# Chapter 3: Hydraulic Analysis of Walnut Cove Wetland Cells

## Abstract

To evaluate the internal hydraulics of the wetland cells several tracer tests were conducted at the site using Rhodamine WT dye. 5 tracer tests were conducted in wetland cell 1 and 4 tracer tests were conducted in wetland cell 2, for a total of 9 tests. In cell 1, 2 of the tracer tests were conducted pre-cleanout and 3 were conducted post-cleanout. Pre- and post-cleanout tests were conducted to quantify the impact of the detritus removal (i.e. cleanout) on the hydraulics of cell 1. Cell 2 was left in its initial state throughout the study to be used as a control. The tracer tests were analyzed using both the method of moments and by fitting a gamma probability distribution function. The hydraulic performance of the wetlands were compared using λe, τ10, and σ2 as recommended in Liu et al (2020). Cell 1 jumped from average λe, τ10, and the Morril index values of to values of , respectively, after detritus removal. Cell 2 remained constant at values of to values of , respectively, after detritus. It can be concluded that the detritus removal substantially improved the hydraulic performance of wetland cell 1.

## Introduction

Constructed wetlands remove nutrients from the water column via a combination of abiotic and biotic processes facilitated by interactions between the various constituents of the wetland. Interactions dependent on microorganism activity or plant uptake, i.e. nitrification/denitrification and assimilation, are heavily dependent on the amount of time the water resides in the wetland (Kadlec & Wallace, 2009; Toet et al., 2005). The time dependency of nitrogen removal was observed in initial research into nitrate removal in wetland microcosms by Gersberg et al. (1983) and Ingersoll and Baker (1998) with both studies observing that decreasing hydraulic loading rates (i.e. increasing duration within the wetland system) resulted in increasing nitrogen removal efficiency.

The duration of time the water spends between the inlet and the outlet of the wetland is known as the wetland residence time, which itself is function of wetland flow dynamics. The most common approach to wetland flow dynamics are to assume that the wetland systems acts as an ideal, plug-flow reactor (Carleton, 2002; Kadlec, 2000; Kadlec & Wallace, 2009). Wetland performance can then be predicted using plug-flow chemical reactor models built using principles borrowed from chemical engineering. Assuming wetlands act as ideal plug-flow reactors, all the influent water at time, t0, will uniformly pass through the wetland and exit the wetland at a future time, tn, determined by equation 1 as the time required for a complete volume exchange in the wetland (Kadlec & Wallace, 2009; Persson et al., 1999; Wahl et al., 2010).

equation 1

Where, tn is the nominal wetland residence time (days), V is the wetland volume (L/d), and Q is the flow rate (L3/d).Wetland treatment performance modeled using plug-flow hydraulics represents the best-case scenario for pollutant removal because it assumes the entire wetland basin is utilized for treatment.

However, since the early 1990s, wetland tracer tests have shown that assumption of uniform plug-flow is not appropriate for modeling constructed wetland hydraulics (Kadlec & Wallace, 2009). Instead, nonideal flow patterns derived from short-circuiting, obstructions, and dead zones in the wetland produce nonuniform flow patterns. The nonuniform flow patterns can reduce treatment efficiency to well below what is predicted using the ideal plug flow condition. In terms of constructed wetland implementation, the lack of uniform flow increases the land area required to achieve the same level of treatment that was predicted using the plug-flow reactor model. The departure from ideal, plug flow conditions results in an actual residence time, τ, that is less than the theoretical tn. The ratio of τ/tn is referred to as the hydraulic efficiency of the wetland and it represents the departure of actual flow from ideal plug flow (Thackston et al., 1987).

### Hydraulic efficiency

A wetland hydraulic

There have been several acceptable hydraulic indexes proposed to evaluate the hydraulic performance of a constructed wetland (Bodin et al., 2013; Persson et al., 1999; Wahl et al., 2010).

A comparison of eight hydraulic indexes, categorized into hydraulic efficiency indexes, short-circuiting indexes, and mixing indexes, was conducted by Liu et al (2020) using classic test theory consisting of compatibility, discrimination, and difficulty comparisons. The results showed major discrepancies between hydraulic efficiency indexes, but only minor discrepancies between short-circuiting indexes and mixing indexes. Liu et al (2020) recommended λe, τ10, and the Morril Index to quantify hydraulic efficiency, short-circuiting, and mixing, respectively.λe and τ10 were used as recommended for the tracer experiments. The Morril Index was not used as the mixing index, instead the σ2 value was used. This was deemed acceptable because there were only minor differences in performance between these two mixing indexes (Liu et al., 2020).

