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Flow patterns of dairy wastewater constructed wetlands in a cold climate

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ABSTRACT

Conservative tracer experiments, and spatial temperature and dissolved oxygen mapping within four subsurface treatment wetlands employed in this study demonstrated the importance of supplemental aeration and vegetation in reducing preferential flows in cold climate treatment wetlands. Four constructed wetlands, employing horizontal subsurface flow were used to treat dairy wastewater in a 2×2 factorial design consisting of two wetland cells with vegetation and two with supplemental aeration. Four tracer studies were conducted between November 2004 and May 2005. Two key observations were made, demonstrating that vegetation and aeration can be utilized in cold regions to prevent clogging and freezing, thereby reducing preferential flow paths which can reduce treatment efficiencies: (1) vegetation contributed to thermal protection and (2) aeration increased temperature and mixing. A comparison of multiple wetland cells with varying flow rates showed that the use of pore volume in tracer response curves was a better indicator of preferential flows than other indicators including volumetric efficiency, hydraulic efficiency and number of continuosly stirred tank reactors (CSTRs). This research helps further establish how constructed wetlands are a viable tool for treating wastewater in cold climates.

1. Introduction

Constructed wetlands (CW) have been demonstrated to be an effective treatment alternative for biological oxygen demand (BOD), total suspended solids (TSS), bacteria (*Escherichia Coli*, total coliforms), nitrogen (N), and metals removal (Kadlec and Knight, 1996; IWA, 2000; USEPA, 2000). However, reliable treatment is often a function of climate conditions (Mander and Jenssen, 2003), design decisions, construction choices, operation and maintenance. It is often difficult for designers, engineers and regulators to identify the cause of wetland treatment system failure. Failure of a wetland treatment system often occurs when a wetland becomes clogged, and preferential flow paths are created (Blazejewski and Murat-Blazejewska, 1997; Platzer and Mauch, 1997). This may result in a decrease in treatment efficiency or allow a physical escape of wastewater out of the system constraints, such as surface ponding in subsurface flow (SSF) wetlands. Clogging may be caused by deposition of organic and inorganic solids, which develop a biological mat, leading to an outer blockage of soil pores (DeVries, 1972) or the formation of ice blockages in cold climates (Smith et al., 2005). Clogged wetlands can create preferential flow patterns, short-circuiting and odors (Blazejewski and Murat-Blazejewska, 1997). Keeping soil under aerobic conditions is seen as a possible remedy to control the clogging process (DeVries, 1972). More research is

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needed to examine clogging and flow patterns of SSF CW, especially in cold climates. The primary objective of this research was to assess hydraulic behavior of SSF CW in cold climate conditions under varying aerated and vegetated conditions.

2. Methodology and materials

2.1. *Study area*

The Constructed Wetland Research Center (CWRC) is located at the University of Vermont in Burlington, Vermont (44°46′N, 73°19W), 300 m above sea level. Burlington has a mean temperature of −8.7 °C in January and 21.4 °C in July. The dairy herd consists of 150 milking cows and 110 calves and heifers (Muñoz, 2005). The CWRC started receiving an influent consisting of a combined feedlot runoff and the milking operation wastewater in October 2003. The drainage area of the feedlot is 1750 m^2. The CW were designed to handle an influent BOD concentration of 4000 $mg\,l^{-1}$ and a peak flow of 37,500 $l\,d^{-1}$, which represents a 24-h storm exceeded on an average once every two years. Actual flow rates vary with weather condition and milking operations but generally ranged between 500 $l\,d^{-1}$ and 10,000 $l\,d^{-1}$ giving a theoretical hydraulic retention time (RT) range of 60 to 3 days per wetland. More detailed information about the milking operation wastewater and feedlot runoff pretreatment design is provided in Muñoz (2005).

2.2. *Constructed wetlands design*

Effluent from the settling tanks is combined, measured and evenly split to each of four constructed wetlands treatment cells with tipping buckets and event loggers (Fig. 1). Each of the four CW treatment cells has a 223 m^2 surface area and 0.6 m depth. A synthetic liner was placed inside each wetland cell to prevent percolation of the wastewater into the ground. The first third of each CW, from the influent side, consists of coarse gravel (∅ 2 cm) having a porosity of approximately 40%; while the remaining two thirds of each CW consist of smaller gravel (∅ 1 cm) with a porosity of 38%. CWs 3 and 4 were planted with *Schoenoplectus fluviatilis* (river bulrush); the remaining two cells were maintained to have no vegetation. Each CW cell is equipped with an aeration system designed by North American Wetland Engineering LLC, (Forest Lake, MN) consisting of 60 linear meters of fine bubble aeration tubing cris-crossing throughout the entire wetland and capable of maintaining 1.13 $m^3\,min^{-1}$ at 1.0 m of water pressure. However, aeration was activated in only cells 2 and 4 during Tracer Study (TS) 1 and 2 in order to enable the investigations on the effects of aeration on the wetlands treatment performance. Aeration was also activated in Cell 1 during the last tracer study, TS3. Aeration system effects on porosity were negligible for this research (Wallace, 2003). A total of 15 sampling locations were placed within each wetland cell providing repeatable points for water quality sampling (Fig. 2). Each location has three 3.8 cm PVC sampling wells installed at shallow, medium and deep depths below grade.

