Cold climate hydrological flow characteristics of constructed wetlands

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Smith, E., Gordon, R., Madani, A. and Stratton, G. 2005. **Cold climate hydrological flow characteristics of constructed wetlands**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **47**: 1.1-1.7. Hydraulic tracers provide a means of estimating retention times (RTs) of constructed wetlands. The removal of pollutants by these systems is closely associated with their RTs. Better understanding RTs under a range of conditions should therefore help to provide insight into the overall treatment efficiencies offered by on-farm wetlands. The objective of this investigation was to estimate RTs in two similar surface flow agricultural constructed wetlands during high flow periods (i.e. April and January) and compare them to their theoretical retention times (TRT) based on plug flow hydraulics. Two side-by-side wetlands were evaluated and operated at different depths. Both systems were loaded with dairy wastewater at a rate of 50 kg of BOD_5 $ha^{-1}d^{-1}$. Bromide was used as the tracing element and was pulse injected into each wetland. Results demonstrated that RTs were 50 to 60% of the TRT. Bromide appears to be a suitable ionic tracer for non-growing season wetland studies. Mass recoveries of the tracer ranged from 72 to 81%. Only 50 to 65% of the volume in these systems was considered to be active, indicating that there needs to be more uniform mixing. Flow conditions however, appeared to be good in both ice covered and unfrozen conditions.

Les traceurs hydrauliques peuvent être utilisés pour estimer les temps de rétentions (TR) des marais artificiels. Le captage des polluants par ces systèmes est étroitement lié aux TR. Une meilleure connaissance des TR sous différentes conditions devrait aider à mieux comprendre l'efficacité de traitement qu'offrent les marais artificiels à la ferme. L'objectif de cette étude était d'estimer les TR de deux marais similaires construits en milieu agricole pour traiter un effluent de surface durant les périodes de hauts débits (c.à.d d'avril à janvier) et de les comparer à leurs temps de rétention théorique (TRT) tels que calculés à partir de leurs débits hydrauliques. Deux marais situés côte à côte ont ainsi été évalués lorsqu'ils étaient opérés à différentes profondeurs. Les deux systèmes étaient alimentés avec des eaux de laiterie à un taux de 50 kg de DBO_5 ha^{-1} j^{-1}. L'élément traceur utilisé était le bromure qui était injecté par cycle dans chacun des marais. Les résultats ont démontré que les TR correspondaient à 50 à 60% des TRT. Le bromure semble être un traceur ionique souhaitable pour les études de marais durant la saison morte. La récupération massique du traceur a varié de 72 à 81%. Seulement 50 à 65% du volume de ces systèmes a été considéré actif, ce qui indique qu'un mélange plus uniforme soit nécessaire. Toutefois, les conditions d'écoulement ont semblé adéquates avec ou sans couvert de glace.

INTRODUCTION

Constructed wetlands are recognized as low input wastewater treatment systems. They have shown promise for agricultural wastewater treatment in warm climates with removal efficiencies for many parameters such as BOD_5 ranging from 70 to 99% (Cronk 1996). As a result, the agricultural sector is rapidly starting to utilize these systems for on-farm wastewater treatment during warm months. Treatment efficiencies have however, been variable (Hammer 1992; Gilman 1994; Kadlec and Knight 1996). This is presumably due to lack of understanding of methods to optimize their physical, chemical, and biological treatment processes, and also the hydraulic characteristics of wetlands (Gilman 1994; Shilton and Prasad 1996). It is also uncertain whether they can effectively treat agricultural wastewater year-round in cooler climates, especially when ice conditions exist (Kadlec and Knight 1996; Pries et al. 1996).

Wetland hydrology influences sedimentation, aeration, biological transformations, and soil adsorption processes (Kadlec and Knight 1996; Persson et al. 1999; Kadlec and Reddy 2001). Factors which affect retention time (RT) and wetland performance include, water velocity and flow rate, operating depth and fluctuation, circulation and distribution patterns, groundwater conditions, and soil permeability (Hammer 1992; Kadlec and Knight 1996; Persson et al. 1999).

