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Wetland residence time distribution modeling

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Abstract

The non-ideal flows of constructed wetlands were modeled with a network of an infinite number of small stirred tanks distributed along a set of main plug flow channels. The stirred tanks represent zones of diminished mixing (ZDMs) because they undergo only limited exchange of water with the main channels. Based on this concept, a computer model, ZDM, was developed to reproduce the experimental wetland residence time distributions (RTDs). This non-site specific model is capable of producing realistic RTDs, and reproducing experimental RTDs determined from impulse tracer studies performed on both steady and variable flow systems. Eight experimental RTDs from the Des Plaines River site in Illinois, USA, along with 41 RTDs from the literature were used to test the flow model. It was found that tracer studies completed with more attention to detail were more readily reproduced by the model. These details include adequate flushing of previous tracer studies, use of inert tracer, adequate sampling frequency and accurate knowledge of the wetland water volume. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

As the use of treatment wetlands continues to increase, so must our understanding of their many varied, yet interconnected processes. A solid understanding of the physical, chemical and biological processes which combine to remove pollutants in a wetland is necessary. Contributing to these processes are soils, microorganisms, plant litter and macrophytes. A principal controlling factor is water movement patterns in the wetland. Mixing and flow of the various parcels of water and the time that each one resides in a wetland determines the extent of reaction for the pollutants of concern.

The investigation of flow patterns and mixing in a fluid system is a well established field of chemical engineering. This field was developed to enable engineers to understand the flow behavior of a chemical reactor, without having to account for the complete history of each fluid element. In his pioneering paper, Danckwerts (1953) pointed out that in place of such a complete description of the flow pattern, it is enough to know how long the fluid elements stay in the reactor. This is, of course, the residence time distribution of the system. The standard procedure is to develop a

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model that produces a similar residence time distribution and use the model to provide a simplified view of the very complex system. This paper is based on the notion that a constructed wetland can be thought of as a 'chemical reactor'. These systems can often have non-standard shapes, irregular flows and variable water volumes. Yet, even such unsteady systems can be investigated with tracer studies and have RTDs determined (Werner and Kadlec, 1996).

The objective of this work is to introduce an improved non-ideal flow model to wetland analysis, and to demonstrate that the model can replicate RTDs from a variety of wetlands. The intention is for the model to balance physical realism with mathematical simplicity so that it can be used as a tool in future studies of wetland performance.

1.1. Residence time distributions

A distribution of times that parcels of water spend in a constructed wetland is known as a residence time distribution. If completely mixed, all parcels have equal probability of leaving the wetland at a given moment, and the system is a continuous stirred tank reactor (CSTR). An exponential curve characterizes the distribution of residence times in a CSTR. If there is not a distribution of times, but rather all parcels spend the same amount of time in the system, the term 'plug flow' is applied to the system. A plug flow reactor (PFR) has a single residence time, or a distribution equal to a Dirac delta function at that single residence time. Much of the constructed wetland design literature presumes this type of ideal flow (United States Environmental Protection Agency, 1988; Water Pollution Control Federation, 1990; Reed et al., 1995), but this presumption of plug flow has been shown to be incorrect by several studies (Fisher, 1990; Urban, 1990; Kadlec et al., 1993; Kadlec, 1994; Tennessee Valley Authority, unpublished dye study results from September 1990 at Benton, KY).

Intermediate degrees of mixing occur in constructed wetlands, so that there is a distribution of times spent in them. Internal flows are non-ideal, not fully mixed and not plug flow. Depending upon the movement of water in the constructed wetland, different parcels will remain in the constructed wetland for varying amounts of time. This will produce varying amounts of treatment; which, when recombined at the outlet, will produce the overall level of treatment. Except for the case of zero order kinetics (with incomplete reaction), this treatment is not the same as the result of using the average time water resides in the wetland. Therefore, the distribution of times that parcels spend in the constructed wetland is a very important factor when determining the treatment level that a constructed wetland achieves.

1.2. Observed wetland behavior

Guidance on model development is provided by field observations and tracer tests. It is clear that several physical phenomena can contribute to the distribution of travel times, including wind mixing, vertical and transverse velocity profiles, bottom topography and vegetation patterns. These effects can be easily identified in the field by visible tracer dosing (Cooper, 1992), or by watching the movement of floating objects, such as duckweed plants (*Lemna* spp.). Water moves more slowly along the bottom than in the surface layers, and detours around thick plant clumps. Dye may be seen to linger or 'park' in patches of litter apart from the main flow paths. Bulk flow velocities are typically so slow that wind shear can drive the surface water layer in any direction, including directly upstream, counter to the main flow.

Velocity profiles can lead to a distribution of residence times. The shortest time is experienced by the water moving at the maximum velocity in the profile, which would normally be in the surface layer of the micro-channels. The longest times would be experienced by water that moves near drag-inducing surfaces, such as the wetland bottom. This type of 'mixing' scales to the distance down the wetland, and to the average speed of the water. If the spread of a tracer impulse (variance of the concentration distribution) is considered as the measure of the degree of mixing, then this non-ideality will produce greater spreads further down the wetland, and greater spreads for higher mean velocities. The dispersion coefficient (D) will be proportional to the mean velocity (u) and to the length (L), and the dispersion number ($\mathscr{D} = D/uL$) will be constant. It may be shown that the dispersion number is characterized by the spread of the tracer distribution ($\Delta\sigma_\theta^2$) with respect to normalized time ($\theta = t/\tau$).

Wind mixing, bioturbation and turbulence-induced mixing, caused by flow around immersed objects or high speed flow, can produce dispersion and hence a distribution of detention times. This type of 'mixing' scales to the size of the turbulence, which in turn depends on the size of the object creating turbulence, or to the square of the mean velocity (Levenspiel, 1972). In that case, the dispersion number ($\mathscr{D} = D/uL$) will increase with velocity, which is equivalent to decreasing with wetland aspect ratio.