2.3. *Measurements and mapping*

Flow was measured utilizing a 0.6 m HS Flume (Tracom Inc., Alpharetta, Georgia) with an Isco 4210 Ultrasonic Flow Meter (Teledyne Isco, Inc., Lincoln, Nebraska). Precipitation was measured using an Isco 674 Rain Gauge. Temperature (*T*) was continuously recorded each 15 min in all cells with a solar-powered CR10X Temperature Measurement and Control Module (Campbell Scientific, Logan, Utah). The *T* recording system utilized twenty thermocouples in each wetland to measure water *T* at the inlet, outlet and nine locations within the wetland cell. Data logging failure resulted in no *T* records of data from Cell 3. *T* data were also recorded by hand in wetland cells 1 and 2 during deep winter conditions with a WTW Multi 340i Meter and Cell O × 325 sensor probe (WTW, Weilheim, Germany).

Dissolved oxygen (DO) was measured in all cells in December 2003, while in March 2005 it was measured only in cells 1 and 2. Contour maps of *T* and DO data were created using MATLAB 7.0 (MathWorks, Natick, Massachusetts) to identify data trends and flow patterns within each cell. Contour maps were also used to analyze for correlation between T, DO, and wetland infrastructure, as well as whether there were preferential flow pathways.

2.4. *Tracer studies*

Four bromide tracer studies were performed between November 2004 and May 2005. The tracer study period was carried out during winter to examine how freezing conditions might alter hydraulic efficiency and flow patterns. Tracer study 0 (TS0) and Tracer study 1 (TS1) were performed in early winter (November 13–December 7, 2004 and December 7, 2004–January 5, 2005, respectively), well after plants became dormant, but before sub-zero temperatures. TS0 was performed only on Cell 1, while TS 1 was performed on all four wetland cells. Tracer study 2 (TS2) was performed in late winter (February 23–March 16), after several weeks of sub-zero °C weather. Tracer study 3 (TS3) was performed in early spring (April 22–May 22, 2005), just after snowmelt with no sub-zero conditions, but prior to wetland plant growth. All four tracer studies (TS0–TS3) were conducted on Cell 1, and only TS1 and TS2 were conducted on all four wetland cells.

In each tracer study, a Potassium Bromide (KBr) tracer solution was prepared ensuring less than a 10% density difference with wastewater influent. As a conservative tracer, KBr sorption onto gravel and into organic matter was neglected (Flury and Papritz, 1993; Netter, 1994). A tracer solution was made in the field by mixing 15 l of wastewater from the inlet sump with 230 mg of KBr in a large plastic container. Once the required volume for the solution was obtained, the solution was vigorously mixed to ensure all of the KBr was dissolved. A Solinst 410 peristaltic pump (Solinst Canada Ltd, Georgetown, Ontario) was used to rapidly inject the tracer solution directly into the wetland cell through a 1 cm polyethylene tube fed through the inlet sump. The tracer injection and sampling locations are shown in Fig. 2. Water samples were taken twice a day during most of the tracer studies, except towards the end of each study when sampling

