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Analysis of constructed treatment wetland hydraulics with the transient storage model OTIS

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Abstract

The model one-dimensional transport with inflow and storage (OTIS) was calibrated to results from tracer experiments conducted in the Orlando Easterly Wetland in order to quantify short-circuiting of the treatment volume and temporary storage of tracer in isolated, low-flow regions. OTIS was found to fit experimental data very well for both steady and unsteady flow conditions. The model calibrations indicate the presence of three different hydraulic 'zones' of the wetland. The first zone is the actively flowing main channel; the second, a temporary storage zone where water and constituents are exchanged with the main flow channel; and the third, completely isolated, 'dead' water. The uncertainty of storage zone parameters was determined to be low due to the experimental Damköhler number that quantifies intra-zone mass transfer processes. The appropriateness of the use of a one-dimensional model for treatment wetlands is also addressed.

Keywords: Constructed treatment wetland; Tracer testing; Transient storage; Short-circuiting; Storage zones; Hydraulics; Modeling

1. Introduction

As the use of constructed wetlands for wastewater treatment increases, there is an increased need for predictive tools to estimate expected levels of contaminant removal. In order to achieve accurate prediction of treatment, there must first be an accurate understanding of wetland hydraulics. Due to the varying degrees of short-circuiting experienced in many systems, tracer tests are required to determine the residence times within them. Models of wetland hydraulics may be calibrated against tracer test results in order to develop a simulation model upon which treatment performance can be forecasted.

Short-circuiting of available volume in a constructed wetland reduces the average pollutant residence time and reduces the contact area of the system, leaving large regions of isolated, stagnant water. These isolated areas may exchange water and constituents with more actively flowing regions by diffusion and dispersion. The turnover of water in these isolated areas is relatively slow compared with that in the actively flowing regions

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so water chemistry and kinetics will likely be different in these two areas.

Much of the constructed treatment wetland design literature assumes ideal plug-flow conditions to estimate expected treatment levels (US EPA, 1988; Water Pollution Control Federation, 1990; Reed et al., 1995). Under plug-flow conditions, an instantaneous spike of tracer injected at the inlet will exit the wetland as an identical spike one nominal residence time (ratio of system volume to volumetric flow through the system) later; no mixing or diffusion is assumed to occur. Models using continuously stirred tank reactors (CSTRs) in series have also been employed and have been recommended by the Water Pollution Control Federation (1990) to model wastewater lagoons. Under continuously stirred conditions, an instantaneous spike of tracer is assumed to mix evenly and instantaneously throughout the reactor. The tanks-in-series model has been used to match field tracer responses with some degree of success by Urban (1990), Stairs (1993), Kadlec (1994) and Niswander (1997).

Experimental results from tracer tests conducted on constructed treatment wetlands typically experience a quick effluent peak of tracer followed by extended tailing (Stairs, 1993). The design models mentioned above have not done well in reproducing such highly skewed tracer responses caused by temporary storage of tracer in stagnant regions and by short-circuiting of the treatment volume. This problem has not been unique to treatment wetlands; previous modeling investigations have tried to deal with the non-ideal flow caused by temporary storage and short-circuiting in other systems. A brief synopsis follows.

Addressing 'dead' flow regions in chemical reactors, Hovorka (1961) used combinations of completely mixed and plug-flow vessels to define a 'finite-stage' model which could also reproduce the two ideal cases (plug-flow and continuously stirred). A 'dead-flow' model element was defined as a completely mixed vessel and a 'live-flow' element was defined as a combination of a completely mixed and a plug-flow vessel in series. Combined in parallel, these two elements represented a single 'model' element where first-order exchange could occur between the completely mixed portions of the 'live' and 'dead' elements. The 'model' element could then be repeated an integral number of times with convective flow occurring between 'live-flow' elements in order to describe the physical system.

Conceptually similar models consisting of CSTRs in series that exchange water and solute with adjacent 'dead' CSTRs have been proposed for modeling flow in porous media (Deans, 1963; Levich et al., 1967); in chemical reactors (Levenspiel, 1972); and for treatment wetlands (Kadlec, 1994). Kadlec (1994) model used Levenspiel's 'Model G' with the addition of a single plug-flow reactor in series to account for the time lag between the injection of the tracer and the arrival of the tracer at the system outlet.

In their 'differential capacitance' model Coates and Smith (1964) coupled the advection–dispersion equation with completely mixed storage zones to model transport in porous media. Their work was further expanded to develop the 'two-region' model for flow in porous media to account for the effects of dead-end pores, aggregated media, and thin-film covered particles (e.g. van Genuchten and Wierenga, 1976; van Genuchten and Wagenet, 1989). Noting the effects of temporary storage in wetland hydraulics, Dierks (1997) applied the two-region model to surface-water wetland tracer tests conducted in an isolation cell at the University of Florida in an attempt to determine the proper scale of a representative elementary volume for a surface flow wetland. Similarly, Werner and Kadlec (2000) extended Levenspiel's 'Model G' and developed the zones of diminished mixing (ZDM) model to simulate wetland tracer responses. The ZDM model consists of an infinite number of plug-flow reactors in series, each exchanging mass with a side CSTR. To make their model more realistic they introduced longitudinal dispersion to the plug-flow reactors, resulting in a model that is very similar to the 'differential capacitance' and 'two-region' models.

