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FLOW PATTERN ANALYSIS OF CONSTRUCTED WETLANDS TREATING LANDFILL LEACHATE

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ABSTRACT

Three series of tracer studies were performed on three constructed wetlands at the New Hanover County Landfill near Wilmington, North Carolina, USA. One vegetated free water surface wetland (FWS-R), one vegetated subsurface flow wetland (SSF-R), and one unvegetated control subsurface flow wetland (SSF-C) were studied. A conservative tracer, lithium chloride, was used to study the chemical reactor behavior of these wetlands under normal operating conditions. Results indicated that short-circuiting is quite common in SSF wetlands, while FWS wetlands are well-mixed and not as subject to short-circuiting. These results were obtained from and reinforced with tracer measurements at interior points in these wetlands, analysis of residence time distributions from two different formulations, and the construction of residence volume distributions. The short-circuiting in the SSF wetlands can be attributed to the following: (1) Vertical mixing is inhibited by a combination of physical barriers and density gradients caused by rainfall and runoff dilution of the upper layer; and (2) Leachate is drawn from the bottom of the wetland, causing it to further prefer a flow path along the bottom.

KEYWORDS

Constructed wetlands; free water surface; landfill leachate; residence time distribution; short-circuiting; subsurface flow; tracer study.

INTRODUCTION

Many studies have assessed the potential for constructed wetlands to treat landfill leachate. In FWS wetlands, exposed plant surfaces provide habitat for the microorganisms responsible for the majority of BOD and nitrogen removal that goes on in these wetlands. In SSF wetlands, the roots of the wetland plants supply habitat for microorganisms, which are responsible for the degradation of many wastewater nutrients (Brix, 1987). For this reason, recent studies have considered maximizing the contact between the wastewater and the rhizosphere, or root zone, is considered a primary objective in designing these systems (Brix, 1987; Breen and Chick, 1995). However, Fisher (1990) noticed that most of the wastewater flow goes below the root zone in SSF wetlands, which adversely affects treatment. Breen and Chick (1995) confirmed this finding, noticing evidence of vertical stratification and short-circuiting along the bottom of the wetland. They claimed the cause of this non-ideal flow is plant uptake of nutrients, plant influence on hydraulics, and root densities in the area of flow.

Analysis of constructed wetlands can be difficult because of unsteady flow patterns. Precipitation and evapotranspiration influence the water budget and cause unpredictable flow of wastewater through the wetland (Kadlec *et al*., 1993; Kadlec, 1994). While wastewater inflows can be controlled in many of these systems, the uncertainty of hydrologic factors affects the reliability of these wetland systems (Kadlec and Tilton, 1979). In this study, flow patterns in one free water surface (FWS) and two subsurface flow (SSF) wetlands subjected to unsteady flows were studied.

Chemical reactor theory

The simplest way of characterizing the chemical reactor behavior of a wetland is by calculating the nominal detention time, or the average time that a water molecule spends in a reactor. The nominal detention time (τ) is calculated with the following equation: $\tau=V/Q$, where V represents the volume of water in the wetland (m^3) and Q represents the average flow rate (m^3/day). This detention time assumes that no stagnation, short-circuiting, or dead zones occur. This nominal detention time is a quick method of calculating the average contact time in the wetland, but its relation to the actual flow behavior in constructed wetlands is minimal. Analysis of chemical reactor behavior is the next step in analyzing constructed wetlands. The residence time distribution (RTD) represents a probability density function of the amount of time that a particle spends in the reactor (Levenspiel, 1972). The RTD is scaled such that the integration of the curve is unity.

Developing an RTD requires injecting a conservative tracer into a wetland and measuring the concentration of that tracer in the effluent with time. With effluent flow measurements and tracer concentrations, a RTD can be constructed from the following formula:

$$E(t) = \frac{Q*C(t)}{\int Q*C(t)\, dt} \qquad (1)$$

where E(t) = RTD function, t = time (days), Q = flow rate associated with that time (m^3/day), C(t) = effluent concentration at time t (mg/L). In steady conditions, the flow term is removed from this equation.

The first moment of the RTD function represents the residence time, the average amount of time that a water molecule spends in the wetland. The residence time (τ) is computed as follows:

$$\tau = \int t*E(t)\, dt \qquad (2)$$

Theoretically, the residence time should be identical to the nominal detention time, but since flow through constructed wetlands rarely flows unhindered through the entire wetland volume, these two values are rarely the same. The residence time calculated from equation (2) is a more accurate representation of the average amount of time a particle spends in the wetlands, as it is based on observed data rather than idealized assumptions about the nature of the wetland flow.