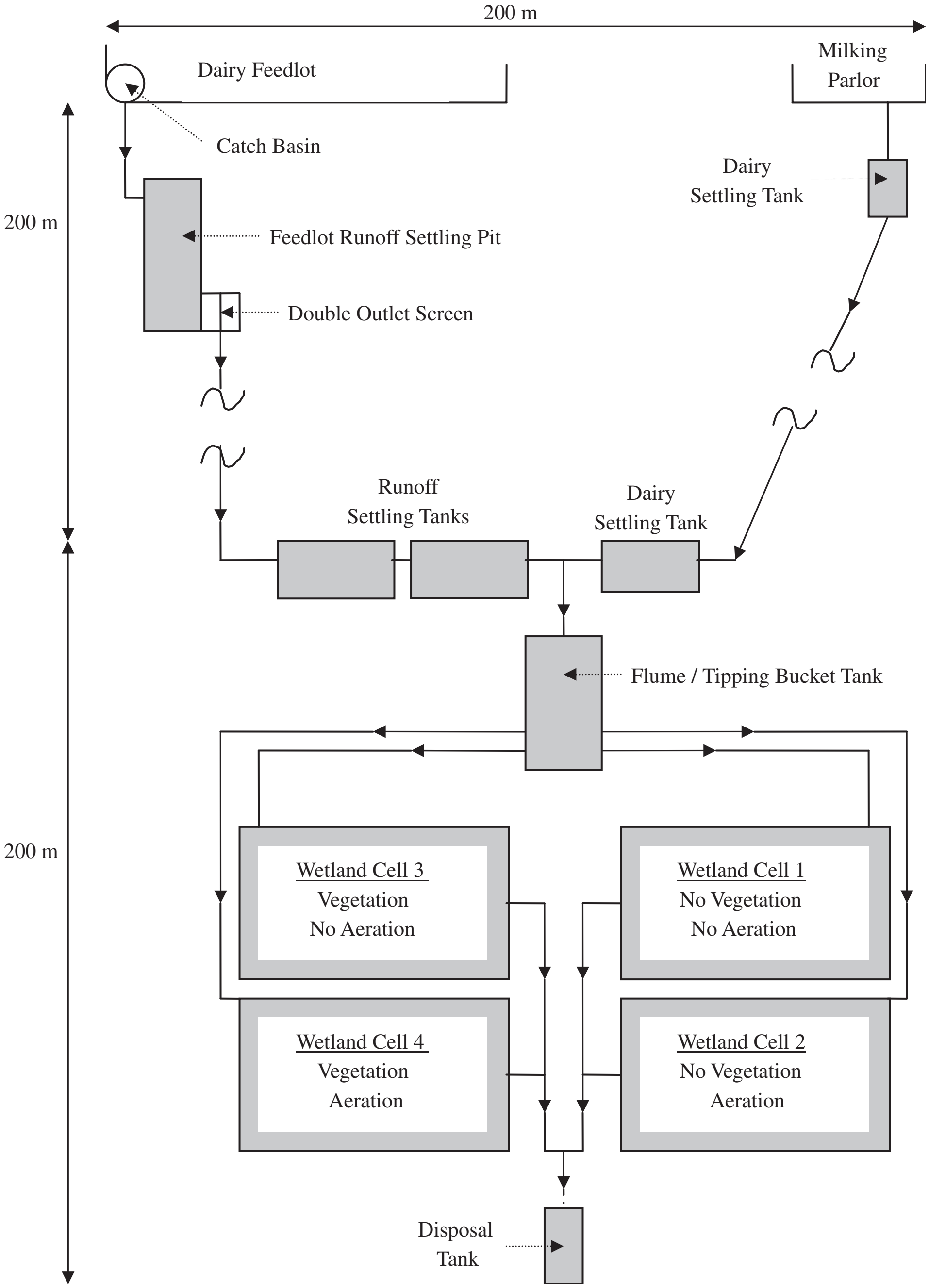

Fig. 1 – Process schematic–Constructed Wetland Research Center (not to scale).

frequency decreased to approximately once every two to four days. More frequent samples were taken during higher flows, such as storm events, to capture a more accurate amount of tracer passing through the wetland cell. Samples from each cell were taken from near the outlet pipe in the outlet sump with a peristaltic pump during TS0 and TS1 and by grab sampling during TS2 and TS3. Samples were filtered in the laboratory with a 5 ml syringe and 0.45 μm Whatman 25 mm GD/X disposable syringe filter (Catalog # 6870-2504) (Whatman, Brentford, Middlesex). Tracer samples were analyzed for bromide using ion chromatography utilizing a Dionex AS50 Autosampler Pump and the Peak Net6 June 2000 software package (Dionex Corporation, Sunnyvale, CA).

2.5. *Modeling and efficiency calculations*

Retention time (RT) represents the amount of time it takes for the wastewater to flow through the wetland. Theoretical RT were calculated for each tracer study according to

$$\mathrm{RT}_n = V/Q, \tag{1}$$

where RT_n is the retention time (d), V the volume of water in the wetland (m^3) and Q the volumetric flow rate of water through the wetland ($m^3\,d^{-1}$).

Mean retention time (MRT) was computed with the Boggs and Adams (1992) 'method of moments' using the area under the breakthrough curve (the zeroth moment), the trapezoidal

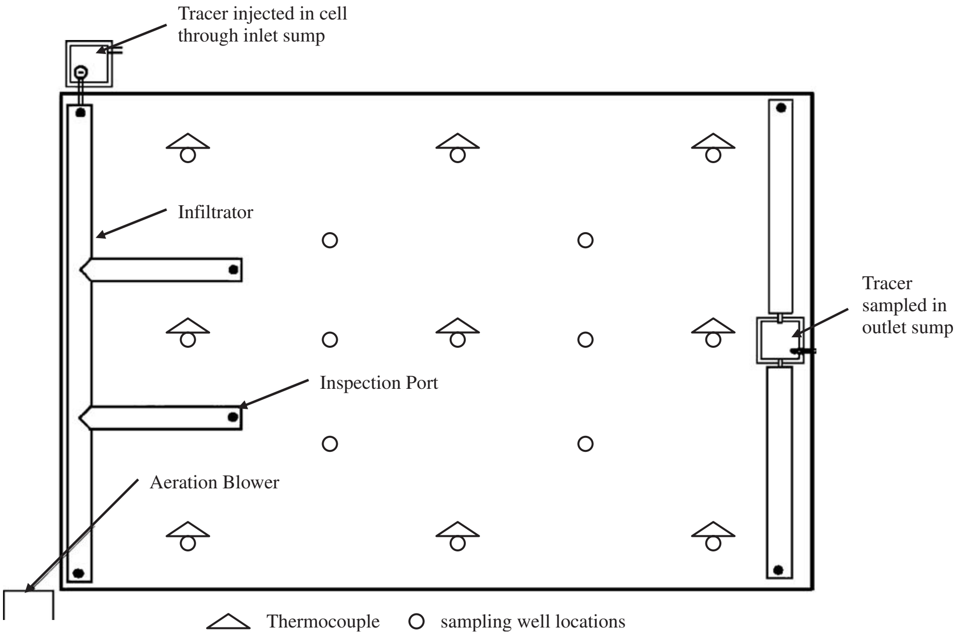

Fig. 2 – Typical research cell layout. Thermocouple (△) and sampling well locations (○).

rule, and mean travel times.

$$MRT = \frac{\int_0^\infty C(t)t\,dt}{\int_0^\infty C(t)\,dt}, \tag{2}$$

where C(*t*) is the tracer concentration ($mg\,l^{-1}$) at time (*t*); *t* the time of sample (d), d(*t*) the change in time between samples (d). Volumetric efficiency was calculated using a ratio of mean detention utilized by Thackston et al. (1987). Pore volume (pv) was used instead of time to compare tracer response with different flow rates

$$e = \left(\frac{pv_{mean}}{pv_n}\right), \tag{3}$$

where e is the effective volume ratio, pv_{mean} the mean hydraulic residence pore volume (pv); and pv_n the nominal hydraulic residence pore volume.