Tracer tests indicate that treatment wetlands are more influenced by velocity profile effects than by dispersion. The spread of the dimensionless RTD was not a function of distance down wetland EW4 at the Des Plaines site (Fig. 1). Aspect ratio produced no effect on spread for wetlands at the Champion site (Fig. 2). The effects of topography and vegetation were reported to show little influence on tracer concentration response on the macroscopic scale of the entire wetland (Kadlec, 1994). Nevertheless, flows in micro-channels will undoubtedly show some true dispersion.

As a consequence of these observations, the best flow pattern model should exhibit the characteristics of velocity profile mixing, or the 'park and go' sequence.

1.3. Models

Modeling the non-ideal flows of a wetland provides an estimation of the internal mixing, and therefore the residence time distribution expected from the wetland. Drawing from the chemical engineering literature, the procedure is to develop a flow model that produces a similar residence time distribution, and use that model to provide a simplified view of the complex system. There are dozens of published methods for constructing such flow models (see the review by Call (1989), for example). The two types of models most often used are plug flow with dispersion and networks of ideal reactors. The plug flow with dispersion (PFD) model was shown to be inadequate in describing wetland flow when bypassing or extended retention of tracer occurs (Kadlec, 1994).

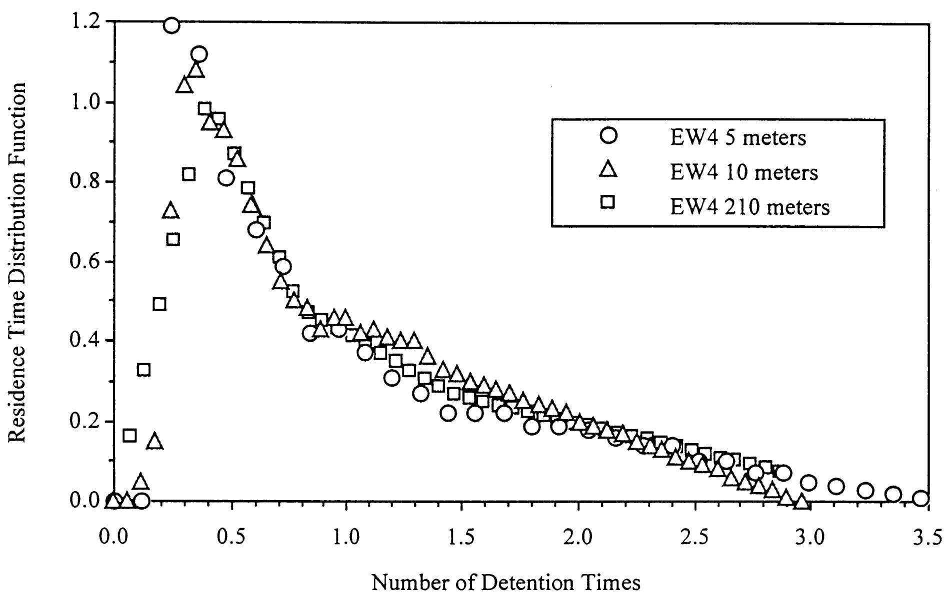

Fig. 1. Normalized and smoothed tracer response for wetland EW4 at Des Plaines.

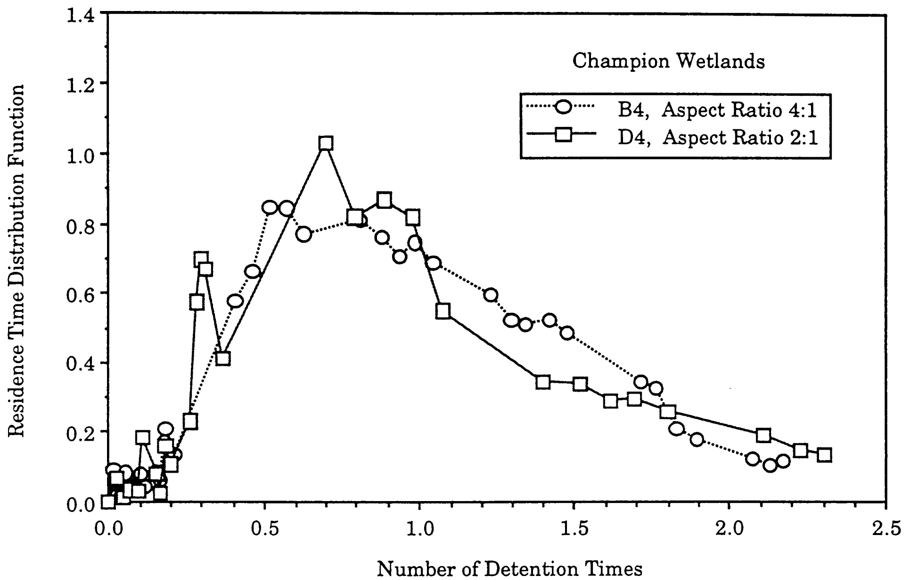

Fig. 2. Tracer response of wetlands of different aspect ratio.

Urban (1990) modeled the flow in a constructed wetland as combinations of ideal reactors in an attempt to reproduce the actual RTD. Three models were developed, three CSTRs in series, eight PFRs in parallel, and three PFRs in parallel. All three models produced RTD functions that fit reasonably well with his experimental data. However, the models were site specific and are not meant as general models to be used for predictive purposes.

Levenspiel (1972) developed an extensive set of network models using various combinations of plug flow stages and fully mixed stages. Among these is included a series parallel network of main flow tanks each connected to a side tank (Levenspiel's model G). Kadlec and Bastiaens (1992) adopted that model, together with a time delay. Calibration was to replicate tracer studies on a single wetland. The site specific model consisted of a series of three CSTRs, with each connected to a side CSTR. This model predicted that the tracer is detected at the outlet of the wetland immediately. However, the experimental RTDs all displayed delays between the pulse tracer input and the time at which the tracer was first measured at the outlet. To account for the time lag, a PFR was added to the model. The model fit quite well to single experimental data sets. Limitations of the model are that it is site specific, and it requires four adjustable parameters. A refined form of this model, along with a CSTRs in series model, and the plug flow with dispersion model were discussed in detail by Kadlec (1994).