Along the lines of the model developed by Coates and Smith (1964), 'transient storage' models that couple the advection–dispersion equation with completely mixed storage zones have been applied to rivers and streams (e.g. Nordin and Troutman, 1980; Bencala and Walters, 1983). Stream and river studies have used transient storage models to investigate pool-and-riffle streams (Bencala and Walters, 1983), solute sorption to sediments (Bencala, 1983, 1984), nutrient-periphyton dynamics (DeAngelis et al., 1995), hyporheic exchange (Harvey et al., 1996), equilibrium chemistry (Runkel et al., 1996), dissolved oxygen (Chapra and Runkel, 1999), and in-stream gas transfer (Chapra and Wilcock, 2000).

The objective of the present work is to apply the United States Geological Survey (USGS) transient storage model one-dimensional transport with inflow and storage (OTIS) to wetland hydraulics using experimental tracer results from a constructed treatment wetland. The use of OTIS has the advantage of being well documented, readily available to users via the World Wide Web, and is complemented with a non-linear regression package for parameter determination.

2. The OTIS model

The transient storage solute transport model OTIS was coded in FORTRAN and documented by Runkel (1998). The model including documentation is free and available via the USGS website (http://www.co.water.usgs.gov/otis). The model was created to quantify the hydraulic parameters that influence temporary storage in rivers and streams.

The term 'transient storage' refers to the temporary detainment of water (and any solutes dissolved or other matter suspended therein) in recirculating eddies and dead zones that are adjacent to the main flow-path. Such temporary storage can explain the long tailing experienced in tracer studies as tracer that entered the storage zones slowly 'bleeds' back out. The transient storage model uses plug-flow with dispersion for the main flow channel and includes adjacent storage zones that exchange constituents with the main flow channel. Constituents are assumed to mix completely and instantaneously within the storage zones; and the exchange with the main flow channel is assumed to follow a first-order mass transfer. Thus, the transient storage model OTIS is composed of two coupled differential equations (Bencala and Walters, 1983):

$$\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + \alpha(C_s - C) \quad (1)$$

$$\frac{dC_s}{dt} = -\alpha\frac{A}{A_s}(C_s - C) \quad (2)$$

where t is time (T); x, the distance along the main channel (L); Q, the volumetric flow (L^3T^{-1}); A is the main channel cross-sectional area (L^2); A_s, the storage zone cross-sectional area (L^2); α, the storage zone exchange coefficient (T^{-1}); D, the longitudinal dispersion coefficient (L^2T^{-1}); C, the main channel solute concentration (ML^{-3}) and C_s is the storage zone solute concentration (ML^{-3}). The concept of the transient storage model is shown in Fig. 1.

The model also includes terms (not used herein) for lateral inflow and ouflow of water and solute, kinetic sorption in both the main channel and storage zone, and first-order decay in both the main channel and storage zone. For a complete derivation of the transient storage model OTIS the reader is referred to Runkel (1998).

In OTIS, the upstream boundary condition can be defined as either a constant or time-variable concentration or flux input. This formulation handles the input of tracer in a straightforward manner. The downstream boundary condition of OTIS is a fixed dispersive flux. Typically, wetland outlets are 'closed' boundaries (such as at a weir), not allowing dispersion back into the wetland. This boundary condition is satisfied by OTIS using a dispersive flux of zero at the downstream boundary.

OTIS can be employed under steady-state or time-variable conditions and can also be used with

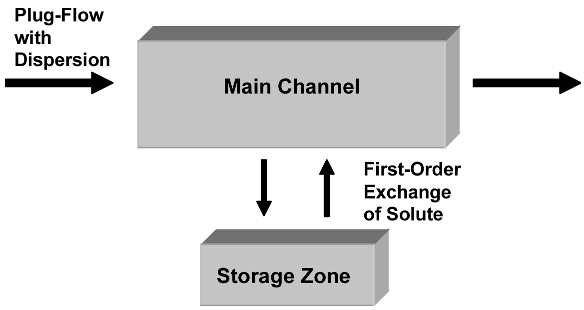

Fig. 1. Conceptual view of transient storage model.

the non-linear regression package STARPAC (Donaldson and Tryon, 1990). This modified version of OTIS, called OTIS-P, can be used to determine optimal sets of parameter values by minimizing the sum-of-squared errors between the observed and simulated solute concentrations. Model convergence is judged by the relative change of the parameter estimates or by the relative change of the sum-of-squared errors.