To optimize wetland treatment processes, it is beneficial to maximize contact between wastewater contaminants, the wetland substrate and aquatic plants, while minimizing short-circuiting (Hammer 1992; Persson et al. 1999). Short-circuiting is the existence of preferential flow paths within the hydraulic regime of any aquatic system (Werner and Kadlec 2000). These flow paths, allow wastewater to move through a wetland more rapidly than the theoretical retention time (TRT) would suggest (Kadlec and Knight 1996). The TRT is a calculation that ignores the influence of obstructions, stagnant regions, and velocity gradients within the wetland. The difficulty however, is that actual retention time (RT) can substantially differ from the TRT due to these assumptions.

Depending on the flow characteristics in a wetland, different parcels of wastewater remain in the system for varying lengths of time. This in turn, can lead to variable levels of treatment (Kadlec and Knight 1996). As a result, a minimum of 12 days of RT has been suggested for the treatment of agricultural wastewater in surface flow wetlands (NRCS 1991).

When estimating wetland treatment it is common to assume that wastewater flow patterns resemble either plug flow or complete mixing (Levenspiel 1999). Agricultural wetland design criteria have been derived from municipal treatment system design criteria, which have traditionally assumed that

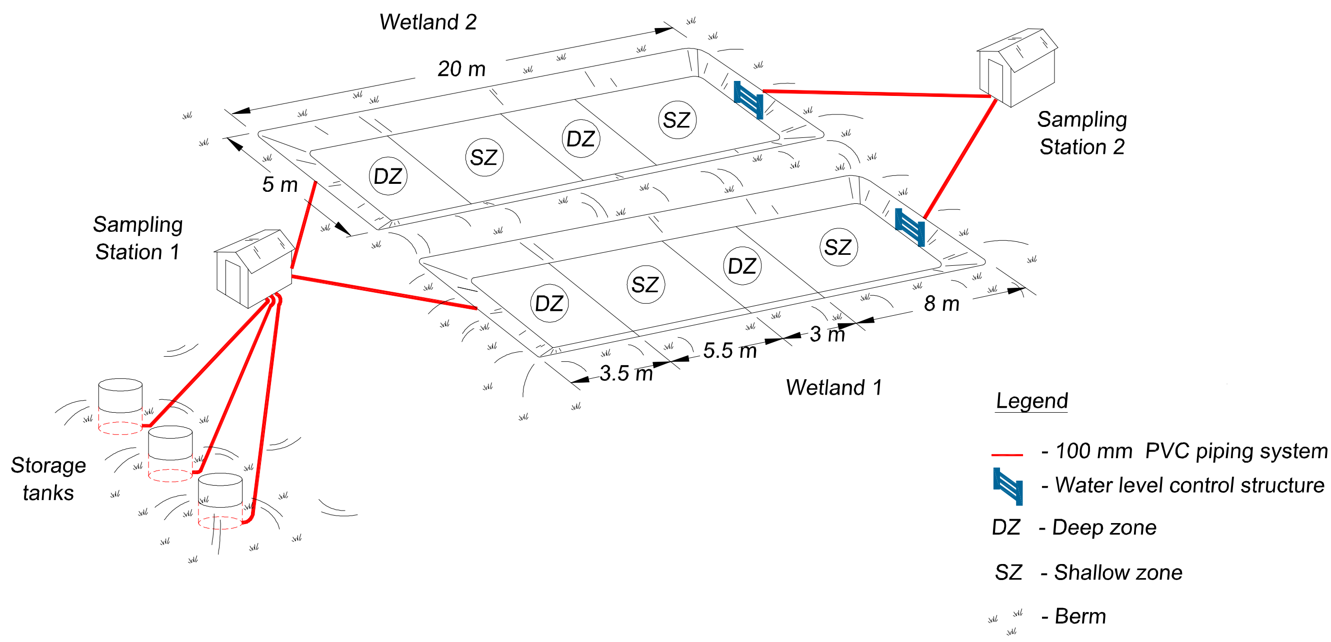

Fig. 1. Schematic of surface flow constructed wetlands located at the Bio-Environmental Engineering Center, Nova Scotia Agricultural College.

plug flow conditions and first order degradation kinetics prevail. Although this model is simple and widely used, it does not fully integrate the complex processes which actually occur in wetlands (Kadlec 2000).