### Objectives

1.

## Methods

### Site Description

At the Walnut Cove WWTP, two parallel wetland cells were built to provide biological nutrient removal as part of tertiary treatment at the site. The two cells were built as basins with a constant depth, identical surface areas of approximately 0.7 ha, and a L:W ratio of 17. The cells were designed with adjustable outlet weir plates that allow wetland pool depths to be varied. The wetland cells are typically operated with a normal depth of 0.3 m resulting in a design volume of 2,110 m3.

### Data Collection

Tracer tests were conducted when outflows were between 3.15 L/s and 6.31 L/s with nominal retention times ranging from 7.75 to 3.87 days, respectively. The cells were hypothesized to contain substantial hydraulic inefficiencies due to detrital buildup and observed preferential flows. Measured retention times would be significantly lower than the nominal retention times. Rhodamine WT was used as a dye in the study due to availability, low cost, access to a submersible fluorescence sensor, and visual observation capabilities. Concern has been raised about the use of Rhodamine WT as a dye to perform hydraulic analysis in wetland systems due to its susceptibility to adsorption on organic material. However, Williams and Nelson (2011) found Rhodamine WT concentrations to be coincident with bromide concentrations in a series of tracer tests conducted on a 1.2-ha treatment wetland. Additionally, Lin et al (2003) suggested that Rhodamine WT is a suitable tracer in wetlands with residence times less than one week. Since the cell cells are each less than 1-ha and have maximum nominal retention times of approximately one week, Rhodamine WT was deemed acceptable as a tracer dye to analysis the hydraulic properties of the Walnut Cove wetland cells.

Nine total tracer injections were conducted, five in wetland cell 1 and four in wetland cell 2. The first pilot test was conducted in cell 1 on March 9, 2019 using 35.7 g of Rhodamine WT in a 1 L solution of deionized water. The tracer solution was injected into the target cell influent at the two-way influent-splitter box. The injection was completed in one half hour. Since the first pilot test, there have been four paired experiments at the site (Table 1). Each subsequent experiment has followed these same procedures.

Samples were obtained approximately 1 m upstream of the outlet weir using 6712 Portable Teledyne ISCO automated samplers with integrated 730 Bubbler Flow Modules (Teledyne ISCO, Lincoln, NE). The automated samplers were arranged with 24 sample bottles. Sampling was restricted to 24 bottles due to travel constraints. Over the 9 experiments, 700mL samples were taken at varying time intervals from every two hours to between one and four hours (Table 1). Experiments with samples taken every 2 hours resulted in a 48-hour window to capture the dominant features of the Residence Time Distribution (RTD). Since the 48-hour window was less than the nominal retention time, a hypothesized actual residence time was required to center the sampling window. Errors in this hypothesis resulted in some tests missing a majority of either the rising or falling limb (Table 3.1). To obtain initial background concentrations (Co), outlet grab samples were taken at the start of each experiment. Samples were brought back to the North Carolina State University Department of Biological and Agricultural Engineering Ecological Restoration Lab for analysis.

##### Table 3.1. Overview of tracer experimental setup

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Experiment | Start Date | Cell | Period | Time Interval | Sampling Start  Cell 1 Cell 2 | |
| 1 | March 8, 2019 | 1 | Pre | Every 2hrs | t0 + 7hrs |  |
| 2 | March 23, 2019 | 1 and 2 | Pre | Every 2hrs | t0 + 6hrs | t0 + 22hrs |
| 3 | July 26, 2019 | 1 and 2 | Post | Every 2hrs | t0 + 30hrs | t0 + 12hrs |
| 4 | August 9, 2019 | 1 and 2 | Post | Every 2 hrs | t0 + 22hrs | t0 + 12hrs |
| 5 | January 31, 2020 | 1 and 2 | Post | Variable (1-4 hrs) | t0 + 12hrs | t0 + 12hrs |

### Data Analysis

Rhodamine WT concentration was measured in each sample using a Cyclops-7 Fluorometer and Databank Handheld Datalogger (Turner Designs, San Jose, CA). Samples were run in accordance with the recommended measurement practices in Appendix B of the Cyclops Submersible Sensors User’s Manual (2019).