3. Description of site and tracer experiments

The simulations conducted here use experimental results of bromide tracer experiments conducted at the Orlando Easterly Wetland (OEW) located near Christmas, FL (Martinez and Wise, 2003). The system was designed for nutrient polishing of tertiary treated domestic wastewater and consists of 17 surface flow constructed wetland cells covering approximately 1250 acres (Fig. 2). The cells are separated by earthen berms and use adjustable thin-plate weirs to control flow (through culverts) from one cell to the next. The cells are arranged into three parallel flow-paths that meet at the terminal cell before discharging offsite. The system is designed for a daily flow of 75 700 m^3/day (nominally 20 MGD) and was operating at 60 600 m^3/day (nominally 16 MGD) at the time of the experiments.

The wetland contains four different communities: deep marsh, mixed marsh, hardwood swamp, and an 80-acre lake. The deep marsh (Cells 1–12), covering approximately 400 acres and composed primarily of dense cattail (*Typha* spp.) and bulrush (*Scirpus* spp.), was designed primarily for bulk nutrient removal. The mixed marsh (Cells 13–15), covering approximately 380 acres and composed of over 60 emergent and submergent plant species, was designed for further polishing of the wastewater and for wildlife habitat. The 400-acre hardwood swamp (Cells 16 and 17) was initially planted with a variety of tree species, however, a delay between planting and flooding of the wetland resulted in a large die-off. Consequently this community more closely resembles a combination of the deep marsh and mixed marsh. For further information on the design and layout of the OEW the reader is referred to US EPA (1993).

Photo-grade potassium bromide was used as the tracer and was injected at the system influent structures (Fig. 2) as step-pulses lasting between 0.5 and 1.0 h. Water samples were taken at the effluent weir(s) of each cell. High pressure liquid chromatography using a UV/Visible light detector set at a wavelength of 205 nm was used for detection of bromide in the effluent water. Flow at each weir was calculated using the Kindsvater and Carter (1959) equation for thin-plate weirs with fully developed side contractions. Heads above the weir crests were found using pressure transducers installed in stilling wells at each weir.

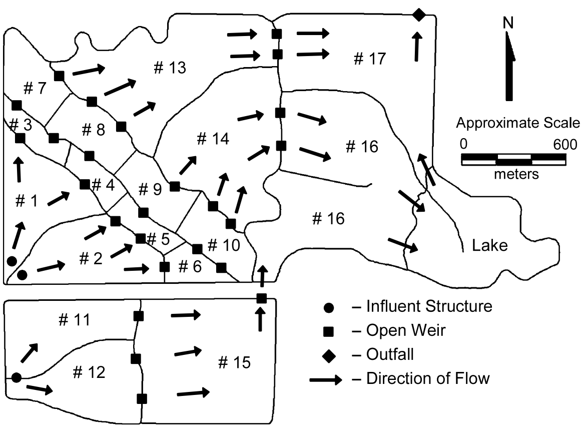

Fig. 2. Plan view of the OEW.

4. Results

Modeling results of Cells 1–15 of the OEW are presented here. Model simulations were made using lumped composite tracer responses for cells with multiple weirs. Flows were approximately constant during the study period for all wetland cells with the exception of Cell 11. Accordingly the remaining cells were modeled assuming steady-flow conditions, while Cell 11 was modeled with a transient analysis to account for unsteady flow. Since cell outflows were found to be approximately equal to inflows (Fig. 3), groundwater exchange and water losses by evapotranspiration were considered to be negligible relative to the

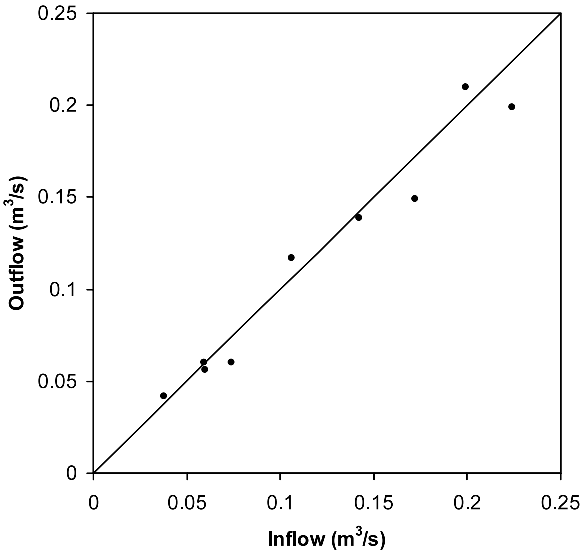

Fig. 3. Comparison of cell inflow and outflow.

magnitude of flow through the wetland cells. Limited groundwater exchange is also supported by the presence of a 2–3 foot thick clayey fine sand layer found at depths of 3–8 feet below ground surface throughout the site (Post, Buckley, Shuh & Jernigan Inc., 1985). Rainfall was minimal to non-existent throughout the study period (Martinez, 2001). The average tracer mass recovery for Cells 1–15 was found to be 99% (range of 75–123%). Acceptable closure of the tracer mass balance confirmed the conservancy of the tracer used and indicated that water gains/losses were in-fact negligible during the tracer experiments.