In this paper, Levenspiel's model G is extended to the case of a very large number of side tanks connected to main PFR channels.

2. Model development

2.1. Conceptualization

The basic concept of the model in this paper is that a constructed wetland has an infinite number of 'micro' zones of diminished mixing (ZDMs) all along a set of main channels. These zones are not excluded 'dead zones', but they only exchange water with the main flows on a limited basis. The main flow paths, from the inlet to the outlet, are represented by a plug flow stage, and the ZDMs are represented by CSTRs (Fig. 3). Thus, there is a plug flow section which has CSTRs attached to it along its length. A parcel of water traveling along the PFR has a small probability of exiting the PFR to enter one of the infinite number of ZDMs. The small probability taken a large number of times results in a good chance of a water parcel spending some finite amount of time in ZDMs. When a parcel of water leaves a ZDM and re-enters the main flow channel, it will not accompany water parcels that it had been traveling with earlier in the PFR.

An infinite number of ideal stages (PFRs and CSTRs) can not be used directly to model wetland flow if each stage requires finite computer time. A balance between reasonable computer time and accurate results was found by simplifying to 100 pairs of ideal stages. Before simplifications were made, however, some understanding of the model was necessary. To help understand this distributed parameter model (infinite stages of CSTRs and PFR), the residence time distribution was analytically determined for a pulse tracer input to the system with a PFR main channel.

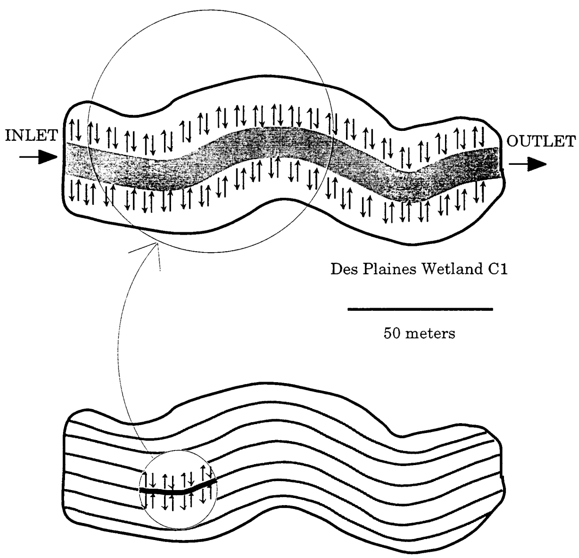

Fig. 3. A wetland can be thought of as a main flow channel flanked by many small regions of limited flow interaction (a, top). The main flow channel can also be thought of as a number of narrower channels exchanging limited flow with neighboring zones (b, bottom).

2.2. Infinite CSTRs along a PFR

Water travelling through the ZDM configuration either travels through a given CSTR, or bypasses it instantly. A tracer impulse of mass M causes a concentration response from a single CSTR and an instantaneous bypass that is a combination of a pulse of tracer at $t=0$ that bypasses the CSTR, and an exponential curve for the balance of the tracer that passes through it:

$$C(t)=\frac{\upsilon_S^2 M}{Q^2 V}\,e^{(-\upsilon_S t/V)}+\frac{M(Q-\upsilon_S)}{Q^2}\,\delta(t) \quad (1)$$

where υ_s is the volumetric flowrate through the CSTR, Q is the volumetric flowrate through the wetland, V is the volume of the CSTR, and $\delta(t)$ is the Dirac delta function. When bypasses and two CSTRs with a combined volume of V undergo a pulse input, a portion of the pulse bypasses both CSTRs, a portion enters one and bypasses the other, and a portion travels through both CSTRs. The concentration response curve is again a combination of a pulse of tracer at $t=0$, and the time dependent response:

$$C(t)=\frac{\upsilon_S M}{QV}\,e^{(-\upsilon_S t/V)}\left[\frac{\upsilon_S^3 t}{Q^2 V}+\frac{2\upsilon_S(1-\frac{\upsilon_S}{Q})}{Q}\right]+\frac{M(Q-\upsilon_S)^2}{Q^3}\,\delta(t) \quad (2)$$

If this idea is extended to n CSTRs with n bypasses, the time dependent response becomes:

$$C(t)=\tfrac{\upsilon_S M}{QV}\,e^{(-\upsilon_S t/V)}\sum_{j=0}^{n-1}\left[\left(\tfrac{\upsilon_S}{Q}\right)^{(n-j)}\left(\tfrac{\upsilon_S t}{V}\right)^{(n-j-1)}\left(1-\tfrac{\upsilon_S}{Q}\right)^{j}\frac{n!}{j!(n-j)!(n-j-1)!}\right]+\tfrac{M}{Q}\left(1-\tfrac{\upsilon_S}{Q}\right)^{n}\delta(t) \quad (3)$$

The mass of tracer exiting the system at $t=0$ is represented on a plot of concentration versus time as a Dirac delta function having an area of:

$$\frac{M}{Q}\left(1-\frac{\upsilon_S}{Q}\right)^{n} \quad (4)$$

Before allowing n to become infinite, simplifications are made by defining a dimensionless concentration, C', and a dimensionless time, θ:

$$C'=C(t)\frac{V}{M} \quad (5)$$

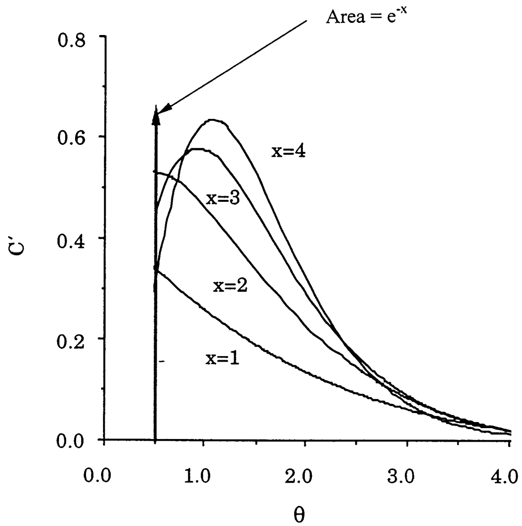

Fig. 4. The concentration response of the infinite bypasses and infinite CSTRs for $z = 0.5$ and various values of x.