In a completely mixed system, the fluid elements are uniform. In this case, it is assumed that the fluid is instantaneously dispersed throughout the wetland. While in a plug flow system, the influent passes along the length of the wetland without any longitudinal mixing. It has been shown however, that treatment wetlands typically do not always follow plug flow hydrology (Kadlec 2000; Stern et al. 2001).

The retention time distribution (RTD) is a prerequisite to understanding the treatment mechanisms provided by wetlands (King et al. 1997; Persson et al. 1999). By utilizing a tracer, RTs can be easily and accurately measured (Kadlec and Knight 1996). Tracer tests help to elaborate flow distributions, the degree of mixing, longitudinal dispersion, short-circuiting, and dead zones within wetlands (Shilton and Prasad 1996; Levenspiel 1999). More accurate representations of treatment wetland hydraulics will therefore help to further the development of improved on-farm wetland design criteria. Additionally, surface flow wetland design criteria have traditionally utilized rectangular treatment cells. Little information exists however on the extent to which RTs resemble plug flow-based TRTs in cold climates. More so, it is important to develop a better understanding of their hydrologic characteristic during high flow periods (i.e. non-growing season) when RTs are minimized. Therefore the objective of this study was to assess the RTs of surface flow constructed wetlands in a cold climate during high flow periods using an ionic tracer. Actual RTs were compared with TRTs based on plug flow assumptions and determining subsequent tracer mass recovery.

METHODS

Two similar 100 m^2 (20 × 5 m) surface flow wetlands (Fig. 1) were constructed in May 2000 at the Bio-Environmental Engineering Center (45° 22’ N, 63° 16’ W, 40 m) of the Nova Scotia Agricultural College in Bible Hill, Nova Scotia (Smith 2002). Both wetlands were single-celled with polyethylene liners at their base. They contained two deep (≈1.0 m) and two shallow zones (≈0.15 m). The shallow zones included 0.30 m of loamy sand soil to act as a bed for aquatic vegetation that included cattails (*Typha latifolia*) and various freshwater grasses. Water level was approximately 0.15 m above the soil substrate in the shallow zone at the start of operation.

Each wetland was loaded with dairy wastewater (manure and milkhouse washwater-based) with a BOD_5 ranging from 1600 to 1800 mg/L (≈1 m^3/d) that was stored in three heated storage tanks (Fig. 1). Low heat was used in the cold months of the year to prevent the wastewater from freezing in the tanks. Wastewater was gravity fed from the storage tanks into Sampling Station 1 (Fig. 1) at a controlled rate of 50 kg BOD_5 $ha^{-1}d^{-1}$. Inflow rates were measured using a calibrated tipping bucket and equal amounts of waste entered each wetland through a single 100 mm PVC pipe by the use of a flow splitter (Fig. 1). Data were recorded using a Campbell Scientific CR10X datalogger (Campbell Scientific, Edmonton, AB).

Meteorological conditions were monitored hourly at the site and recorded using a Campbell Scientific CR10X datalogger (Campbell Scientific, Edmonton, AB). Measurements included, precipitation using a heated rain gauge (Campbell Scientific, Edmonton, AB) and air and water temperatures using copper constantan thermocouples referenced to a calibrated thermistor. Average water temperatures were measured by placing two thermocouples in the first deep zone of each wetland. One thermocouple was placed 100 mm from the bottom of the deep