Steady-state flow simulations of the tracer responses of Cells 1, 7, and 12 are shown in Figs. 4–6. The remaining model fits were found to be as good as or better than that of Cells 7 and 12. An unsteady flow simulation for Cell 11 is presented in Fig. 7. The flow exiting Cell 11 was not constant due to an adjustment in weir height made on day 37 of the experiment (Fig. 7) resulting in an immediate ten-fold increase in flow followed by a gradual decrease as the water level in the cell dropped to a new equilibrium level (Martinez, 2001). As can be seen in Fig. 7 the model accounted for this abrupt change in flow quite well.

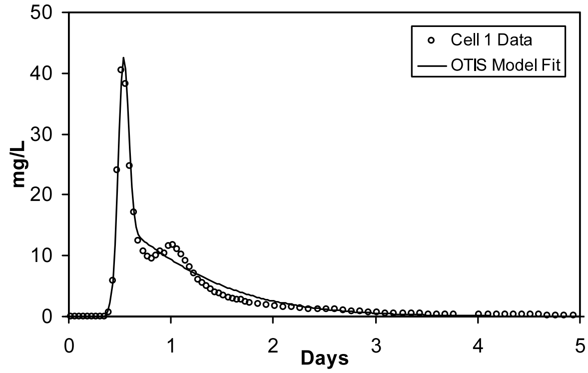

Fig. 4. Cell 1 OTIS model fit.

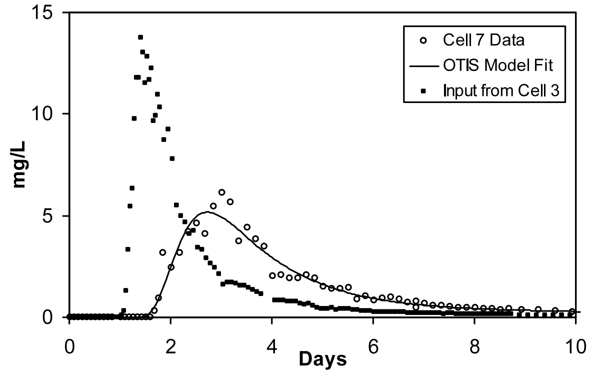

Fig. 5. Cell 7 OTIS model fit.

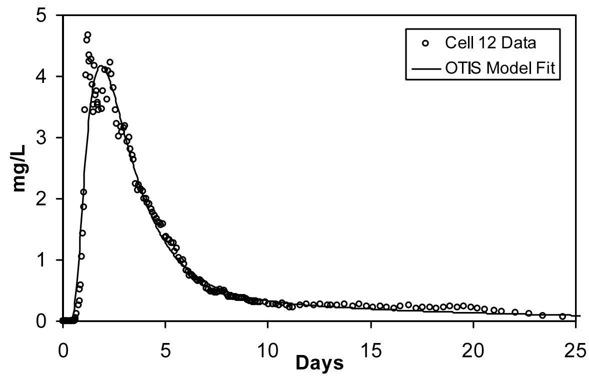

Fig. 6. Cell 12 OTIS model fit.

For each cell, the non-linear regression package in OTIS-P was used to determine parameter values for the main channel cross-sectional area (A), the

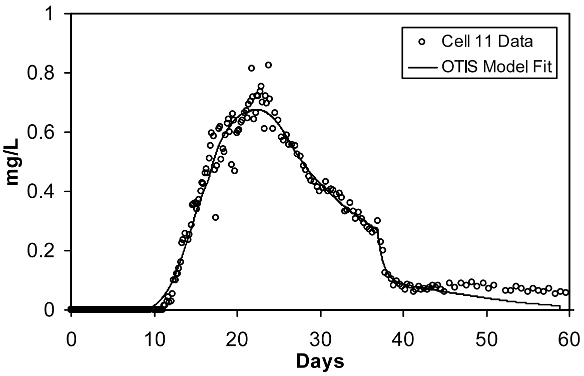

Fig. 7. Cell 11 OTIS model fit.

storage zone cross-sectional area (A_s), the longitudinal dispersion coefficient (D), and the storage zone exchange coefficient (α). The resulting model parameters found using OTIS-P are listed in Table 1. Included in Table 1 are values for the non-dimensional vessel dispersion number, $\mathscr{D}$, which is defined as (Levenspiel, 1972):

$$\mathscr{D} = \frac{1}{\text{Pe}} = \frac{\text{D}}{\text{uL}} \tag{3}$$

where Pe is the Peclet number; u, the water velocity (Q/A) (LT^{-1}), and L is the flow-path length (L). Flow-weighted straight-line distances from influent points to outflow weirs were used as the flow-path lengths for calculation of $\mathscr{D}$ as well as inputs to the model. The model was considered to have converged on a solution when the relative change of the parameter values or of the sum of the squared errors was less than 1×10^{-5}.