$$\theta = t\frac{Q}{V} \tag{6}$$

The tracer that leaves the system of infinite CSTRs and instantaneous bypasses after $\theta = 0$ is then represented by:

$$C'(\theta) = \frac{x}{e^{x(1+\theta)}\theta^{1/2}} I_1(2 \times \theta^{1/2}) \tag{7}$$

where x is defined by:

$$x = \lim_{n \to \infty} \frac{n v_S}{Q} \tag{8}$$

and I_1 is the hyperbolic Bessel function of type 1. As the number of CSTRs becomes infinite, the mass fraction of tracer that bypasses all the CSTRs to exit at $\theta = 0$ becomes:

$$\text{Fraction in delta} = e^{-x} \tag{9}$$

In the proposed model, CSTR bypasses are not instantaneous, but require a transit time of $(1 - z)\tau$, where z is the fraction of the total volume which comprising ZDMs. Therefore, the delta response occurs at that time, and the CSTR portion is translated by the same amount (Fig. 4).

2.3. Parameters

The time dependent response of the system described above has a delta function at the nominal detention time of the PFR. As x becomes large, the area of this delta function (Eq. (9)) approaches zero; however, the combined PFR and CSTR system causes Eq. (7) to produce a separate delta function at the nominal detention time of the entire system. In this case, the system is acting as a PFR because each PFR/CSTR pair exchanges water so rapidly that they act as a single CSTR, and an infinite series of CSTRs is a PFR.

A value of zero for x represents elimination of flow to the ZDMs. Only in this extreme case do the ZDMs become true ‘dead’ zones in that they have no interaction with flow through the wetland. In such an instance, the volume of the system is effectively reduced to the volume of the main PFR channel. It should be noted that the shape of the response for $x = 1$ is similar to that for velocity profile mixing in channels (Fogler, 1992).

The second parameter, z, is defined as the fraction of wetland volume comprised of ZDMs. If z is zero, then the entire wetland volume is represented by the main PFR channel (Fig. 5). At the other extreme, when $z = 1$, the PFR is eliminated so that the RTD is that of the ZDMs (Fig. 5).

In real wetland systems, delta functions representing plug flow do not exist. The delta functions of Fig. 5 must be transformed in some manner. To account for the additional mixing that spreads and softens delta functions, a channel dispersion term, in the form of a Peclet number, $\mathrm{Pe} = uL/D = 1/\mathscr{D}$, is added to the plug flow channel of the model system:

$$\frac{\partial C}{\partial t} = \frac{uL}{\mathrm{Pe}} \frac{\partial^2 C}{\partial y^2} \tag{10}$$

In Eq. (10), y is the fractional distance from inlet to outlet. The addition of Pe as a third parameter prevents the use of analytical solutions such as Eq. (7). Therefore, a computer program is required, in which a finite difference method is employed.

2.4. Computer simulation

Accounting for the movement of tracer through the network model begins with mass balances on each CSTR element:

$$\frac{d(V_s C_{s,j})}{dt} = \upsilon_s C_{p,j} - \upsilon_s C_{s,j} \tag{11}$$

and each PFR segment:

$$\frac{d(V_p C_{p,j})}{dt} = QC_{p,j-1} - QC_{p,j} + \upsilon_s C_{s,j-1} - \upsilon_s C_{p,j-1} + \left[\frac{uLV_p}{\mathrm{Pe}(\Delta y)^2}\right](C_{p,j-1} + C_{p,j+1} - 2C_{p,j}) \tag{12}$$

In the above equations, V_s is the volume of a CSTR segment, V_p is the volume of a PFR segment, $C_{s,j}$ and $C_{p,j}$ are the concentrations of tracer in CSTR j, and PFR j,respectively. A Fortran 77 program, ZDM, was compiled to solve Eqs. (10)–(12) on a Sun Sparc20 workstation. The constant flow version of ZDM requires the following data: mass of tracer impulse, background tracer concentration, water volume of the wetland, volumetric flowrate through the wetland, and the three parameters x, z and Pe. To perform parameter estimations, the actual tracer study results are read by ZDM as a data file of exit concentrations and time.

For systems having changing flows and volumes, additional data is necessary. In such cases, an equation is needed to calculate the changing exit flow rate using the current wetland volume. To keep track of the wetland volume, data files of inlet flow, precipitation, and evapotranspiration must be included. Additional pieces of information required are the area of the wetland, the water volume below the outlet flow structure, and the initial water level in the wetland. Together, the hydrology and the non-ideal flow model allow the computer program to generate an RTD.

To fit a tracer data set, the RTD produced for the constant or variable system is compared to the experimental data and the cumulative normalized absolute error is calculated. This objective function is volume weighted to reduce the effects of samples taken at irregular time intervals, and to properly account for data taken at various flow rates. Volume weighted concentration differences are simply differences of mass. Therefore, the objective function is the cumulative normalized difference between the experimental tracer mass balance and the simulated tracer mass balance. A search technique is then employed to minimize the objective function by adjusting the three parameters. To avoid local minima, the three dimensional parameter space was searched using a robust technique of successively smaller parallelepiped volumes.