METHODS

Site description

Three series of tracer studies were performed on three pilot-scale constructed wetlands that had operated for two years at the New Hanover County Landfill near Wilmington, North Carolina, USA. Average length and width were 14.8 m and 4.0 m, respectively. One vegetated free water surface wetland (FWS-R), one vegetated subsurface flow wetland (SSF-R), and one unvegetated control subsurface flow wetland (SSF-C) were studied. Softstem bulrush (*Scirpus validus*) was the dominant plant species. Each of these wetlands received raw leachate from the same lagoon, so leachate characteristics did not vary between wetlands.

Sample ports

Sample ports to be used for interior sampling for this tracer study were driven in the interior of the subsurface flow cells. The side ports (S1-S6) were all driven to sample from a depth of 15 cm. Groups of three sample ports along the centerline were driven to sample from three different depths, 15 cm, 29 cm, and

42 cm, at four locations (A - D). Ten locations were marked for interior sampling in FWS-R, with #1 closest to the inflow. Samples were only taken at the surface in the free water surface wetland so that the flow patterns would not be disturbed.

Sampling

A total of seven tracer studies were initiated on three different dates. In May 1997, FWS-R and SSF-R were studied; in June/July 1997, FWS-R, SSF-R, and SSF-C were all studied extensively; and in December 1997, SSF-R and SSF-C were studied again. Total dissolved solids (TDS) in the leachate ranged from 3000 to 6000 mg/L, with an average of 5000 mg/L in the influent. For each tracer study, 500 grams of lithium chloride were diluted in 100 litres of water to reach a TDS concentration of 5000 mg/L, which was approximately the same as that of the leachate.

For the May and December tracer studies, effluent samples were taken once a day, and the flow readings from the effluent dippers were recorded at that time. For the extensive tracer study in June/July, effluent samples were taken every six hours for the first ten days, then every twelve hours for the next eleven days, then every 24 hours for the next fourteen days. The higher sampling frequency early in the June/July study was used to ensure that concentration peaks or valleys would not go undetected.

Interior points were sampled during the June/July study at 24 hour intervals in the subsurface flow cells, while they were sampled every two to three days in the free water surface cell. Analysis for lithium was performed on a Perkin-Elmer Model 5000 Atomic Absorption Spectrophotometer.

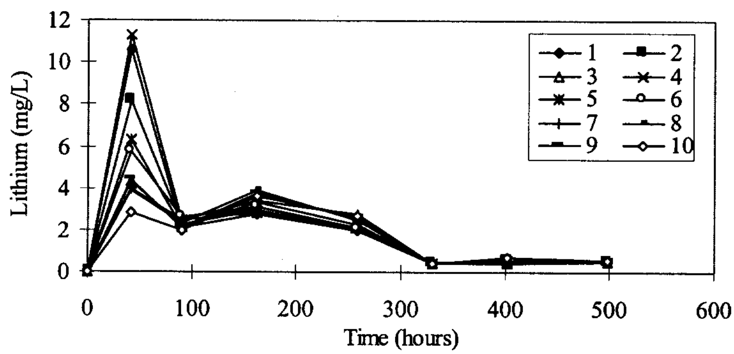

Figure 1: Concentration Curves, FWS-R Interior Points

Tracer concentrations at interior points

Internal tracer concentrations taken from the FWS wetland show that this wetland is well-mixed (Figure 1). Lithium concentrations varied substantially before the first rain event, which occurred after two days. Internal tracer concentrations did not vary much spatially after the first rain event, which indicates that these wetlands allow for free mixing of influent leachate and the water in the wetland.

The subsurface flow wetlands had more complex internal flow patterns. Figure 2 (a, b, c, and d) summarizes the internal flow patterns in SSF-R. On these figures, the letter associated with each curve (A, B, C, or D) represents the location along the centerline of that triad of sample ports, with A representing the one closest to the influent structure and D representing the one closest to the effluent structure. The number (1, 2, or 3) represents the depth of the sample port, with 1 representing the 15 cm depth, 2 representing the 29 cm depth, and 3 representing the 42 cm depth. Total lithium recovery was 98% in this wetland.