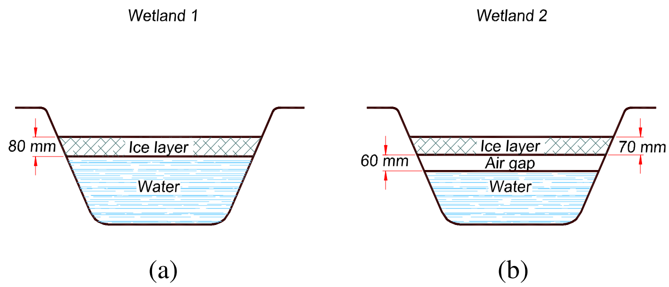

Fig. 2. Schematic of ice conditions that existed during the start of the January 2002 tracer study for (a) wetland 1 and (b) wetland 2.

zone, while the other was placed 100 mm down from the top of the wetland water level. In addition, plant debris density was measured as the number of cattail stems per square meter.

Tracer studies (each lasted approximately 30 days) were performed for both wetlands starting on: (i) April 1, 2001 and (ii) January 1, 2002. Throughout the April study, the wetland water depths and volumes were similar for both wetlands. Water depths ranged from 0.690-0.755 m and 0.710-0.762 m for W1 and W2, respectively. Average water depths were 0.726 m for W1 and 0.736 m for W2. Wetland water levels increased throughout the April study, through rainfall events (93.1 mm) and high wastewater loading. Prior to the January study, wetland 1 (W1) remained at a constant water depth; while the water level in wetland 2 (W2) was altered during the time of freezing (December 2001) to achieve an insulating effect and prevent total ice formation (Fig. 2). Monitoring in January 2002 was performed when ice was present in both wetlands. There was approximately 80 and 70 mm of ice on W1 and W2, respectively, at the start of January. Ice thickness increased throughout the study period in W1. The air gap left in W2 (≈60 mm) prevented subsequent ice formation throughout most of the month. When air temperatures dropped rapidly however, an additional ice layer was formed below the air gap in W2 by mid-January (Fig. 2). Visual observations of both wetlands in the January study found that snow accumulation on W1 was greater, presumably due to drifting. As snow-melt conditions existed in late January 2002, the water depth increased. Throughout both study periods no vegetation was growing in either wetland however, plant debris from the previous growing season was present and was more dense in January 2002 compared to April 2001 (Table 1).

Wastewater flow rates for both study periods were established to produce a 30 d TRT as :

$$TRT = \frac{V\eta}{Q} \quad (1)$$

where:

V = wetland operating volume (m^3) calculated using GPS technology,

Q = wastewater loading rate (m^3/d), and

η = porosity (the ratio of the volume of the constructed wetland occupied by water to the volume of the wetland occupied by plants and water; 0.95 for cattails) (Kadlec 1994; Kadlec and Knight 1996).

On average, 1000 L/d of wastewater entered each wetland throughout each tracer study. Outflow volumes differed due to variable precipitation, evaporation, and ice and snow-melt. Wetland outflows were obtained through a single 100 mm PVC pipe that was located in the final shallow zone (Fig. 1). Outflows were recorded using a Campbell Scientific CR10X datalogger (Campbell Scientific, Edmonton, AB) and calibrated tipping buckets for each wetland in Sampling Station 2 (Fig. 1).

Bromide (Br^-) is regarded as one of the best tracers for use in soil and water environments (Freeze and Cherry 1979; Everts et al. 1989; Chendorain et al. 1998; Whitmer et al. 2000; Jamieson et al. 2001) as it is: (i) nonreactive in most environments, (ii) found at low background concentrations, (iii) easy to analyze, and (iv) has a low toxicity (Whitmer et al. 2000). Studies have indicated Br^- mass recoveries in wetlands ranging from 48 to 87% (Chendorain et al. 1998; Whitmer et al. 2000; Jamieson et al. 2001). Reduced mass recoveries were believed to be caused by plant uptake (Whitmer et al. 2000). Therefore, it is considered as a more appropriate tracer during periods of reduced plant growth (Whitmer et al. 2000). For this study, potassium bromide (KBr) with 99.5% purity was used as the tracing element.

