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# Influence of residence time analyses on estimates of wetland hydraulics and pollutant removal

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SUMMARY

Hydraulic tracer studies are frequently used to estimate wetland residence time distributions (RTDs) and ultimately pollutant removal. However, there is no consensus on how to analyse these data. We set out to (i) review the different methods used and (ii) use simulations to explore how the data analysis method influences the quantification of wetland hydraulics and pollutant removal. The results showed that the method influences the water dispersion ($N$) most strongly and the removal least strongly. The influence increased with decreasing effective volume ratio ($e$) and $N$, indicating a greater effect of the method in wetlands with low effective volume and high dispersion. The method of moments with RTD truncation at 3 times the theoretical residence time ($t_n$) and tracer background concentration produced the most dissimilar parameters. The most similar parameters values were those for gamma modelling and the method of moments with RTD truncation at tracer background concentration. For correct removal estimates, $e$ was more important than $N$. However, the results from the literature review and simulations indicated that previously published articles may contain overestimated $e$ and underestimated $N$ values as a result of frequent RTD truncations at $3t_n$ when using the method of moments. As a result, the removal rates may also be overestimated by as much as 14% compared to other truncation methods or modelling. Thus, it is recommended that wetland hydraulic tracer studies should use the same method, specifically, RTD truncation. We conclude that the choice of tracer data analysis method can greatly influence the quantifications of wetland hydraulics and removal rate.



## 1. Introduction

Water movement, i.e., hydraulics, has been recognised as an important factor in pollutant removal rates in treatment wetlands (Kadlec and Wallace, 2009). One basic tool for learning more about hydraulics in wetlands is through hydraulic tracer experiments, and numerous such studies have been performed in the last 30 years (Graham, 1984; Kadlec, 1994; Stern et al., 2001; Martinez and Wise, 2003; Persson, 2005; Ronkanen and Kløve, 2007; Speer et al., 2009; Passeport et al., 2010; Lange et al., 2011; Bodin and Persson, 2012; Bodin et al., 2012). However, it has been noted that analysing tracer data using different computational methods can result in different interpretations of wetlands hydraulics (Wang et al., 2006; Wang and Jawitz, 2006; Kadlec and Wallace, 2009; Keefe et al., 2010; Bodin et al., 2012). Additionally, the effects of the tracer data analysis method on the estimation of wetlands pollutant removal rates have been observed (Kadlec and Wallace, 2009); however, this aspect has been investigated less thoroughly than others. Against this background, it is pertinent to investigate (i) which methods of analysis are used and (ii) the extent to which the method of tracer data analysis influences the interpretation of wetland hydraulics and ultimately their pollutant removal rates. We reviewed wetland tracer studies conducted in free-water surface (FWS) wetlands using the pulse injection technique. Based on our findings, we then devised relevant simulation cases using simulated tracer data, allowing us to evaluate the effect of the data analysis method on the interpretation of wetland hydraulics and pollutant removal.

## 2. The methodology of hydraulic tracer studies in wetlands

The basis of hydraulic tracer experiments is that the selected inert tracer should act as a good indicator of water flow and movement through the wetland. Thus, water residence time distributions (RTDs) can be quantified by pulse-injecting inert tracers into wetlands and measuring their concentrations at the outlet at certain frequencies (Fig. 1).

Usually, the characterisation of wetland hydraulics begins with the quantification of the mean ($t_m$) and variance ($\sigma^2$) of the RTD.

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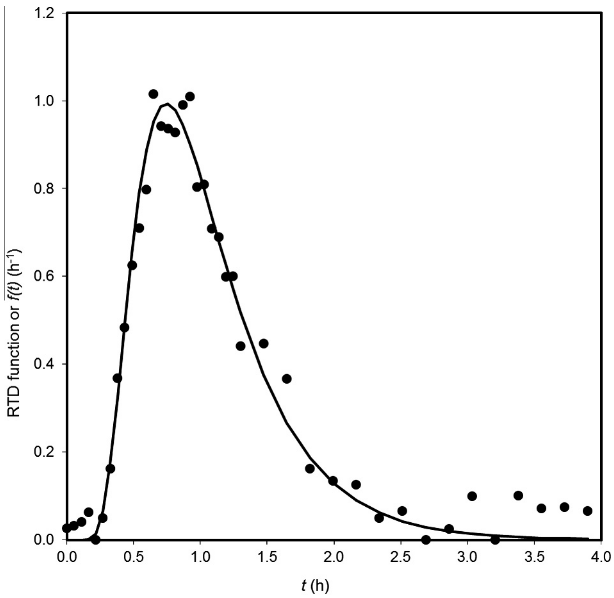


**Fig. 1.** Conceptual residence time distribution (RTD) curve from a wetland hydraulic tracer experiment. The dots show the measured tracer concentration data and the line shows a fit of the measured data.