From each triad of sample ports to the next, the concentration peaks decreased, broadened, and were shifted later in time. This behavior is expected as diffusion and dispersion move the tracer through the wetland. However, a comparison of each depth sample down the centerline reveals a downward migration of the tracer. At the A points, the 15 cm sample port reached the highest peak concentration, while the 42 cm port reached the lowest. By the C and D points, this trend was reversed. Similar results can be seen with relative tracer mass recovery, which can be represented by the area under the curve of interior tracer concentration vs. time. Again, mass recoveries decreased with increasing depth at the A points, while at the C and D points, much more tracer was recovered at the 42 cm sample port than at the 15 cm sample port.

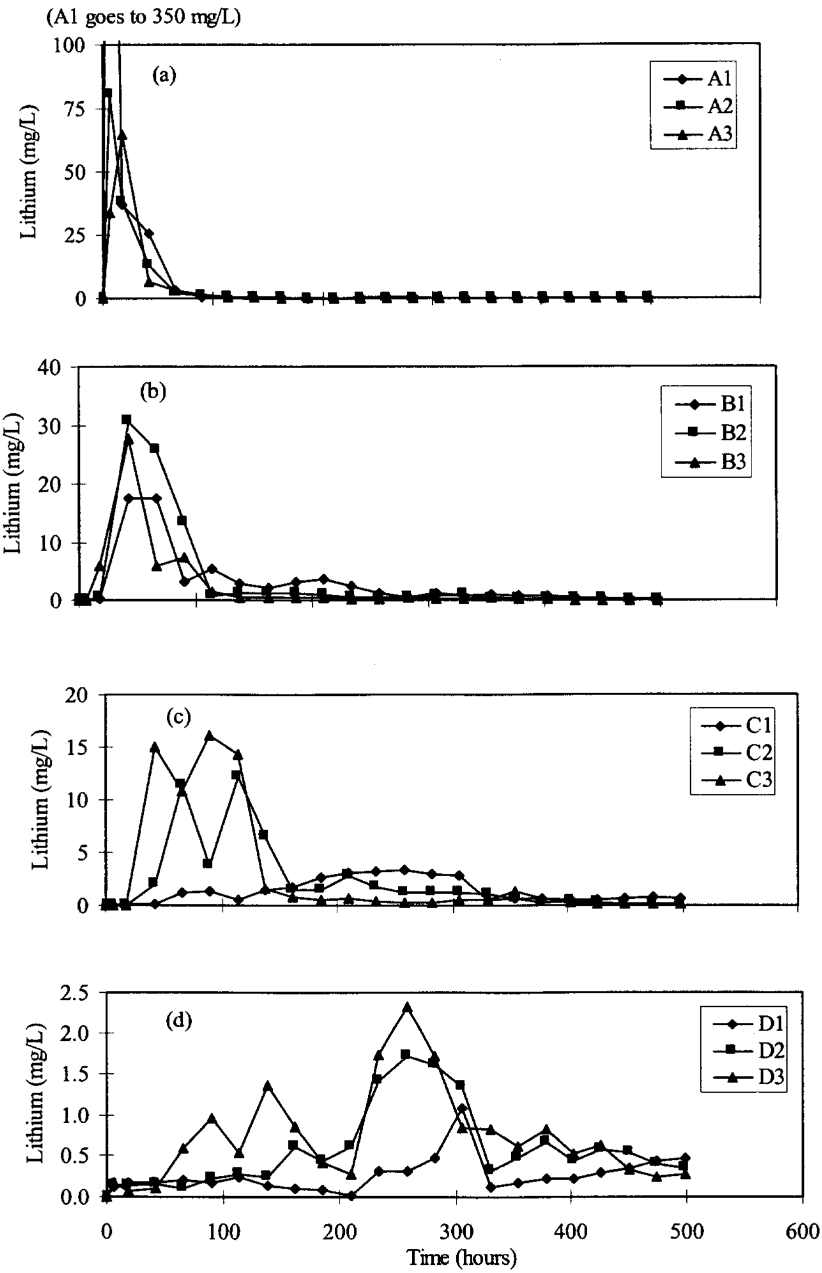

Figure 2: SSF-R Interior Concentration Curves: (a) "A" Points; (b) "B" Points; (c) "C" Points; (d) "D" Points