The RTD represents the time various fractions of wastewater spend in the wetland (Kadlec 1994; Kadlec and Knight 1996). It is measured by injecting a known amount of tracer into the wetland inlet and then measuring the outlet concentration over time (Kadlec 1994). For the input of a tracer into a non-steady flowing system (such as the wetlands used in this study), the function *E(t)* is calculated by:

$$E(t) = \frac{Q_e C(t)}{\int_0^\infty Q_e C(t) dt} \quad (2)$$

Table 1. Site conditions at the Bio-Environmental Engineering Center, Nova Scotia Agricultural College, during both tracer studies and for both wetlands, W1 and W2.

Tracer study	Plant density (cattails/m^2)	Air temperature (°C)	Water temperature (°C)		Wetland rainfall (m^3)	Wetland snowfall (m^3)	Wastewater inflow (m^3)	Outflow (m^3)	
			W1	W2				W1	W2
April 2001	5	2.3	5.7	6.1	9.31	0.0	31.6	30.2	29.2
January 2002	10	-4.1	4.7	5.1	7.95	5.33	33.9	32.5	29.5

where:

$E(t)$ = fraction of time that the tracer spends in a wetland between sample periods,
Q_e = wastewater flow rate (m^3/d),
$C(t)$ = tracer outlet concentration (mg/L), and
t = time (d).

The numerator is the mass flow of tracer at the wetland outlet at time, t, after the addition of the tracer, while the denominator is the sum of all the tracer collected and should be equal to the known total mass of the injected tracer (Kadlec 1994; Whitmer et al. 2000). When $E(t)$ for each sample time is calculated, the values can be added to determine the fraction mass recovery of the tracer.

In the present study, Br^- was injected simultaneously at the inlet of each wetland. A general rule for tracers is that the tracing element should be at least 20 times the background concentration (Bowman 1984). Background concentrations in both wetlands were <0.25 mg/L, so based on their volumes, 53 and 62 g of KBr were injected in April and 74 and 85 g in January for W1 and W2, respectively. The volumes at the time of the tracer studies were slightly different due to excavation. Water samples were collected daily, at 0800h, from each outlet (Sampling Station #2), for 30 d. Samples were also collected at 35 and 40 d to ensure that Br^- concentrations had returned to background levels.

Water samples were analyzed by ion chromatography according to USEPA method #9056 (APHA 1998), using a Dionex Model DX500 Ion Chromatography System (Dionex Corp., Sunnyvale, CA), which consisted of a Model GP50 Gradient Pump, a Model CD20 Conductivity Detector, a model LC10 Chromatography Organizer with Injector, and a Model 4600 Integrator. The analytical column used was a Dionex 4 × 250 mm IonPac AG14 anion-exchange column with a corresponding 4 × 50 mm guard column. The detection system included a Model ASRS-Ultra Anion Self-Regulating Suppressor. An isocratic separation was employed using an aqueous 3.5 mM sodium carbonate/1.0 mM sodium bicarbonate mobile phase at a flow rate of 1.2 mL/min (Dionex Corp., Sunnyvale, CA).

The RT is determined from a RTD curve and is calculated from the first moment of the tracer curve (Kadlec 1994; Jamieson et al. 2001) as:

$$RT = \int_0^\infty tE(t)dt \tag{3}$$

The RT is a location parameter describing the centroid of the distribution. The variance (σ^2) can be calculated from the second moment as the spread of the tracer:

$$\sigma^2 = \int_0^\infty \left(t - RT\right)^2 E(t)dt \tag{4}$$

where σ^2 is the RTD variance (d^2). The greater the variance, the greater the distribution's spread (Kadlec 1994; Levenspiel 1999).

From the RT it is also possible to calculate the active volume (V_a) of each wetland, with the assumption that the total and active flow rates are equal (i.e. $Q = Q_a$), which is normally the case (Torres et al. 1997; Simi and Mitchell 1999). Active volume in a wetland is the volume in a wetland that is responsible for the mixing of that system and can be stated as:

$$V_a = \frac{Q_a \times RT}{V_T} \times 100 \tag{5}$$

where:

V_a = active volume of the wetland (%),
Q_a = active flow rate (m^3/d), and
V_T = total volume (m^3). The V_T was calculated by measuring the volume of each wetland three times, during each study.