5. Discussion

As can be seen in Figs. 4–7, OTIS modeled the data very well for both the steady and unsteady flow simulations. The response of Cell 1 appears to be bimodal, indicating that two distinct flow-paths, one 'slow' and one 'fast', exist (Fig. 4). As can be seen the resulting fit is a compromise between the two. This will be addressed further below. Storage zone exchange coefficients were found to vary over four orders of magnitude and the ratio of A/A_s varied over a three orders of magnitude (Table 1 and Fig. 8).

Using global parameter uncertainty analysis, Wagner and Harvey (1997) showed that the experimental Damköhler number, *DaI* is a valuable indicator of the reliability of storage zone cross-sectional area and exchange coefficient estimates. The use of the experimental Damköhler number was adapted from similar subsurface transport research conducted by Bahr and Rubin

Table 1
Transient storage using OTIS—model parameters

Cell	Q (m^3/s)[a]	L (m)	A (m^2)	A_s (m^2)	α (per s)	D (m^2/s)	$\mathscr{D}$	*DaI*
1	0.181	740	11.0	11.4	2.99×10^{-5}	5.83×10^{-2}	4.80×10^{-3}	2.64
2	0.283	850	133.6	29.2	9.47×10^{-7}	9.49×10^{-2}	5.27×10^{-2}	2.12
3	0.139	266	42.0	12.3	1.43×10^{-4}	1.11×10^{-1}	1.26×10^{-1}	50.6
4	0.042	183	17.2	19.0	9.18×10^{-6}	1.01×10^{-2}	2.28×10^{-2}	1.33
5	0.060	152	13.8	18.8	2.22×10^{-6}	5.12×10^{-1}	7.67×10^{-1}	0.13
6	0.199	283	42.1	52.2	1.36×10^{-5}	2.23×10^{-2}	1.67×10^{-2}	1.47
7	0.060	305	35.5	31.8	1.54×10^{-6}	1.62×10^{-1}	3.16×10^{-1}	0.59
8	0.117	258	2.3	37.9	1.05×10^{-4}	1.00×10^{-2}	7.55×10^{-4}	0.56
9	0.056	262	22.1	24.8	2.62×10^{-6}	3.30×10^{-1}	4.99×10^{-1}	0.51
10	0.210	256	89.4	42.1	1.74×10^{-5}	1.00×10^{-2}	1.67×10^{-2}	5.94
11	0.042	822	75.8	36.2	1.46×10^{-6}	1.09×10^{-2}	2.39×10^{-2}	6.69
12	0.130	755	67.8	72.1	1.27×10^{-6}	3.88×10^{-1}	2.68×10^{-1}	0.97
13	0.176	1130	81.4	98.2	5.70×10^{-7}	1.10×10^{-1}	4.50×10^{-2}	0.54
14	0.266	920	86.9	76.1	1.54×10^{-6}	4.84×10^{-1}	1.72×10^{-1}	0.99
15	0.149	892	59.9	44.3	3.81×10^{-6}	3.55×10^{-2}	1.60×10^{-2}	3.31

[a] Average flow during study period.

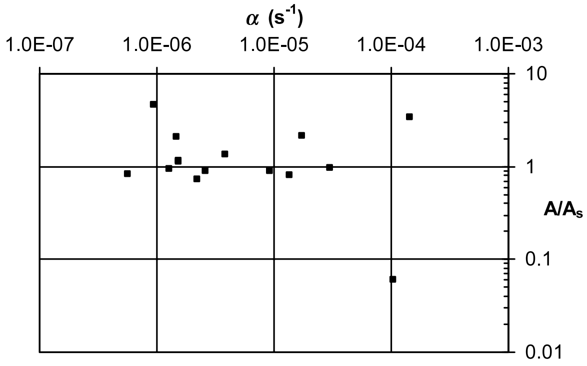

Fig. 8. Plot of A/A_s vs. α.

(1987). The experimental Damköhler number is defined as:

$$DaI = \frac{\alpha(1 + A/A_s)L}{u} \tag{4}$$

The experimental Damköhler numbers found from the transient storage modeling conducted here are listed in Table 1.

Wagner and Harvey (1997) found parameter uncertainties to be lowest when *DaI* was on the order of 1.0 and concluded that parameters were “well estimated” when *DaI* was on the order of 0.1–10. When *DaI* values were much less than 1 (<0.01), due to high velocity, large exchange time scale (α or A/A_s is small), and/or short flow-path length, parameter uncertainties are high because only a small amount of tracer interacts with the storage zones over the length of the flow-path. When *DaI* values are much greater than 1, solute exchange rates are high compared with the velocity, or the flow-path is long. In such cases, most, if not all solute undergoes some exchange into the storage zone and the storage zone parameters can only be estimated with large uncertainties. At *DaI* values greater than 100, exchange of tracer with the storage zone is effectively at equilibrium with the movement of tracer downstream (Fernald et al., 2001) making estimates of α and A_s uncertain. In such cases a ‘best fit’ can usually be found equally well by varying D or α and A_s. It can be seen in Table 1 that *DaI* values for all cells were found to be within acceptable limits.