3. Results

Experimental results from the following four constructed wetland sites are considered in this work: Champion pilot constructed wetland treatment system, Florida (Knight et al., 1994), Des Plaines River Wetland Demonstration Project, Illinois (Kadlec, 1994), Pope & Talbot pilot wetlands, Oregon (Stairs, 1993) and Lighthorne Heath storm reed bed, England (Green and Martin, 1994). Table 1 provides a summary of the tracer study data, and the sources. Included in this collection of tracer studies is previously unre-

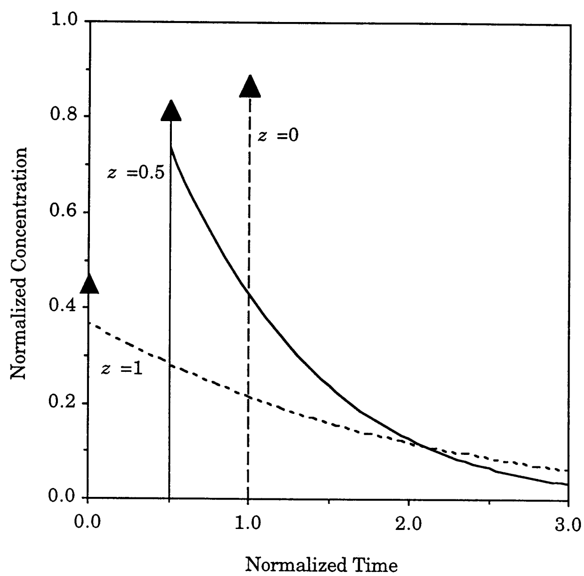

Fig. 5. The concentration response of the PFR with infinite CSTRs to a tracer impulse for three values of z. In all three cases, $x = 1$.

Table 1
Tracer study data included in this work

Site	Site description	Number of wetlands	Multiple runs	Total runs
Des Plaines	Kadlec, 1994	2	Yes	15
Champion	Knight et al., 1994	6	No	6
Pope & Talbot	Stairs, 1993	5	Yes	27
Lighthorne Heath	Green and Martin, 1994	1	No	1

ported data taken in 1993 from two wetlands, EW3 and EWC1, at the Des Plaines site. Data from EW3 collected in 1991 and 1992 have been presented previously by Kadlec (1994). The methods for collecting and analyzing 1993 samples were identical to those of the earlier work (Kadlec, 1994). In 1993 the two wetlands at the Des Plaines site underwent 'event' driven flows. Tracer was added just prior to the start of pumped flow to the systems. After a predetermined amount of time, the pumping ceased, and the outflows slowly tapered off.

From the four wetland sites, a total of 49 tracer studies produced the same number of experimental RTDs. Each of the data sets was fit by the ZDM computer model by optimizing a corresponding simulated RTD. Fig. 6 shows sample experimental results and the corresponding simulation results. For constant flow wetlands, Champion and Pope & Talbot, normalized effluent concentrations are plotted against normalized time, θ. For variable flow wetlands, Des Plaines and Lighthorne Heath, normalized effluent concentrations are plotted against flow weighted time, ϕ (Werner and Kadlec, 1996).

4. Discussion

The ZDM model produces realistic RTDs, but can not accurately reproduce all experimental RTD data. Each of the four wetland sites' tracer data contained a different anomaly to consider when applying ZDM. These imperfections highlighted the ability of ZDM to better reproduce RTDs from more reliable and carefully performed experiments.

The concentrations of tracer in the effluent of Des Plaines wetland EW3 did not always return to background levels before the start of succeeding studies. Because of this, in 1993 three of the four studies began when the effluent concentrations from the previous studies had only dropped to approximately one half of the peak concentrations. The computer simulations account for this difficulty by having an estimation of the tail concentrations (Curl and McMillan, 1966) from the previous study subtracted from the current study's exit concentrations.

The amount and regularity of effluent concentration data collected from the Champion wetlands was not always ideal for simulations. The results from Champion wetland E provide an example (Fig. 7). There are only two data points

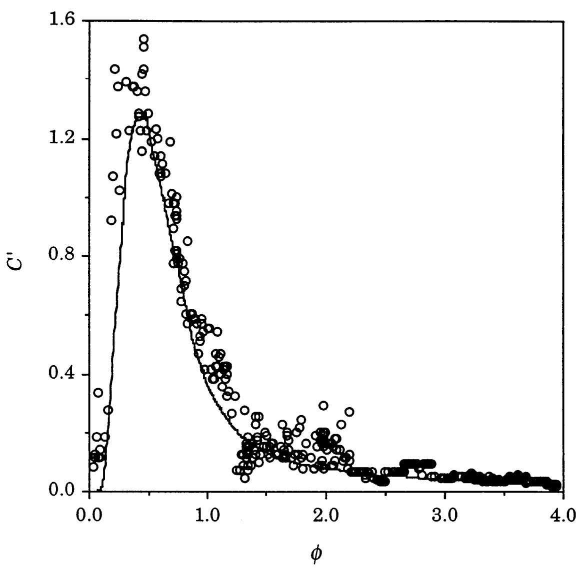

Fig. 6. The ZDM model fit to the experimental volume based RTD from Des Plaines EW3 in June 1991.

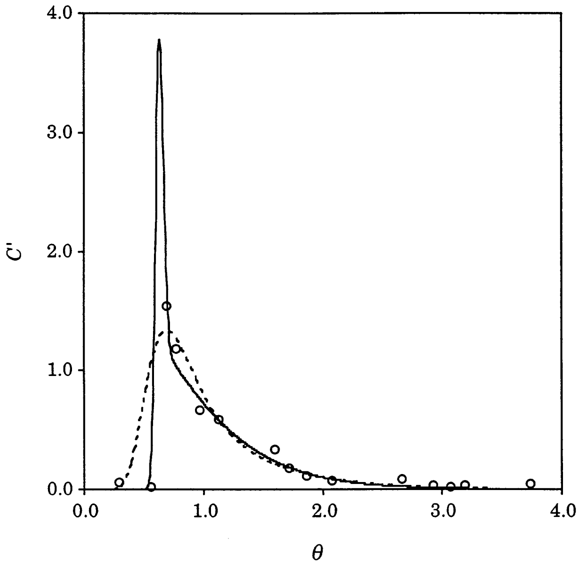

Fig. 7. The ZDM model fit to the experimental RTD from Champion wetland E in 1991. The solid line is the result when all of the data points are included in the fitting, and the dashed line is the result when all but the second data point are included.

prior to the peak concentration. Using these points, the simulation produces an extremely sharp rise to a peak concentration more than twice that of the highest experimental value. The simulation can not simply connect the second and third data points by a more direct route, because the area under the curve must be unity; the mass balance must close. With the removal of just a single point, the second point, the simulation produces a very different result (Fig. 7). An increased effluent sample collection frequency, especially around the peak concentration, would provide a more continuous and reliable tracking of the rise and fall of the effluent tracer concentration. The omission or inclusion of a single data point would then have a very insignificant effect on what the model is attempting to simulate.