Site conditions throughout the April 2001 and January 2002 studies are summarized in Table 1.

RESULTS and DISCUSSION

RTD curves

Response curves for the non-ideal flow systems were achieved for both wetlands for both study periods (Fig. 3a and b). Results demonstrated that the tracer did not travel as a single non-spreading slug, as would be the case for plug flow, nor did it instantaneously disperse, as with a completely mixed flow, but rather traveled under conditions somewhere in between. Results demonstrate that plug flow conditions did not exist, this can be seen by a sharp increase in Br^- concentration followed by a decline in concentration (Fig. 3a and b). The results also demonstrate that they are not completely mixed systems because the Br^- concentration coming out of the system is not constant (Fig. 3a and b), meaning that the Br- is not uniformly mixed within the wetlands.

The RTD curve for W1 (Fig. 3a) had a maximum Br^- concentration of 23.4 mg/L, occurring at 14 d. Following this, concentrations declined to background levels (detection limit: <0.25 mg/L) at 27 d. In April 2001, W2 (Fig. 3b) took longer to reach a maximum concentration (22.0 mg/L) at 16.5 d, however, this curve displayed a similar trend to W1. Following tracer injection in January 2002, Br^- concentrations initially appeared at 5 d in W1 and 6 d in W2 (Fig. 3a and b). Peak concentrations were at 18 d in W1 and 20 d in W2. Once maximum concentrations were reached, there was again a rapid decline in Br^- levels. Reductions to background concentrations appeared by 30 d in each wetland (Fig. 3a and b).

Mass recoveries, RTs, and σ^2 were computed from the RTD curves (Fig. 3a and b) and are provided in Table 2. Retention time distribution curves (Fig. 3a and b) did not display a skewed pattern, similarly observed by Kadlec and Knight (1996), King et al. (1997), Kadlec (2000), Werner and Kadlec (2000), and Whitmer et al. (2000). As indicated by the sharp increase in Br^- concentrations followed by their rapid decline, the existence of dead zones and short-circuiting are present within the wetlands. This is similar to other surface flow wetlands (Kadlec and Knight 1996; King et al. 1997; Kadlec 2000; Werner and Kadlec 2000; Whitmer et al. 2000). Minimal adsorption of Br^- in each wetland was observed based on this rapid return to background levels. This was believed to be partially due to the fact that our studies were conducted outside the active growing season. Previous studies (Whitmer et al. 2000) have suggested that Br^- has a tendency to be taken up during periods of rapid plant growth. Effluent samples collected at 35 and 40 d had Br^- concentrations <0.25 mg/L, suggesting that the tracer had either left both wetlands or was resident within dead zones.