Flow out of each wetland passes over a sharp-crested fully contracted rectangular weir. Head was measured at each outlet every 15 minutes using the 730 Bubbler Flow Modules with measurement sites placed at a distance greater than four times the maximum expected head over the wear in accordance with the standard fully contracted weir requirements in the Bureau of Reclamation’s *Water Measurement Manual* (2001). Outflow was calculated using the Francis (1883) equation as stated in the *Manual.*

Where *Q* = volumetric flow (ft3/s), *L* = length of the weir (ft), and *H* = head on the weir (ft). This equation is valid where H/L ≤ 0.33, which was the case for each experimental period. The 15-minute outflow data were converted to SI units and averaged to daily outflows to reduce the influence of measurement errors during the experiments. Debris has been observed to catch on the weir crest and alter short-term flow measurements. The average daily outflows were assigned to all samples taken during that day. Any missing data during the study periods were filled using linear relationships between inflows and outflows for the seasonal period around which the experiment was conducted. For example, if tracer experiments were conducted in March, the linear relationship would be built with data inflow and outflow data from the winter months of January, February, and March. To alleviate concerns of premature truncation due to limited sampling times, the tails of all tests were extended past the last sample to approximately 2tn using an exponential decay curve fit to the recession limb. The nominal retention time (tnom) for each tracer experiment was calculated using equation X, which assumes ideal plug flow conditions.

(Equation X)

Where, V is the volume of the wetland, based on the design basin volume with a water depth based on the outlet weir crest height, and Qavg is the time-weighted average flow during the tracer experiment. While ideal plug flow is typically used in constructed wetland design, in practice the assumption of plug flow is invalid, instead flow typically follows a tanks-in-series flow pattern that can be represent using residence time distributions (RTD)s.

#### Residence Time Distribution Analysis

Tracer experiment data were represented using RTDs to evaluate the hydraulic performance of each cell (Bodin et al., 2012, 2013; Kadlec & Wallace, 2009; Levenspiel, 1999; Martinez & Wise, 2003; Wahl et al., 2010). There are two common methods to convert tracer experiment data to an RTD. The first method was the method of moments, which uses numerical integration of measured data. The second method was fitting the observed data to a gamma distribution function by minimizing the sum of squared errors. Both methods were used in the analysis of Walnut Cove tracer experiment data. The theoretical RTD is expressed as a function of time, , shown in equation X (Martinez & Wise, 2003). For direct comparison of the RTDs under different experimental conditions, can be normalized by multiplying by the nominal residence time (tnom).

(Equation X)

Where,

E(t) = residence time distribution (d-1)

Q(t) = volumetric flow exiting the wetland cell (L/d)

C(t) = concentration of tracer exiting the wetland cell (mg/L)

Using the method of moments, the RTD function for each tracer experiment was estimated using the trapezoid integration rule (equation X). The zeroth, first, and second moments for the RTD, which correspond to the mass of tracer recovered (Mrec), observed mean retention time (τ) and the spread of the RTD curve (σ2), respectively, can also be estimated using this method (equations X, X, and X).

(Equation X)

(Equation X)

(Equation X)

(Equation X)

All tracer experiments were evaluated regardless of the percent of mass recovered. Tests with less than 50% recovery of the mass applied were denoted with an asterisk. Additionally, an important check on these estimations is that the unity of the RTD is equal to 1. From the observed mean retention time (τ) and the spread of the curve (σ2), the number of tanks-in-series (TIS) parameter (N), and the dimensionless dispersion parameter (σθ2) were calculated using equations X and X.

The tracer data was also analyzed by fitting the data to the probability density function of the gamma distribution as a function of the parameters (x,α,β). The data were fit by minimizing the sum of squared error between the gamma function results and the estimated E(t) from the method of moments.

(Equation X)

Where, *x* is time, α is the N parameter, and β is N/τ. To fit the data, the initial values τ and N parameters were set to those estimated using the method of moments. The sum of squared errors was then calculated using equation X.

(Equation X)

#### Hydraulic Parameters

For each test, the hydraulic efficiency (e), the number of tanks (N), and the estimated mean residence time (τ) were obtained from both the method of moments and the gamma method. To compare hydraulic efficiency, short-circuiting, and mixing, the hydraulic efficiency index (λe), the dimensionless dispersion (σΦ2), and dimensionless time at which 10% of recovered tracer mass has left the basin (t10) were calculated from the results of both methods. Evaluation of performance was based on value ranges modified from those given in Liu et al (2020) (Table 3.2). Hydraulic analyses were conducted using R software. The R script used to perform analysis is in Appendix A.