The frequency and regularity of sample collection at the Pope & Talbot site was more than adequate, yet the mass balances close for only a few of the tracer studies. An assumption was made, for the purposes of this paper, that the tracer used by Stairs (1993) binds with a first order disappearance rate constant. Rate constants ranging from 0.000 to 0.026 h^{-1} were used to bring the zeroth and first moments closer to unity. Attempts were then made to simulate these modified RTDs.

A final concern that was highlighted by the Lighthorne Heath tracer data, but is not isolated to that case, is the accurate measurement of a wetland's water volume. An inaccurate measurement, or incomplete knowledge of a wetland volume distorts the normalized RTD so that the zeroth and first moments are also distorted. In the case of the Lighthorne Heath wetland, only an estimation of the volume was available for the simulation, and no knowledge of the relation between system volume and volumetric flowrate was available.

4.1. Parameters

A compilation of the parameters z and x, optimized in the simulations, is shown in Fig. 8. This mapping of z and x has darker points representing better data fits, and lighter points representing poorer data fits. A clear diagonal trend is visible, and shows the tendency of z to fall between 0.2

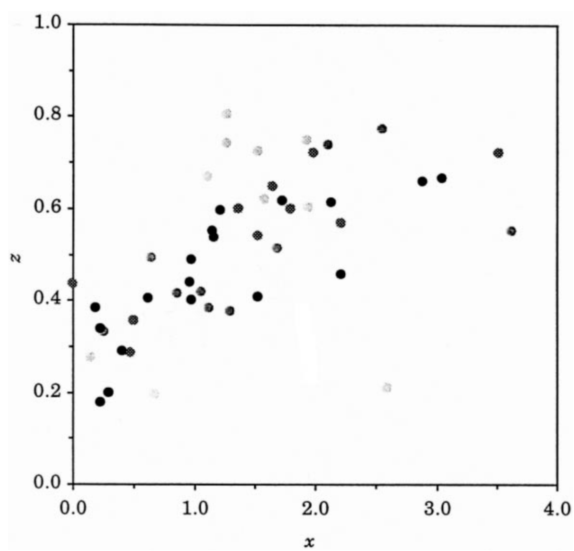

Fig. 8. The range of values of the parameters x and z found by optimizing the model fit to each experimental RTD. The darker markers represent simulations with better fits (smaller objective function values).

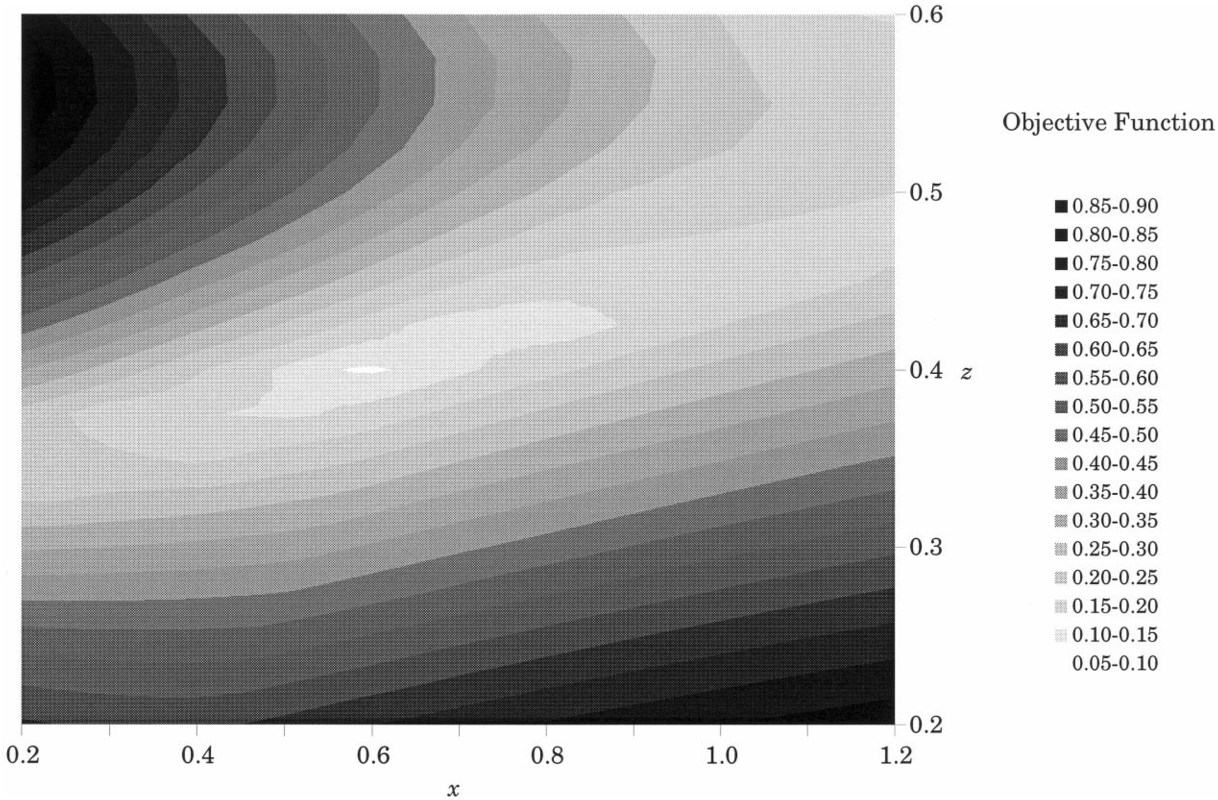

Fig. 9. An example of how the parameters x and z influence the objective function. The second tracer study from Des Plaines EWC1 in 1993 is the data source.