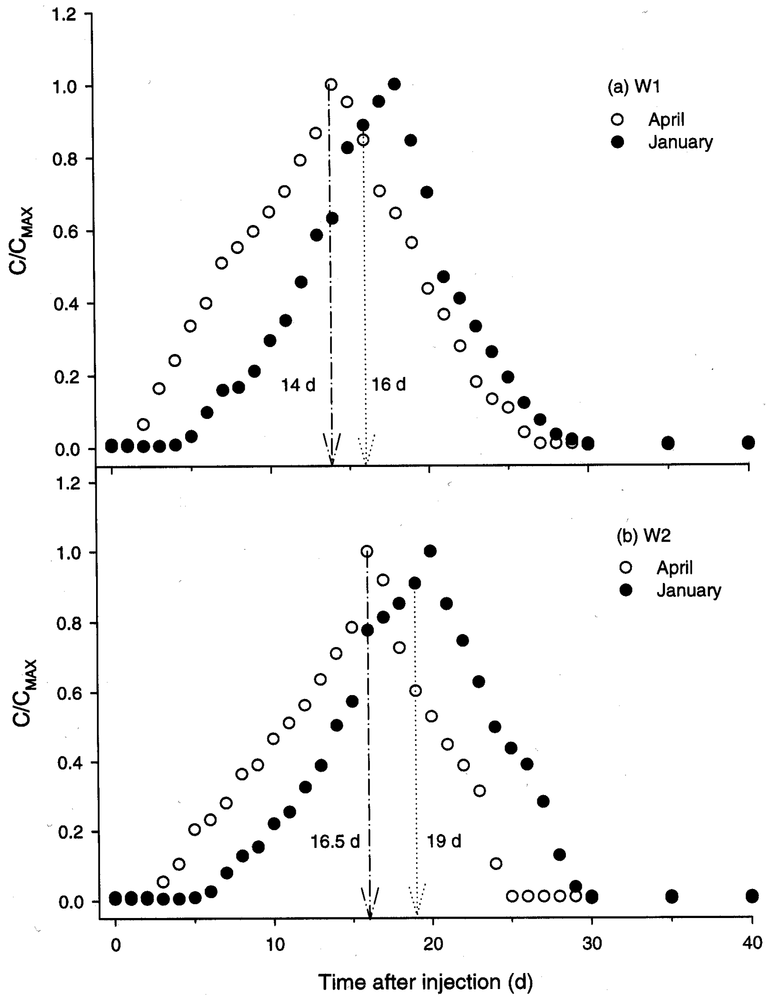

Fig. 3. Retention time distribution curves for bromide (Br⁻) tracer at the outlets for (a) wetland 1 (W1) and (b) wetland 2 (W2) in April 2001 and January 2002). The vertical line denotes the calculated retention time.

Mass recovery

Mass recoveries from April 2001 were calculated to be 81 and 78% for W1 and W2, respectively (Table 2). During periods when ice conditions were present, mass recoveries were reduced but were still high (>70%). For W1 they were 75 and 72% for W2 (Table 2). This demonstrates that adequate flow through the wetlands continues to prevail even during frozen conditions. With these same wetlands, Smith (2002) observed high winter-time treatment efficiencies for wastewater parameters including BOD_5, TSS, TP, SRP, TKN, NO_3^--N, NH_3-N, and fecal coliform (Table 3).

The slightly reduced mass recoveries, for January 2002, may have been due to some of the Br^- being bound up in the ice layers; however, we can only speculate as this was not measured. All mass recoveries were still higher than Whitmer et al. (2000) and comparable to Jamieson et al. (2001), who also used KBr as a wetland tracing element.

Table 2. Summary of bromide (Br^-) mass recoveries in outlet samples, retention time (RT), variance (σ^2), and active volume (V_a) for two tracer studies and two wetlands.

Tracer study	Wetland	Br^- mass recovery (%)	RT (d)	σ^2 (d^2)	V_a (%)
April 2001	W1	81	14.0	20.6	50.2
	W2	78	16.5	18.7	56.5
January 2002	W1	75	16.0	19.7	53.5
	W2	72	19.0	21.0	65.0

Retention time

Mean RTs were determined for both study periods. The RT of both wetlands in April 2001 and January 2002 were approximately 50% of the 30 d TRT (Table 2). For W1, the RT was 14 d in April 2001 and 16 d in January 2002 (Fig. 3a). In January 2002, the RT of W1 was 16.5 d and 19 d for W2 (Fig. 3b). These large differences between RT and TRT suggest that channeling was occurring within these systems.

To optimize wastewater treatment it is important to maximize contact between wastewater contaminants, the wetland media, and the plant roots and stems, as well as minimizing any short-circuiting (Hammer 1992). Although our results demonstrated that the RTs in both wetlands exceeded the 12 d minimum RT recommended (NRCS 1991) for surface flow agricultural wetlands, the discrepancy between the TRTs and RTs warrants further research to attempt to optimize wetland flow characteristics.

For both wetlands, RTs were longer in January 2002 compared to April 2001, although inflow and precipitation combined were greater than outflow rates (Table 1) during this period. It is believed that the ice layers (which existed in January 2002) reduced the volume of liquid in each wetland and therefore, reduced the outflow at the beginning of the study. The ice layers may have also been responsible for capturing some of the tracer, resulting in a longer RT and reduced mass recoveries. Ice layers tended to accumulate in both systems, possibly causing Br^- to be bound up in these layers. In addition, the greater plant debris in January 2002 created an increased

Table 3. Removal rates (%) from both wetlands (W1, W2) for the two tracer studies.