Kadlec and Knight's (1996) method for calculating the number of continuously stirred tank reactors (CSTRs) was used in analysis of wetland hydraulic characteristics

$$N = \frac{pv_{mean}}{pv_{mean} - pv_p}, \tag{4}$$

where N is the number of CSTRs in series; and pv_p the peak pore volume. Hydraulic efficiency was calculated with an equation derived by Persson et al. (1999), which uses volumetric efficiency and the number of CSTRs

$$\lambda = e\left(1 - \frac{1}{N}\right) = \left(\frac{pv_{mean}}{pv_n}\right)\left(1 - \frac{pv_{mean} - pv_p}{pv_{mean}}\right) = \frac{pv_p}{pv_n}. \tag{5}$$

A short-circuiting value (S) was calculated using a ratio developed by Ta and Brignal (1998)

$$S = \frac{pv_{16}}{pv_{50}}, \tag{6}$$

where pv_{16} is the hydraulic residence pore volume at which 16% of the tracer is recovered; and pv_{50} the hydraulic residence pore volume at which 50% of the tracer is recovered.

Much attention was given to achieving accurate flow measurements, as pore volumes, mass recovered and mean retention time calculations are all dependent upon this wetland parameter. Sampling frequency increased during KBr recovery peaks in order to achieve a high accuracy of tracer mass recovered. The percent of mass recovered reported in the literature generally range from 80% to 120% (Hayden, 2005). However, recovery rates vary due to flow rate fluctuations and accuracy, as well as tracer curve interpolations. The drastic changes of recovery rates indicate lateral flow within the wetland. MATLAB 7.0 was used to normalize tracer study data for statistical analysis. Kolmogorv-Shirnov statistics were generated with SAS (SAS Institute Inc., Cary, North Carolina) to compare tracer response curves (Table 1).

3. Results and discussion

3.1. *Tracer study*

Four tracer studies were conducted on Cell 1 (TS0–TS3). Tracer concentration response curves for the four tracer studies are shown in Fig. 3 and a summary of tracer response characteristics and hydraulic parameters are presented in Table 2. Br–tracer concentrations were plotted against flow pore volume to eliminate differences in the quantities of influent flow between studies. One pore volume is equal to approximately 30,000 l of influent moving through the wetland. The study of flow patterns conducted on Cell 1 displays strong evidence that cold climate conditions contribute to the occurrence of short-circuiting in SSF CW. Short circuiting and preferential flows were more prominent during the tracer study TS2, carried out during the coldest, sub-zero tempera-

Table 1 – Pre and post wetland construction influent and municipal wastewater concentrations

Constituent	Unit	UVM dairy farm Pre-construction[a]		Actual flow	Municipal strength
		Barnyard	Milkhouse	Combined sources	Wastewater[b]
BOD_5	$mg\,l^{-1}$	>4000	1200	2393	250
Total suspended solids	$mg\,l^{-1}$	2500	2600	932	220
Ammonia	$mg\,l^{-1}$ N	346	52	185	25
Nitrate	$mg\,l^{-1}$ N	1	1	1	0
Total phosphorus	$mg\,l^{-1}$	44	44	35	12

[a] (Whitney, 2003).
[b] (Metcalf and Eddy, 2003).

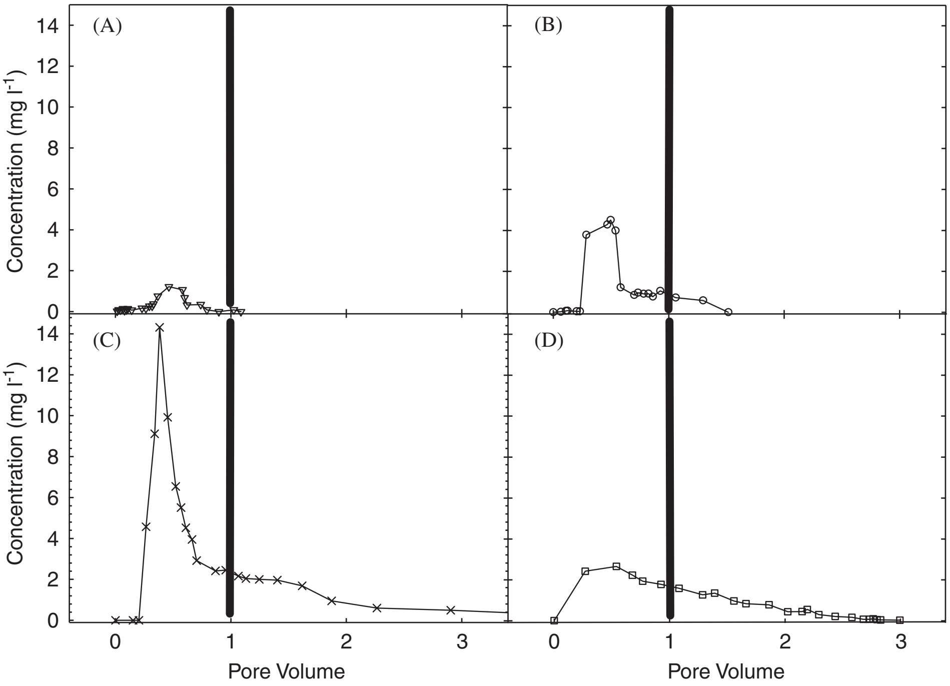

Fig. 3 – Wetland cell 1 tracer concentration response curves for tracer study 0–3. TSO (A), TS1 (B), TS2 (C), and TS3 (D).