Because of the difficulty in quantifying the contribution of the many mechanisms contributing to storage, the storage zone cross-sectional areas and storage zone exchange coefficients found here are lumped values representing the effects of transient storage over the entire length of each wetland ‘reach’. Referring to the transient storage model, Bencala and Walters (1983) stated that, “the application of a one-dimensional (or pseudo-two-dimensional) transport analysis remains empirical”. They were referring to the fact that storage zones present in a stream or river (or a wetland in our case), such as side pockets, deep pools, and shallow vegetated zones, are easy to visualize, while the physical driving mechanisms that uniformly distribute the solute throughout the storage zone and transfer mass between the storage zone and the main flow channel are not. Thus, the transient storage model may not be completely physically descriptive, but does provide a good empirical simulation considering previous modeling efforts that have used the model or similar forms of it with good results for streams (e.g. Nordin and Troutman, 1980; Bencala and Walters, 1983) and treatment wetlands (Keefe, 2001).

The OTIS model has been shown to only produce reliable simulations when used under the same riverine flow conditions as those for which it was calibrated. Extrapolation of transient storage parameters to different flow and seasonal conditions has proven difficult (Hart et al., 1999). This constraint likely applies to the application of OTIS for wetlands, also. Thus OTIS is not yet capable of performing as a predictive model for constructed wetlands without first conducting tracer experiments.

The model fits presented here were conducted with no cross-sectional area constraint, that is the values of A and A_s calculated were not required to sum to an average ‘observed’ cross-sectional area of each wetland cell. This ‘observed’ cross-sectional area of each wetland cell is simply the quotient of the total volume of the cell and the length of the cell. It is more intuitive to determine and compare volumes of the storage zone and main channel to the total volume of each wetland cell rather than to compare their cross-sectional areas. The volumes of the main channels (V_c), and storage zones (V_s) are the product of their cross-sectional areas and flow-path lengths. Values of V_c and V_s for each wetland cell can be found in Table 2. Total cell volumes (V_T) were determined using bathymetric data from the site grading and drainage plans and backwater profiles generated using water surface elevations at downstream weirs as the datum (Martinez and Wise, 2003). The sum of the volume of the main channel (V_c) and storage zone (V_s) can be thought of as the effective volume of each cell (V_e). This effective volume is the volume of each cell that is contacted by tracer. As can be seen in Table 3, ratios of V_e to V_T were found to be consistently low with an average of 0.48. The remaining volume can be considered to be purely 'dead' water. Under such conditions there are effectively three 'zones' in each wetland cell: the first being the main channel, defined spatially by the cross-sectional area determined; the second is the storage zone, also defined by the cross-sectional area determined by the model; the remaining cross-sectional area of the wetland is considered to be purely 'dead' water (which may be exchanging water (and therefore, tracer) but at such small amounts and/or at such slow rates to be considered to be negligible).

Also in Table 3 the effective and total volumes determined as above are compared with the effective volumes determined by moment analysis (V_m) (Martinez and Wise, 2003). The effective volume determined by moment analysis is found from:

$$V_m = \bar{t}Q \quad (5)$$

where $\bar{t}$ is the first moment of the tracer response curve (T). Ratios of moment derived volumes and total volumes were found to be on average 0.47. The moment derived volumes found here were found to generally correspond with the effective volumes as determined above (Table 3). These volumes also strongly indicate the presence of a purely 'dead' water zone.

A major assumption of the OTIS model is that all storage/exchange processes of the system modeled are represented by a single storage zone. This use of a single first-order mass transfer to characterize the bulk response of the storage zones present in a system is equivalent to assuming that solute retention times in the storage zone are exponentially distributed (Levenspiel, 1972). It is intuitively obvious that this can not be entirely physically accurate. This assumption is violated if multiple storage zones with distinctly different first-order rate constants are present. It has been shown that the tracer response fitting approach to characterizing storage and exchange processes is

Table 2
Main channel and storage zone volumes

Cell	V_c (m^3)	V_s (m^3)
1	8150	8470
2	114 000	24 800
3	11 200	3270
4	3150	3470
5	2100	2850
6	11 900	14 800
7	10 800	9700
8	590	9780
9	5790	6500
10	22 900	10 800
11	62 300	29 800
12	51 200	54 400
13	92 000	111 000
14	79 900	70 000
15	53 400	39 500

Table 3
Effective volumes determined by OTIS and moment analysis and total observed cell volumes

Cell	V_T (m^3)	V_e/V_T	V_m/V_T
1	70 800	0.23	0.30
2	158 000	0.88	0.88
3	30 900	0.47	0.52
4	32 300	0.21	0.25
5	21 000	0.24	0.11
6	39 400	0.68	0.71
7	67 000	0.31	0.20
8	29 700	0.35	0.42
9	32 400	0.38	0.30
10	62 500	0.54	0.57
11	220 000	0.42	0.49
12	131 000	0.81	0.69
13	324 000	0.64	0.40
14	287 000	0.53	0.45
15	161 000	0.58	0.74

biased towards representing faster exchange pathways (Harvey et al., 1996).