The $t_m$ parameter indicates the average time that a tracer particle spends in the wetland, and $\sigma^2$ specifies the spread of the RTD curve (Fogler, 2006). Furthermore, the $N$ parameter, frequently used in the tanks-in-series (TIS) model to characterise wetland water treatment, describes wetland water flow patterns, i.e., dispersion, and is quantified by

$$N = \frac{t_m^2}{\sigma^2} \tag{1}$$

where $N$ is the number of tanks in TIS model, $t_m^2$ is mean squared hydraulic residence time (h$^2$), and $\sigma^2$ is variance of RTD (h$^2$). $N \approx \infty$ indicates plug-flow conditions, which are considered to be essential for optimal wastewater treatment in wetlands. Under such conditions, the total wetland volume is active in flow and all of the water parcels move through the wetland at the same velocity, thus reaching the wetland outlet at exactly the same time. This exit time is referred to as the wetland nominal hydraulic residence time, $t_n$, and can be calculated as

$$t_n = \frac{V_{sys}}{Q} \tag{2}$$

where $t_n$ is the nominal hydraulic residence time (h), $V_{sys}$ is the theoretical (empirical) wetland volume (m$^3$), and $Q$ is the water flow rate through the wetlands (m$^3$ h$^{-1}$). However, it has been well established that actual treatment wetlands experience some deviation from plug-flow, as shown by the RTDs from numerous tracer experiments (Kadlec and Wallace, 2009). One way to quantify the "active" and thus treatment-effective wetland volume is to quantify the relationship between $t_m$ and $t_n$ (Thackston et al., 1987) as in

$$e = \frac{t_m}{t_n} = \frac{V_{effective}}{V_{sys}} \tag{3}$$

where $e$ is the effective volume ratio (–), $V_{sys}$ is the theoretical (empirical) wetland volume (m$^3$), and $V_{effective}$ is the total active wetland volume (m$^3$) derived from tracer data. The $e$ parameter has been shown to be more important than $N$ for accurately modelling the wetland treatment with the TIS model, at least when modelling nitrogen removal (Persson and Wittgren, 2003). Nevertheless, most of the literature regarding wetland treatment modelling has focused on the significance of $N$ (Kadlec and Wallace, 2009).

### 2.1. Selection of tracer data analysis methods

Each RTD from a tracer study has its own unique mathematical expression, leading to different data analysis methods for wetland hydraulic tracer data. Generally, two methods can be used to analyse measured data from tracer experiments: the method of moments, which uses the numerical integration of measured data, and data modelling methods, which use suitable mathematical equations along with objective fitting functions to minimise the distance between the measured and modelled data.

Several recommendations have been to set forth to assist the wetland researcher with selecting the proper method for analysing tracer data and thus estimating hydraulic parameters (Wang and Jawitz, 2006; Headley and Kadlec, 2007; Kadlec and Wallace, 2009). However, ultimately, such a routine is strongly affected by the subjective judgement of which is the most "correct" method because the actual hydraulic parameter values are unknown. Thus, depending upon the data analysis method chosen, different degrees of error may be introduced in the parameter estimations. Theoretically, the RTD function, $f(t)$, is expressed as in the following equation

$$f(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \tag{4}$$

where $C(t)$ is the outlet tracer concentration (mg L$^{-1}$). From this function, it is possible to calculate $t_m$ and $\sigma^2$; however, in practice, there are only a finite number of sampling points, denoted $t_1$, $t_2,\ldots,t_n$, and we must choose a method to estimate the unknown parameters $N$ and $e$.

#### 2.1.1. Tracer data analysis with the method of moments

In the method of moments, the unknown RTD function $f(t)$ is estimated using an integral, which may be achieved using the trapezoid integration rule (Eq. (5)):

$$f(t) = \frac{C(t)}{\int_0^\infty C(t)dt} \approx \frac{C(t_i)}{\sum_{i=2}^{n}\left(\frac{C(t_i)+C(t_{i-1})}{2}\right)(t_i - t_{i-1})} \tag{5}$$

Using Eq. (5), we can estimate (Haas, 1996)

$$t_m = \int_0^\infty tf(t)dt \approx \frac{\sum_{i=2}^{n}\left(\frac{t_iC(t_i)+t_{i-1}C(t_{i-1})}{2}\right)(t_i - t_{i-1})}{\sum_{i=2}^{n}\left(\frac{C(t_i)+C(t_{i-1})}{2}\right)(t_i - t_{i-1})} \tag{6}$$

$$\sigma^2 = \int_0^\infty t^2 f(t)dt - t_m^2 \approx \left[\frac{\sum_{i=2}^{n}\left(\frac{t_i^2\ C(t_i)+t_{i-1}^2\ C(t_{i-1})}{2}\right)(t_i - t_{i-1})}{\sum_{i=2}^{n}\left(\frac{C(t_i)+C(t_{i-1})}{2}\right)(t_i - t_{i-1})}\right] - t_m^2. \tag{7}$$

#### 2.1.2. Residence time distribution modelling

Over the past decade, the most common mathematical model for analysing wetland tracer data and estimating hydraulic parameters has been the gamma model, expressed as in the following equation:

$$f(t; t_m, N) = \frac{N^N t^{N-1}}{t_m^N \Gamma(N)} \exp^{\left(-\frac{Nt}{t_m}\right)} \tag{8}$$

where $\Gamma(N) = \int_0^\infty t^{N-1}\exp(-t)dt$ is the gamma probability distribution function. With this parameterisation, the mean of the distribution is $t_m$ and the variance is $\sigma^2 = t_m^2/N$, as in Eq. (1). Generally, in data modelling, the wetland hydraulic parameters $t_m$ and $N$ are derived directly from the model parameters using an objective fitting function, such as the sum of the squared errors (Eq. (9)), which aims