tures. TS2 showed an elevated tracer concentration peak of $14.4\,mg\,l^{-1}$, five fold greater than all the other response peaks conducted in wetland Cell 1 (Fig. 3). An earlier response peak illustrates short-circuiting, which may be attributed to ice formation during cold climate conditions. This was further confirmed by the mean retention time in this wetland cell, (that was 7.6 fold shorter then the theoretical residence time calculated in this period) and the percent of Br^- mass recovered (2.85 and 2.14 fold higher during TS2 when compared to TS0 and TS3 (Table 2). The discrepancy between the theoretical and actual residence times was reported by other researchers (Sanford et al., 1995; Drizo et al., 2000). MRT in Cell 1 during TS2 tracer study was highest among all four tracers studies (TS0–TS3) and among all four wetland cells. Similarly, other parameters (pore volumes at tracer response peak, number of CSTRs) also confirm that Cell 1 had the lowest hydraulic efficiency during TS2 (Table 2). TS0, TS1, and TS3 tracer response peaks all occurred between 0.50 and 0.54 pore volumes, while TS2 response peak occurred at an earlier period of 0.38 pore volumes. Cell 1's hydraulic behavior during four tracer studies was also examined using a ratio of MRT and theoretical RT. The greatest time ratio occurred in Cell 1 during TS2, illustrating a shorter retention time as compared to other tracer studies. Similar findings of ice formations were reported by Reed et al. (1995) and poorly insulated wetlands by Wallace et al. (2000). Kadlec et al. (2003) reported that the creation of preferential pathways during cold conditions can eventually lead to hydraulic failure of a wetland.

The poorest hydraulic efficiency of wetland Cell 1 during TS2 was further confirmed in the values obtained for a number of CSTRs: during TS2 it was 1.62, smaller than any other CSTR number for this cell (Table 2). Kadlec and Knight (1996) used the number of CSTRs to examine flow hydrodynamics and hydraulic efficiency. Comparatively, a smaller number of CSTR indicates a less efficient system.

Further illustrating evidence of highest amount of preferential pathways and/or short-circuiting during TS2 are Cell 1 tracer ratios of concentration versus maximum concentration (C/Cmax; Fig. 4). A progressive elongation of the tracer response curve decline is observed in both Figs. 3 and 4 for the first three tracer studies, and is most prominent in TS2. TS3 has an elongated tracer response tail as a direct result of activation of the aeration system on March 21, 2005 (Figs. 3 and 4).

Many parameters and variables, including pore volume at tracer response periods, number of CSTRs, and short-circuiting number were determined in order to evaluate hydraulic characteristics and behavior of treatment wetlands during the cold winter months (Tables 2 and 3). The use of pore volume in tracer response curves as a way of comparing multiple wetlands with varying flow rates proved a valuable tool in research and evaluation of treatment systems. Pore volume at tracer response peak showed to be a better

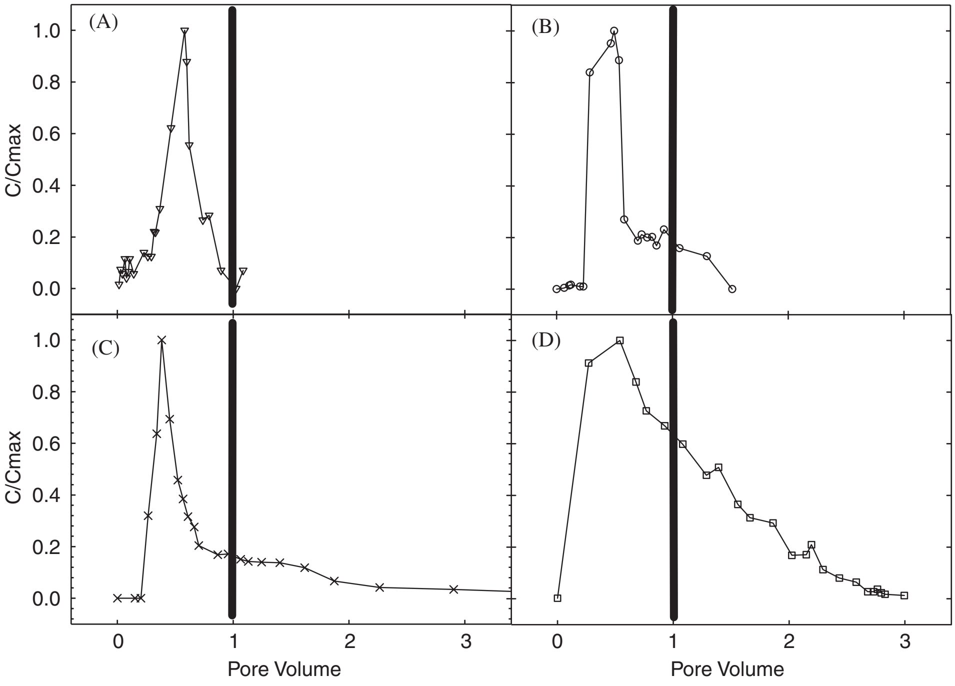

Fig. 4 – Wetland cell 1 tracer concentration over maximum concentration response curves for tracer study 0–3. TSO (A), TS1 (B), TS2 (C) and TS3 (D).