##### Table 3.2. Ranges of performance for the three evaluated hydraulic indexes. Ranges modified from thresholds presented in Liu et al (2020).

|  |  |  |  |
| --- | --- | --- | --- |
| Hydraulic Index | Performance Ranges | | |
| **compromised** | **acceptable** | **excellent** |
| λe | ≤ 0.5 | 0.5 – 0.75 | > 0.75 |
| σΦ2 | > 0.2 | 0.1 – 0.2 | 0.0 – 0.1 |
| t10 | 0 – 0.3 | 0.3 – 0.7 | > 0.7 |

## Results

## Discussion

## Conclusion

## References

Bodin, H., Mietto, A., Ehde, P. M., Persson, J., & Weisner, S. E. B. (2012). Tracer behaviour and analysis of hydraulics in experimental free water surface wetlands. *Ecological Engineering*, *49*, 201–211. https://doi.org/10.1016/j.ecoleng.2012.07.009

Bodin, H., Persson, J., Englund, J.-E., & Milberg, P. (2013). Influence of residence time analyses on estimates of wetland hydraulics and pollutant removal. *Journal of Hydrology*, *501*, 1–12. https://doi.org/10.1016/j.jhydrol.2013.07.022

Carleton, J. N. (2002). Damköhler number distributions and constituent removal in treatment wetlands. *Ecological Engineering*, *19*(4), 233–248. https://doi.org/10.1016/S0925-8574(02)00094-0

Francis, J. B. (1883). *Lowell Hydraulics Experiments* (fourth). D. Van Nostrand.

Gersberg, R. M., Elkins, B. V., & Goldman, C. R. (1983). Nitrogen removal in artificial wetlands. *Water Research*, *17*(9), 1009–1014. https://doi.org/10.1016/0043-1354(83)90041-6

Ingersoll, T. L., & Baker, L. A. (1998). Nitrate removal in wetland microcosms. *Water Research*, *32*(3), 677–684. https://doi.org/10.1016/S0043-1354(97)00254-6

Kadlec, R. H. (2000). The inadequacy of first-order treatment wetland models. *Ecological Engineering*, *15*(1–2), 105–119. https://doi.org/10.1016/S0925-8574(99)00039-7

Kadlec, R. H., & Wallace, S. D. (2009). *Treatment Wetlands* (2nd ed.). CRC Press.

Levenspiel, O. (1999). *Chemical Reaction Engineering* (3rd ed.). Wiley.

Lin, A. Y.-C., Debroux, J.-F., Cunningham, J. A., & Reinhard, M. (2003). Comparison of rhodamine WT and bromide in the determination of hydraulic characteristics of constructed wetlands. *Ecological Engineering*, *20*(1), 75–88. https://doi.org/10.1016/S0925-8574(03)00005-3

Liu, J., Dong, B., Zhou, W., & Qian, Z. (2020). Optimal selection of hydraulic indexes with classical test theory to compare hydraulic performance of constructed wetlands. *Ecological Engineering*, *143*, 105687. https://doi.org/10.1016/j.ecoleng.2019.105687

Martinez, C. J., & Wise, W. R. (2003). Hydraulic Analysis of Orlando Easterly Wetland. *Journal of Environmental Engineering*, *129*(6), 553–560. https://doi.org/10.1061/(ASCE)0733-9372(2003)129:6(553)

Persson, J., Somes, N. L. G., & Wong, T. H. F. (1999). Hydraulics Efficiency of Constructed Wetlands and Ponds. *Water Science and Technology; London*, *40*(3), 291–300.

Thackston, E. L., Shields, F. D., & Schroeder, P. R. (1987). Residence Time Distributions of Shallow Basins. *Journal of Environmental Engineering*, *113*(6), 1319–1332. https://doi.org/10.1061/(ASCE)0733-9372(1987)113:6(1319)

Toet, S., Logtestijn, R. S. P., Kampf, R., Schreijer, M., & Verhoeven, J. T. A. (2005). The effect of hydraulic retention time on the removal of pollutants from sewage treatment plant effluent in a surface-flow wetland system. *Wetlands*, *25*(2), 375–391. https://doi.org/10.1672/13

Turner Designs. (2019). *Cyclops Submersible Sensors User’s Manual*. Turner Designs. http://docs.turnerdesigns.com/t2/doc/manuals/998-2100.pdf

US Department of the Interior. (2001). *Water Measurement Manual* (3rd ed.). US Department of the Interior, Bureau of Reclamation.

Wahl, M. D., Brown, L. C., Soboyejo, A. O., Martin, J., & Dong, B. (2010). Quantifying the hydraulic performance of treatment wetlands using the moment index. *Ecological Engineering*, *36*(12), 1691–1699. https://doi.org/10.1016/j.ecoleng.2010.07.014

Williams, C. F., & Nelson, S. D. (2011). Comparison of Rhodamine-WT and bromide as a tracer for elucidating internal wetland flow dynamics. *Ecological Engineering*, *37*(10), 1492–1498. https://doi.org/10.1016/j.ecoleng.2011.05.003