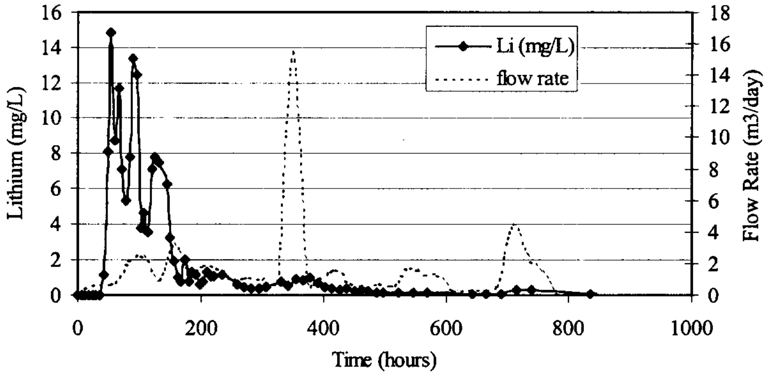

Figure 3: Effluent Concentrations and Flow Rates, SSF-R, June/July 1997

Further evidence of nonideal flow is apparent from comparison of the concentrations at the D points (Figure 2d) to the effluent concentrations gathered from SSF-R (Figure 3). While concentrations were mostly near or below 1 mg/L at the D points, effluent tracer concentrations peaked at around 15 mg/L. A great deal of the tracer mass was not caught at all by the interior points, particularly those far from the influent structure. These SSF wetlands are 61 cm deep at the bottom, but the deepest sample port was only 42 cm deep. That leaves about 19 cm of room through which flow could pass and not be caught by the interior sample ports. The study of the subsurface flow control wetland (SSF-C) confirmed this behavior as well.

The non-ideal flow in SSF wetlands can be attributed to vertical stratification. This stratification pattern was likely caused by rainfall and the effluent structure in the wetland. Since the effluent was drawn from the bottom of the wetland, the flow tended to migrate to the bottom, after the influent structure originally deposited it at the top of the wetland. When rain fell in the wetland, it remained above the much more dense leachate. In the FWS wetland, mixing of rainwater and leachate occurred freely, but in the SSF wetlands, the gravel medium prevented adequate mixing. These three effects led to the tracer behavior shown in Figure 2.

Unsteady residence time distributions

In the highly unsteady conditions to which most real-world constructed wetlands are subjected, constructing a meaningful residence time distribution (RTD) is difficult. Combining flow rate and concentration can be useful for observing when masses of tracer leave the wetland, but this form of RTD is dependent on the flow conditions the wetland undergoes; high flow rates mask low concentrations. For example, Figure 4, the June/July RTD for FWS-R, shows the irregular pattern resulting from irregular flow rates.

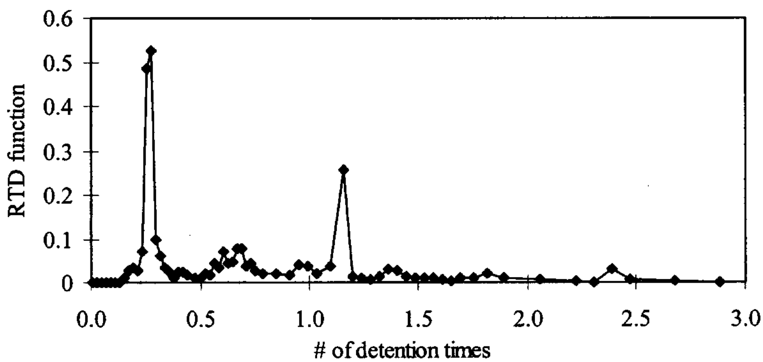

Figure 4: Residence Time Distribution, FWS-R, June/July 1997

Residence times were calculated from these unsteady RTDs for each wetland and each tracer study. These residence times are summarized in Table 1 along with nominal detention times and mass recoveries for each wetland. The residence times calculated from these RTDs are labeled as "unsteady flow RTD".