Table 2 – Wetland cell 1 response curve characteristics for tracer studies 0–3

Tracer study	0	1	2	3
Month of study	November–December	December–January	February–March	April–May
Length of study, *t* (d)	25	33	20	31
Average flow rate, Q ($\mathrm{l\,d^{-1}}$)	4743	5440	1978	3110
Theoretical retention time, RT_T (d)	6.4	5.5	15.2	9.7
Peak time, PT (d)	12.5	4.0	2.0	2.2
Mean retention time, MRT (d)	12.4	3.9	2.0	2.2
Nominal retention pore volume, pv_n	1	1	1	1
Pore volume at center of mass, pv_{mean}	0.47	0.48	0.68	0.76
Pore volume at tracer response peak, pv_p	0.50	0.50	0.38	0.54
Pore volume at 16% tracer response peak, pv_{16}	0.36	0.27	0.35	0.22
Pore volume at 84% tracer response peak, pv_{84}	0.65	0.90	1.82	1.66
Percent mass recovered[a]	48	125	137	64
Volumetric efficiency, *e*	0.47	0.48	0.68	0.76
Number of CTSRs, *N*	2.00	1.99	1.62	2.17
Hydraulic efficiency, λ	0.23	0.24	0.26	0.41
Short-circuiting, *S*	0.77	0.56	0.52	0.29

[a] Percent mass recovered values reported in the literature generally range from 80-120% (Hayden, 2005).

Table 3 – Tracer study 1 response curve characteristics for wetland cells 1–4

Tracer study	1	1	1	1	2	2	2	2
Wetland cell	1	2	3	4	1	2	3	4
Vegetation			×	×			×	×
Aeration		×		×		×		×
Average flow rate, Q (l d^{-1})	5440	5440	5440	5440	1978	978	1020	995
Theoretical retention time, RT_T (d)	5.5	5.5	5.5	5.5	15.2	30.8	29.5	30.3
Peak time, PT (d)	4.0	3.8	3.8	3.8	2.0	3.7	1.3	2.4
Mean retention time, MRT (d)	3.9	3.9	3.7	4.0	3.9	3.9	2.5	3
Nominal retention pore volume, pv_n	1	1	1	1	1	1	1	1
Pore volume at center of mass, pv_{mean}	0.48	0.53	0.43	0.51	0.68	0.77	0.49	0.59
Pore volume at tracer response peak, pv_p	0.50	0.47	0.47	0.47	0.38	0.72	0.26	0.45
Pore volume at 16% tracer response peak, pv_{16}	0.27	0.33	0.27	0.28	0.35	0.58	0.27	0.39
Pore volume at 84% tracer response peak, pv_{84}	0.90	0.89	0.89	0.79	1.82	1.11	1.15	0.96
Percent mass recovered[a]	125	135	135	186	137	73	98	80
Volumetric efficiency, e	0.48	0.53	0.43	0.51	0.68	0.77	0.49	0.59
Number of CTSRs, N	1.99	1.88	1.88	1.88	1.62	3.51	1.36	1.83
Hydraulic efficiency, λ	0.24	0.25	0.20	0.24	0.26	0.55	0.13	0.27
Short-circuiting, S	0.56	0.62	0.61	0.55	0.52	0.75	0.55	0.65

[a] Percent mass recovered values reported in the literature generally range from 80% to 120% (Hayden, 2005).

indicator of the preferential flows than the pore volume at center of mass because elongation of tracer curve tails could skewed the mean tracer concentration. Similarly, the volumetric efficiency is a better indicator then volumetric efficiency or number of CSTRs as it is calculated using both parameters.

3.2. *Effects of aeration*

Several observations suggest that supplemental aeration alters flow patterns under normal weather conditions (early winter). Cell 1 tracer response curves had similar profiles except for TS3, which had an early increase and slow decline in concentration ratio (Fig. 4). TS3's characteristics are evidence of increased dispersion and diffusion from its aerated conditions. TS1 and TS2 were performed on all four wetland cells during early and deep winter climate conditions, respectively. Tracer ratio response curves are shown in Fig. 5A and B, and tracer response curve characteristics and wetlands hydraulic parameters are presented in Table 3. Fig. 5A shows a more gradual decline in tracer response for wetland Cells 2 and 4, signifying increased dispersion under their aerated conditions. During TS 1, the pore volume center of mass of the concentration ratio response curves was different ($p<0.117$) in vegetated aerated and non-aerated cells. During TS2, aerated wetland Cells 2 and 4 had tracer response peaks at higher pore volumes than non-aerated Cells 1 and 3. Both aerated cells (2 and 4) had a peak shift (to the right) toward one pore volume and the more gradual decline in tracer response curves, again signifying increased dispersion under aerated conditions (Fig. 5B). The effect of aeration is also noted in a significant difference ($p<0.000$) in pore volume center of mass of the concentration ratio response curves between non-aerated wetland Cells 1 and 3 and aerated Cells 2 and 4 . Aerated cells also had smaller pore volume recorded at 84% of tracer response and higher number of CSTRs, further identifying them as more hydraulically efficient (Kadlec and Knight, 1996). However, similar MRTs were observed in both aerated and non-aerated wetlands during TS2 (Table 3).

