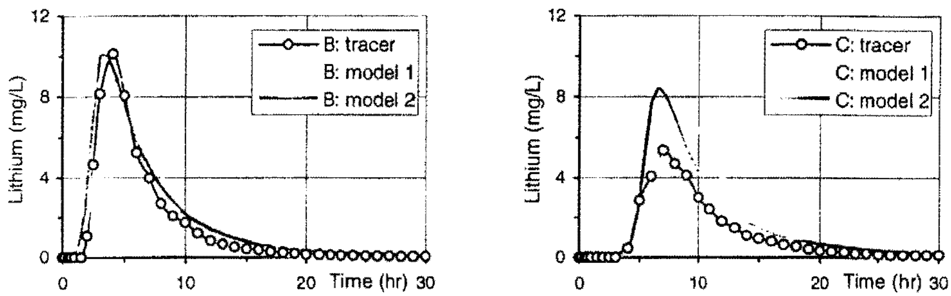

Figure 6. Average tracer response curves in the gravel section at sample groups B and C.

CONCLUSIONS

We have constructed a pilot scale SSF wetland incorporating a sampling system which allows rigorous monitoring of the wetland's hydraulic behaviour. Tracer studies indicate that the flow of water through the beds is not uniform and cannot be adequately described by a single parameter, plug flow with dispersion model. We have developed a multiparameter model, incorporating four plug flow reactors, which provides a better approximation of our experimental data. With further development this model will allow improvements to current SSF wetland design procedures and operational strategies, and will underpin investigations into the pollutant removal mechanisms at the Oxley Creek Wetland.

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