and 0.6, and of x to fall between 0 and 2. Qualitatively, this is most likely caused by increased flow to ZDMs when the ZDMs are a larger fraction of the wetland. The Peclet number tends to group about the value 11 for the whole range of simulation errors. These clusterings of values can provide a reduced range of parameter values for RTD estimation when a tracer study is not feasible.

The $\{x,z,\mathrm{Pe}\}$ results were also examined with consideration of the geometry of wetlands simulated, but no trends were found. Likewise, the aspect ratios of the wetlands simulated were not found to correlate with the parameters. In a similar finding, Kadlec and Knight (1996) demonstrated that aspect ratios are not clearly related to RTDs for open water systems.

An example of the sensitivity of the objective function to changes in parameter values is shown in Fig. 9. The second tracer study from Des Plaines EWC1 in 1993 is the source of data. The objective function is plotted against each of the three parameters. The minimum objective function value is 0.083, and occurs at $z = 0.405$, $x = 0.623$, and $\mathrm{Pe} = 23.8$. For this example, Pe had little influence on the value of the objective function.

Using the third of the simulations with the smallest objective functions (best data fits), a band of RTDs was plotted to depict the likely range of future experimental RTDs (Fig. 10). A quantitative certainty can not be assigned to the likelihood that an experimental RTD will fall along this band, yet experience has shown that a majority of past RTDs do experience such a limited range. The heavy line in Fig. 10 represents the "average" RTD generated with $x = 1$, $z = 0.4$ and $\mathrm{Pe} = 11$.

This typical RTD can not be reproduced well by a tanks in series model because of the early peak concentration. The tanks in series model can not account for the tall narrow peaks that exit the wetlands early in the tracer studies. When a sufficient number of CSTRs are linked together to produce a narrow peak, the peak moves closer to unity (away from the experimental peak). For example, to achieve a peak normalized concentration greater than one, the number of tanks in series must be greater than five. However, more than five tanks produces a normalized mode greater than 0.8; not representative of current constructed wetland RTDs.

4.2. Shortcut method

Numerical investigation of the interrelations of the model parameters x and z with the normalized variance and normalized mode led to the development of a parameter estimation method. A value for z can be calculated using:

$$z = (1 - 1.32\theta_p) \tag{13}$$

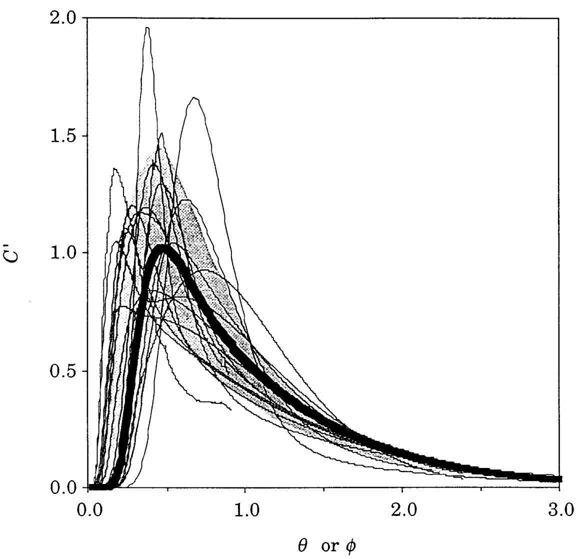

Fig. 10. Simulation results from the best fit RTDs. The shaded band represents a qualitative region in which RTDs are likely to fall. The thick line is the result of a simulation with $x = 1$, $z = 0.4$ and Pe = 11.

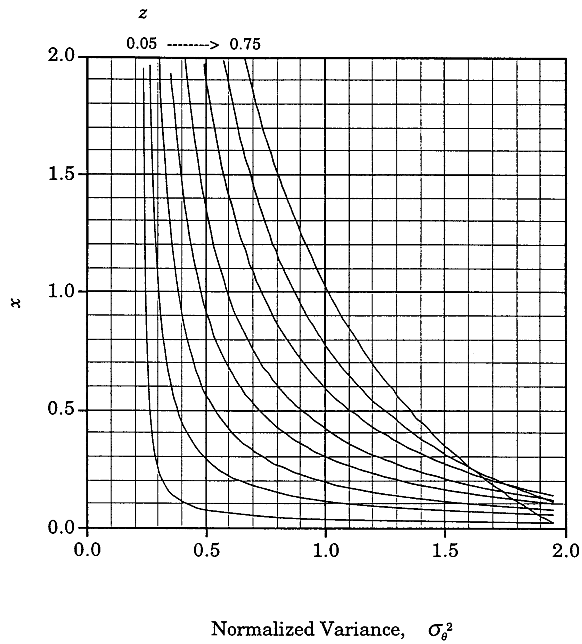

Fig. 11. The family of curves provides estimates of the parameter x when the normalized variance and the parameter z are known. The curves are drawn for values of z from 0.05 to 0.75 at intervals of 0.05.

where θ_p is the normalized mode (time to peak concentration). The calculated value of z together with the normalized variance, σ_θ^2, allow a value of x to be read from Fig. 11. This estimation method produces values of z that are $101 \pm 21\%$ of the model values, and values of x that are $102 \pm 9\%$ of the model values. The following is an example of the estimation of parameter values for the Des Plaines wetland EW3 in June 1991. From the value of the θ_p taken as 0.46 from the normalized data, a value of 0.40 is calculated for z. Using this value of z and a value of 1.19 for σ_θ^2, a value for x of 0.28 is read from Fig. 11. This estimation of the values of z and x is reasonably close to the values $z = 0.33$ and $x = 0.26$ found by ZDM. An estimation of Pe = 11 is also a reasonable approximation of the optimized parameter estimate of 8.2 found for Pe.