A modification of the transient storage model that would be more suitable for the use of a cross-sectional area constraint (requiring the main channel and storage zone volumes to sum to the total system volume) is that detailed by Choi et al. (2000), who addressed the question of whether the effects of storage by different mechanisms can be lumped together into a single storage zone. Choi (1998) found storage in the hyporheic zone as well as in areas of the stream that had abundant aquatic vegetation. These two storage areas were found to experience distinctly different time scales of solute exchange with the main flow channel. In order to account for this disparity, Choi et al. (2000) extended OTIS to include a secondary storage zone and evaluated the effectiveness of the original one-storage zone model to reproduce data sets generated by the new two-storage zone model.

Of the data sets generated with the two-storage zone model, Choi et al. (2000) found ninety percent could be fit adequately by the one-storage zone model when the storage zones had similar storage zone retention times, or had different storage zone retention times (ratio of larger to smaller >5) and had dominance of both storage capacity and exchange flux in a single storage zone. The one-storage zone model could not fit the data well when one storage zone had a much larger mean retention time than the other (ratio of larger to smaller >5) and when one storage zone was dominant only in terms of storage capacity but not in exchange flux. When one storage zone had a much larger capacity as well as a larger retention time, the one-storage zone model accurately fit the large storage zone response and was insensitive to that of the smaller storage zone (Choi et al., 2000). The storage zone retention time and exchange flux for each storage zone are defined as:

$$t_{s,i} = \frac{A_{s,i}}{\alpha_i A} \quad (6)$$

and,

$$q_{s,i} = A\alpha_i \quad (7)$$

respectively, where subscript i denotes the storage zone index.

The use of a two-storage zone model would make the use of a cross-sectional area constraint more realistic where the region defined as purely 'dead' water here could be considered as a second storage zone with a large capacity and large retention time. This would also aid in better fitting of the extended tailing experienced in this study where the one-storage zone model more often then not dropped off before tracer observations.

Since wetlands are usually not homogenous in terms of depth, rate of organic material accumulation, vegetative type and density, and may be irregular in shape, the appropriateness of one-dimensional models for modeling wetland tracer responses is somewhat difficult to address. On one hand, physically based models strive to accurately describe the entire model domain in order to achieve better results. On the other hand, Danckwerts (1953) believed it was enough to know only the probability distribution of residence times of a system in order to successfully fit a model that could be then used to predict future operation. Central to this idea is that reaction (decay or uptake) occurs as a first-order process and only depends on the concentration of the reactant present and the time spent in the system, the location within the system being irrelevant. This assumption is likely untrue in the case of treatment wetlands, where water chemistry, biota, etc. can vary spatially.

The use of a one-dimensional model creates difficulty in cases when tracer responses from one cell appears to bimodal, as is the case for Cell 1 (Fig. 4), where two distinct flow-paths appears to exist. In such cases the model used herein cannot account for the secondary parallel flow-path and can only provide lumped parameters describing the combined effects of the primary and secondary flow-paths. In the case of Cell 1, the two flow-paths appear to be leading to different effluent weirs. Perhaps simulating each perceived flow-path as separate and unconnected may provide better parameterization of each flow-path (Fig. 9). Modeling flow-paths separately is not easily done when two different flow-paths appear to exist leading to the same weir as with weir 12-Y in

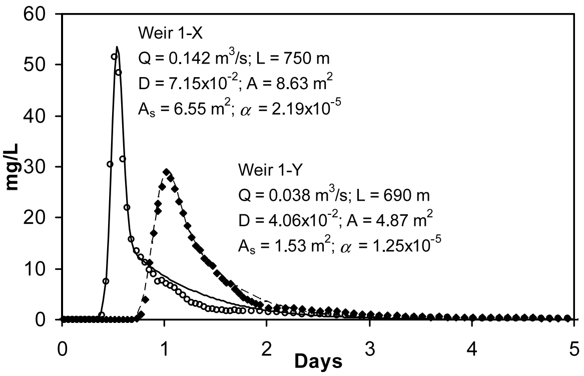

Fig. 9. Cell 1 individual weir OTIS model fits.

Cell 12 (Fig. 10). Even an OTIS model fit of individual effluent weirs cannot effectively explain the signal seen for weir 12-Y. However, if data are not available for which to support two- (or even three-) dimensional models, they should be eschewed as a matter of course.