Parameter	April 2001		January 2002	
	W1	W2	W1	W2
BOD_5	98.7	99.7	99.0	97.0
TSS	88.0	95.4	89.3	94.5
TP	92.1	98.3	87.7	89.0
SRP	95.4	99.5	85.7	87.4
TKN	91.4	98.8	96.0	96.8
NO_3-N	83.5	86.0	90.7	91.2
NH_3-N	95.6	99.7	98.6	98.9
FC	99.9	99.9	99.9	99.4

resistance compared to April 2001 (Table 1). As a result, more dead zones with less apparent channeling may have caused the increased RT in January 2002. Although some differences occurred between April 2001 and January 2002, results suggest that adequate below ice flow for both wetlands occurred, as evidenced by the high mass recoveries and V_a (Table 2).

The variance provides an indication of the distribution of the tracer (Levenspiel 1999). Results from April 2001 show that the Br^- spread was greater for W1 (the wetland with the reduced water volume). This could be an indication that depth may have affected the spread of distribution. The V_a of the wetlands in April 2001 was 50.2 and 56.5% for W1 and W2, respectively (Table 2). For January 2002, the V_a was 53.5 and 65.0% for W1 and W2, respectively (Table 2). Effective volumes >50% are considered appropriate for surface flow wetlands (Kadlec and Knight 1996; Simi and Mitchell 1999). Within these wetlands it appears that there is a good level of mixing, but channeling and short-circuiting still exist.

In January 2002 the variance of W2 was increased. The V_a was again the highest (Table 2), suggesting that depth may not have a direct effect on mixing, rather flow rate, precipitation, wind, and vegetation density may play a greater role. Although the spread of Br^- was greater in W2, the V_a was higher, indicating that the tracer spread may not be a function of water depth. One would speculate that the decreased water depth in W1 may promote increased mixing since the loading rates and velocities into both wetlands were similar. This however, was not the case. Mixing was more likely promoted by wind and precipitation.

Perhaps as a consideration to promote additional wetland mixing, the commonly used rectangular design for constructed wetlands should be abandoned for less traditional designs (i.e. egg or kidney shapes). The elimination of corners may help reduce dead zones. Additionally, it may be beneficial to employ greater length to width ratios (>8:1) for rectangular cells. Elongated wetlands or baffled systems have been found to provide high hydraulic efficiencies (Mitsch and Cronk 1992; Persson et al. 1999). Additionally, installation of horizontal inlet distribution pipes may help to ensure more uniform flow delivery and enhance overall mixing within wetlands.

CONCLUSION

It appears that Br^- is a suitable hydrologic tracing element for surface flow wetlands as high mass recoveries (72 to 81%) in both spring and winter studies suggest. The absorption of Br^- within the wetlands was minimal, although monitoring occurred during periods without active plant growth.

Both wetlands demonstrated mean RTs that were approximately 50% of the TRT. Mean RTs were slightly longer in the winter, with 16 d for W1 and 19 d for W2, when compared to the spring, with 14 d for W1 and 16.5 d for W2. This may be due to Br^- being bound up in the various ice layers and greater flow resistance due to greater plant debris. It should be noted that there still appeared to be adequate below ice flow conditions during the winter months in both systems, as indicated by the high mass recoveries and RTs.

These studies demonstrate that the flow path within each wetland were not uniform. The RT distribution curves indicated non-ideal flow. Therefore, channeling and short-circuiting within wetlands may hinder attempts to achieve high treatment efficiencies, as improved mixing is vital for hydraulic efficiency. It is recommended that new constructed wetland design (i.e. egg or kidney shape) considerations be explored, including a horizontal perforated inlet pipe, or an aeration system. Incorporation of these designs may enhance more uniform mixing.

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