5. Conclusions

The ZDM model is based on a physical interpretation of wetland flow as a main flow path

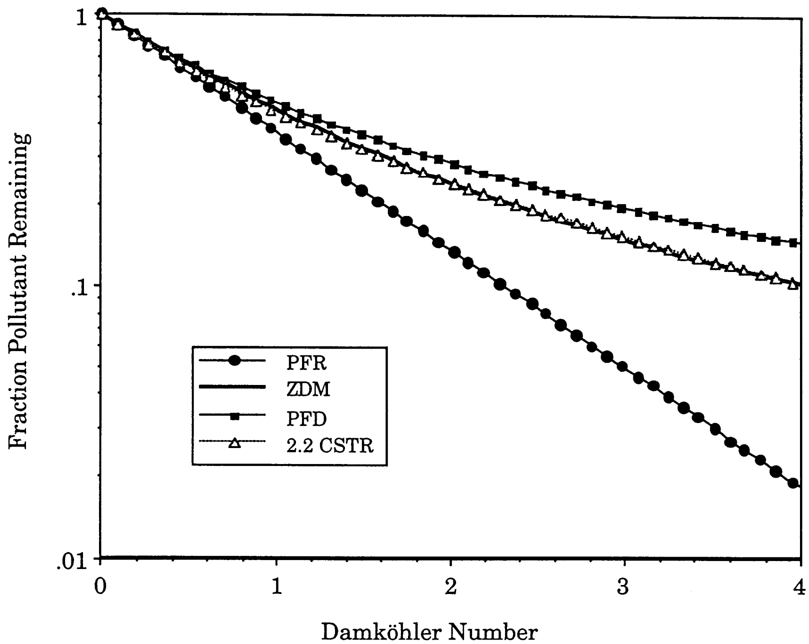

Fig. 12. The effect of non-ideal flow on pollutant reduction. All non-ideal lines use the same RTD parameters (first three moments).

flanked by zones of limited interaction. This model has the ability to reproduce RTDs from carefully conducted tracer studies, and aid in the understanding and design of constructed wetlands. It can accommodate high, early peaks and long tails.

An analysis of current and previous studies demonstrates the need for carefully thought-out and performed experiments.

In order for a tracer study to be worth an investment of time and money, a mass balance of the tracer must have reasonable closure. If the tracer is meant to be conserved, then what enters the system must exit the system after a sufficiently long time. Laboratory tests should be conducted to insure that the tracer is inert in the wetland environment. As it is not always practical to follow a study to completion, the method of Curl and McMillan (1966) should be used to estimate the RTD tail in such cases.

Care should be taken when collecting effluent samples to not allow too much volume to exit without being sampled. A spike or dip in the concentration could be partially or even completely missed, especially at high flowrates. Such an omission will exacerbate the already difficult task of closing the mass balance. When effluent samples are collected at regular intervals, and frequent enough not to miss significant dips or spikes in concentration, the zeroth and first moments provide a check of the data's quality.

These moments and the RTDs themselves depend on wetland water volumes. Therefore, whether a steady flow or variable flow system is being studied, every effort should be made to gain knowledge of the water volume of the wetland.

Finally, before beginning a tracer study, investigators should be certain that tracer from previous studies has been flushed from the wetland.

5.1. Effect on conversion

The ZDM model can be used as a tool in future work, and coupled with kinetics to aid in the study of a compounds fate in a wetland. Simple first order reactions can be combined with RTDs to forecast pollutant removal by a wetland. However, for more complex kinetics, a model of wetland flow such as ZDM is necessary to account for where the water spends its time in the wetland. For example, Wehner and Wilhelm (1956) analytically solved for the average conversion in a dispersed plug flow system:

$$X_{avg} = 1 - \frac{4a e^{Pe/2}}{(1+a)^2 e^{a Pe/2} - (1-a)^2 e^{-a Pe/2}} \quad (14)$$

where:

$$a = \left(1 + 4\frac{T}{Pe}\right)^{1/2}$$

Similarly, the average conversion for the ZDM model in this paper is:

$$X_{avg} = (1 - e^{Tz - T - x + [x^2/(Tz + x)]})(1 - 0.13e^{-0.076Pe}) \quad (15)$$

The Damköhler number $T = kt$ is the normalized first order reaction rate constant. Eq. (15)may be used with parameter estimates to perform calculations of wetland performance, without the use of a computer workstation.

A typical example of the results of non-ideality is shown in Fig. 12. The PFR is shown for comparison, and produces higher reductions than any mixing model. The PFD model reduces the conversions. The ZDM and CSTR models show virtually identical conversions.

6. Notation

C	Concentration
C'	Normalized concentration
$\mathscr{D}$	Dispersion number
D	Dispersion coefficient
E	Residence time distribution function
I_1	Hyperbolic Bessel function of type 1
j	Counter of reactor number
k	First order reaction rate constant
L	Length of the wetland
M	Mass of tracer added to the system
n	Number of ideal stirred reactors
Pe	Reactor Peclet number
Q	Volumetric flowrate
t	Time
T	Damköhler number
u	Linear water velocity
V	Wetland water volume
x	Model parameter: ratio of main flow to flow exchanged with ZDMs
X	Conversion of reactant
X_{avg}	Average conversion of reactant
y	Length measurement
z	Model parameter: fraction of water volume not part of main flow path
δ	Dirac delta function
θ	Normalized time
θ_p	Normalized mode
υ_s	Volumetric flowrate through a side CSTR
σ_θ^2	Normalized variance
τ	Nominal detention time
ϕ	Flow weighted time

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