<u>Adjusted residence time distributions</u>

Another method of constructing a residence time distribution was developed that employs a dilution method for correcting for rainfall flows (Cardona-Trujillo, 1998). A steady inflow rate was assumed, but concentrations were adjusted continuously by the amount of external flow from rain that enters the wetland. This RTD assumes that rainfall mixes evenly in the wetland and dilutes the tracer by the ratio of the volume of rain to the volume of water in the wetland. If rainfall is the primary source of unsteady flow (a fairly accurate assumption for these wetlands), this creates a RTD which can be generated fairly consistently regardless of unsteady external flows. This form of RTD is calculated assuming steady flows after the dilution factors are applied to the concentration values, according to equation (1). The residence time from this RTD is calculated as it is in equation (2). In the FWS-R tracer studies for May and June/July, the tails of the RTDs were exponentially extrapolated because effluent samples were not taken through the three detention times necessary to adequately quantify a RTD. The adjusted residence time distribution for FWS-R during the June/July tracer study (Figure 5) shows that the adjusted RTD curve is much smoother than the unsteady RTD (Figure 4). Residence times calculated from these adjusted RTD (Table 1) are similar to values calculated using the unsteady flow RTD. The adjusted RTD may give better estimates of average residence time because it allows the use of a steady flow rate; however the difference in values calculated by these two methods does not appear to be large.

Table 1. Residence times and tracer mass recoveries

		FWS-R	SSF-R	SSF-C	
May 1997	unsteady flow RTD:	10.8	3.7	*	(days)
	adjusted RTD:	12.6	4.1	*	(days)
	nominal detention time:	11.6	14.7	*	(days)
	percent recovery**:	101.6%	117.5%	*	
June/July 1997	unsteady flow RTD:	10.5	6.2	2.5	(days)
	adjusted RTD:	9.8	5.3	2.9	(days)
	nominal detention time ***:	10.1	12.1	12.6	(days)
	percent recovery:	99.0%	97.9%	96.3%	
December 1997	unsteady flow RTD:	*	3.3	1.9	(days)
	adjusted RTD:	*	3.4	1.9	(days)
	nominal detention time:	*	10.5	12.4	(days)
	percent recovery**:	*	98.9%	148.7%	

* No tracer test run on this wetland at this time

** Inaccurate percent recoveries can be attributed to unsteady flow and low sampling frequency

*** Due to abnormally high rainfall during the latter three weeks of this study, these nominal detention times are based on the first 14 days of the study, which corresponds to the period when tracer concentrations were significant. The nominal detention times over the entire sampling period were 6.5 days for FWS-R, 11.2 days for SSF-R, and 11.4 days for SSF-C.

For the FWS wetland, the unsteady RTDs and the adjusted RTDs were both within one day of the nominal detention time for each study period. This discrepancy in either direction is within expected limits of measurement errors. These results indicate that the FWS wetland was not subject to short-circuiting, and that the nominal detention time is usually a good estimate of the actual detention times in the wetland.

The calculated residence times for SSF-R and SSF-C are much shorter than the theoretical nominal detention times for these wetlands. In the SSF-R wetland, the residence times calculated from the adjusted RTD are approximately one third of the nominal detention time. In the SSF-C wetland, the highest residence time calculated is less than 25% of the nominal detention time of approximately 12.5 days. Therefore, significant short-circuiting occurred in these wetlands, as was confirmed by the interior concentration profiles.

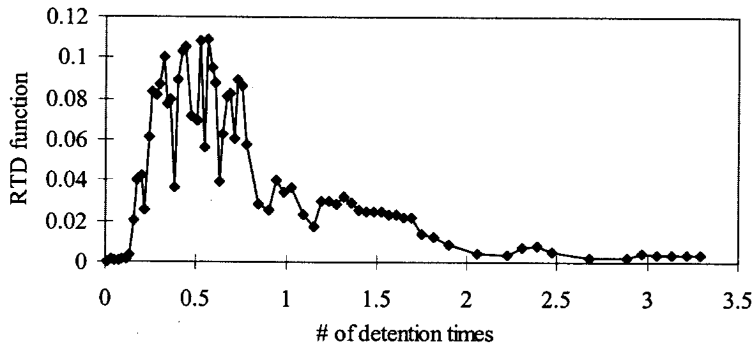

Figure 5: Adjusted FWS-R RTD, June/July 1997

CONCLUSIONS

In SSF wetlands, vertical stratification is a common mechanism which causes short-circuiting. This vertical stratification can be attributed to density differences in leachate and rainwater, the removal of the effluent from the bottom of the wetland, and gravel and root densities which prevent vertical mixing. This vertical stratification causes leachate to flow below the root zone, adversely affecting treatment.

In FWS wetlands, mixing can occur more freely in the water. This greater level of mixing increases leachate contact with plant matter and can make FWS wetlands more efficient than SSF wetlands in terms of hydraulic efficiency.

ACKNOWLEDGEMENTS

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