3.3. *Effects of vegetation*

Vegetation effects on flow patterns were more prominent during TS2, when there was a significant difference in pore volumes at center of mass of the concentration ratio response curves between non-vegetated Cells 1 and 2 ($p<0.000$) and vegetated Cells 3 and 4 ($p<0.076$) . During TS2, pore volumes at tracer response peaks were also different between non-vegetated and vegetated cells, the peak occurring later in a vegetated Cell 4 (by 0.25–0.5 pore volumes) indicating greater hydraulic treatment efficiency in this cell (Fig. 5B). The effects that vegetation on the wetlands treatment and hydraulic performance were discussed by several authors over the last two decades (Bowmer, 1987; Marsteiner et al., 1996; Brix, 1997; Drizo et al., 2000; USEPA, 2000), Braskerud (2001) carried out investigations on the effects of vegetation on sedimentation and resuspension of soil particles in small constructed wetlands in cold climate and showed that the presence of vegetation diminishes short particle settling distance by hindering resuspension. Other cold-climate wetland research carried out by Allen et al. (2002) and Kadlec and Reddy (2001), also reported that vegetation contributes to decrease in the removal of organic material resulting in more effective hydraulic performance in cold climate wetlands.

3.4. *Temperature and dissolved oxygen mapping*

Mapping (T) and (DO) gradients further supports our findings of short-circuiting and preferential pathways occurring during cold months. Average minimum wastewater temperature and DO gradients for Cells 1 and 2 during TS2 are presented in Fig. 6A and B. The higher T and DO gradient density near the inlet of the non-aerated Cell 1 indicate occurrence of

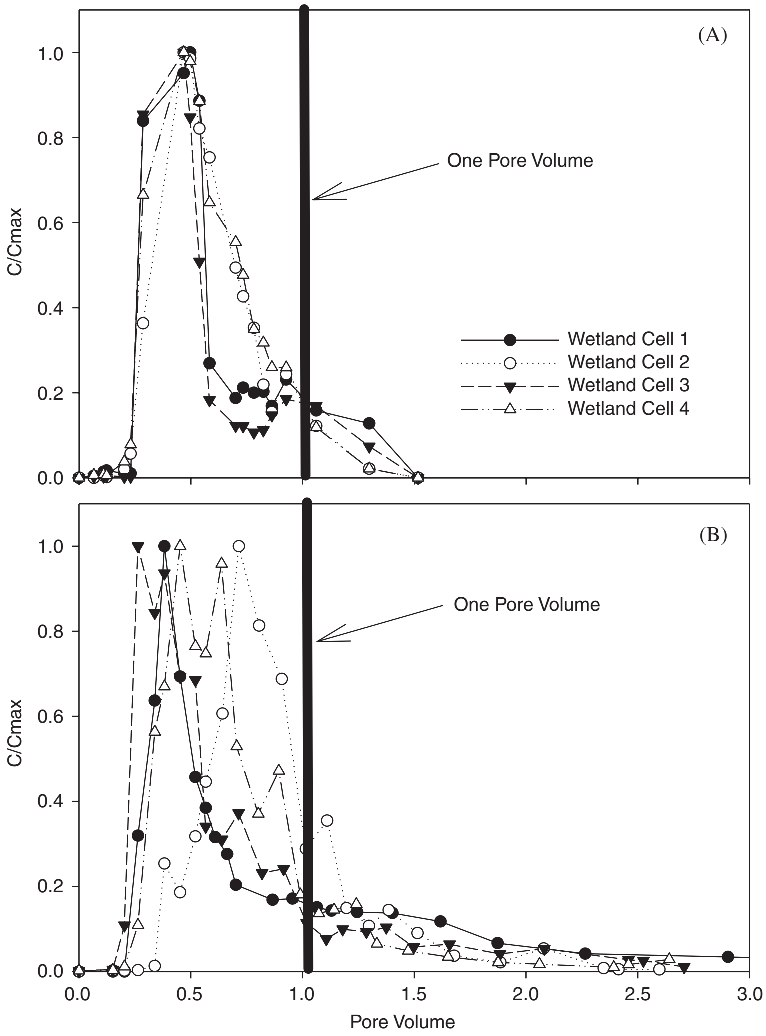

Fig. 5 – Tracer response curves for wetland Cells 1–4. TS1 (A) and TS2 (B).

preferential pathways or short-circuiting. Similar occurrence of short-circuiting along wetland boundaries and from inlet locations were also reported by Reed et al. (1995), Wittgren and Maehlum (1997), Persson et al. (1999), and Chazarenc et al. (2003). The T and DO gradients were more evenly distributed in aerated Cell 2 (Fig. 6C and D) when compared to Cell 1. This confirms the effects of aeration on wastewater mixing in non-vegetated Cell 2 (Fig. 6C and D). T in C cell 2 remained warmer throughout the investigation (Fig. 6A and C), even when measured under the extreme cold conditions of TS2. Generally, DO levels in wetlands decrease from inlet to outlet (Kadlec and Reddy, 2001); however, effluent DO levels in aerated Cell 2 were higher than influent levels (Fig. 6D). It took half of the length of the wetland cell at average flow rates to bring the DO levels back to the influent levels (Fig 6D).