The use of a one-dimensional model also creates difficulty in the assumption that flow-paths can be defined as straight line distances from inlet to outlet, particularly since it is known that wetlands can often exhibit highly tortuous flow-paths. Upon inspection of equations (1) and (2) it can be seen that an increase in flow-path length is accompanied by decreases in main channel and storage zone cross-sectional areas; however, the resulting volumes will remain the same since they are the product of the flow-path length and their respective areas. It can also be shown that all parameters defined here (including α, $\mathscr{D}$, and DaI)

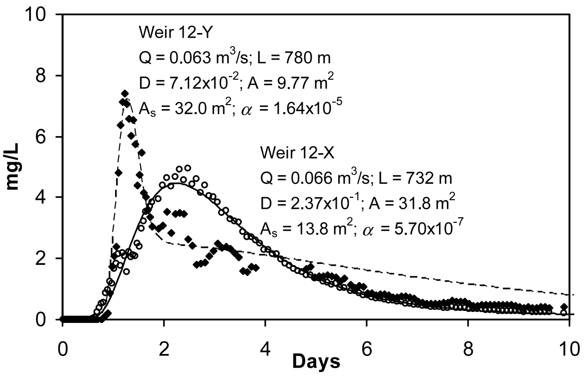

Fig. 10. Cell 12 individual weir OTIS model fits.

with the exception of the longitudinal dispersion coefficient, D, will remain the same when simulating the same tracer response using different flow-path lengths.

The effect that multiple flow-paths have on predictions of treatment is difficult to ascertain. Only if biogeochemical processes can be determined to be identical in different parts of the wetland occupied by the different flow-paths can cross-flow of water from one flow-path to another be ignored. Otherwise cross-flow will serve to mask the treatment effectiveness of a particular flow-path should the cross-flow contain water that has been treated to a significantly different degree.

Reaction rates have been noted to differ between the main channel and storage zones in other studies. Choi et al. (2000) noted different rates of reaction in the hyporheic zone of streams and rivers. White et al. (2002) noted that areas of the OEW that are isolated from actively flowing regions can be identified by their water chemistry, where limited exchange of water and constituents, low dissolved oxygen, and decomposing organic material results in the release of phosphate from the soil. This can result in these areas being a net source rather than sink of phosphorus. OTIS can account for different rates of uptake in the main-channel and storage zones and could thus be effective in predicting treatment levels when these reaction rates are known.

While we have attempted to identify storage and dead zones here and have contemplated their affects on treatment there remains a significant challenge to link physical field measurements of the size, flux, and biogeochemical process rates of storage zones in treatment wetlands to fully understand their implications on achieved treatment levels. Such a task would require a fairly detailed monitoring network that could possibly accompany a simultaneous injection of both tracer and the pollutant of interest.

6. Conclusion

The transient storage model OTIS was found to fit and parameterize experimental tracer responses from treatment cells of the OEW. The model can account for short-circuiting of the treatment volume and temporary storage of tracer in storage zones once calibrated to experimental tracer responses. Short-circuiting and temporary storage in constructed treatment wetlands are likely caused by variable bathymetry, plant communities and densities, and possibly hyporheic exchange. Parameter uncertainties were evaluated with an experimental Damköhler number and were determined to be acceptable. After calibration the model could then be used to help predict pollutant removal. The model could also simulate different rates of pollutant removal in the main channel and storage zones of the wetland.

Three distinct hydraulic 'zones' of the wetland were identified using the model. The first is the actively flowing region of the main flow channel. The second is a low-flow, isolated storage zone which temporarily stores water and solute and exchanges mass with the main channel. The third zone is purely 'dead' water which has little or no contact with tracer as it passes through the wetland. Future work is needed to delineate and characterize storage and dead zones directly in order to evaluate the performance of the model.

7. Symbols used

A main channel cross-sectional area (L^2)
A_s storage zone cross-sectional area (L^2)
$A_{s,i}$ storage zone cross-sectional area of storage zone i (L^2)
C main channel solute concentration (ML^{-3})
C_s storage zone solute concentration (ML^{-3})
D longitudinal dispersion coefficient (L^2T^{-1})
DaI experimental Damköhler number
L flow-path length (L)
Pe Peclet number
Q volumetric flow (L^3T^{-1})
$q_{s,i}$ storage zone exchange flux (L^2T^{-1})
T time (T)
$t_{s,i}$ storage zone retention time (T)
$\bar{t}$ first moment of the tracer response curve (T)
U water velocity (LT^{-1})
V_c main channel volume (L^3)
V_e effective cell volume (L^3)
V_m effective cell volume determined by moment analysis (L^3)
V_s storage zone volume (L^3)
V_T total cell volume (L^3)
x distance along the main channel (L)
α storage zone exchange coefficient (T^{-1})
α_i storage zone exchange coefficient for storage zone i (T^{-1})
$\mathscr{D}$ vessel dispersion number

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