T levels in wetland cells were higher at the ends of the inlet infiltrator extensions in both non aerated and aerated cells (1 and 2). Cooler T pockets observed away from the infiltrator ends indicate the presence of dead zones or short-circuiting pathways. Protruding inlet structures, such as the placement of the infiltrators used in the research wetland cells, can create these dead zones as observed in constructed wetlands and ponds by Persson et al. (1999) and Persson and Wittgren (2003).

4. Conclusions

- Preferential flow pathways did occur in wetland cells during cold climate conditions.
- Supplemental aeration increases dissolved oxygen levels in subsurface constructed wetlands, contributing to a decrease in clogging and prevention of the occurrence of preferential flow patterns by increasing temperature and mixing.
- Under extreme cold climate conditions, the presence of vegetation is beneficial in providing addition thermal protection against ice formations.
- Dead zones were observed in all cells primarily due to the configuration of the inlet infiltrator structures.
- Temperature and dissolved oxygen mapping are an effective tool in investigating occurrence of preferential flow patterns.
- The use of pore volume in tracer response curves as a way of comparing multiple wetlands with varying flow rates proved to be a valuable tool which facilitated evaluation of their hydraulic treatment efficiencies.

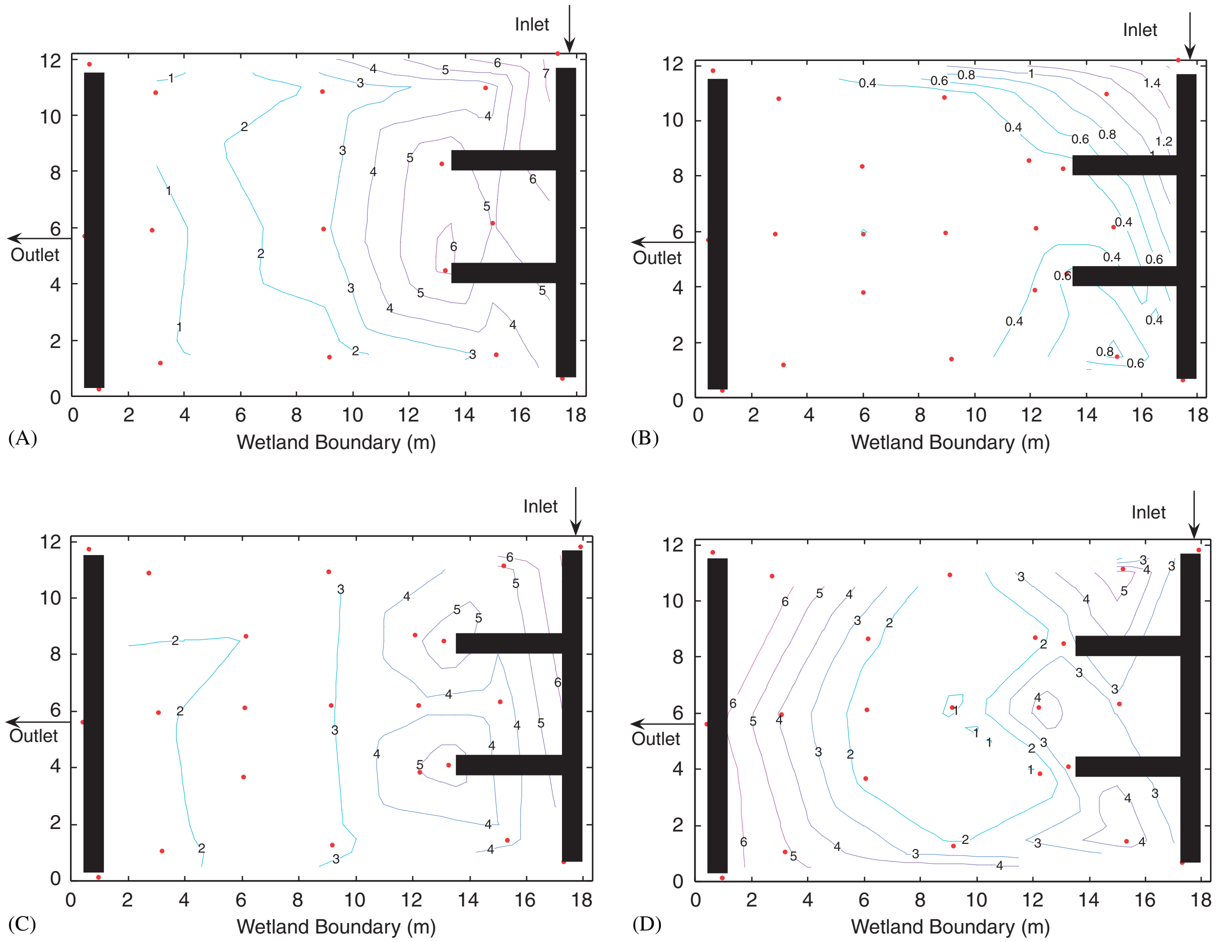

Fig. 6 – Tracer study 2: Temperature (°C) and dissolved oxygen ($mg\,l^{-1}$) gradients. Cell 1-Temperature (A). Cell 1-DO (B). Cell 2-Temperature (C). Cell 2-DO (D).

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