Quantifying the Hydraulic Performance of Treatment Wetlands

Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in
the Graduate School of The Ohio State University

By
Mark Douglas Wahl, B.CE.

Graduate Program in Food, Agricultural, and Biological Engineering

The Ohio State University
2010

Thesis Committee:
Dr. Larry C. Brown, Adviser
Dr. Norman R. Fausey
Dr. Jay Martin
Dr. Alfred B.O. Soboyejo
Abstract

Conventional water treatment is typically not practical for addressing non-point source water pollution and can be cost prohibitive even for point sources. Constructed wetlands are becoming an increasingly common best management practice for reducing pollutants. Processes like rhizofiltration, settling of suspended particles, and degradation are all time dependent. These treatment mechanisms can be limited by hydraulic inefficiencies like short-circuiting in treatment wetlands. It is not known exactly what role such inefficiencies play in treatment, but when expected water quality gains are not realized the adoption of treatment wetlands as a best management practice can be slowed. One reason the effects on treatment are not well understood is that hydraulic inefficiencies are difficult to quantify. The aim of this work was to develop a universally applicable hydraulic index to quantify the hydraulic performance of treatment wetlands. An index demonstrating strong correlation to pollutant reduction is needed to identify the optimal wetland configuration for maximizing residence time. Such an index should be related to the various wetland parameters that influence the RTD. The index would not only be useful in quantifying the effects of vegetation, bathymetry, and wetland shape on residence time; it could then be used to supply the bounds for pollutant reduction.

Three existing hydraulic indices were evaluated for their suitability both as a measure of hydraulic performance and as a predictor of treatment. Of the three existing hydraulic indices evaluated, only one demonstrated strong correlation to the effluent pollutant fraction. However, that index could not detect variations among residence time
distributions that had a common centroid implying the index could not detect attenuation of a residence time distribution. Other indices are needed to better quantify the influence that various wetland parameters have on residence time and develop predictive models for treatment.

Three new indices were proposed. The moment index was derived using residence time distribution theory. The approach quantifies hydraulic inefficiencies according to the juxtaposition of the hold back parameter relative to the nominal residence time. The index was evaluated for its ability to detect variation, for conformity with qualitative assessments, and for correlation to effluent pollutant fractions in order to assess its suitability as a predictor of treatment. Further, two other indices were derived using a statistical approach. Recognizing the close relationship between the residence time distribution and a probability density function, an approach typically associated with failure analysis was used to develop the two new indices. The hazard index demonstrated superior agreement with qualitative assessments implying this index could be useful for characterizing the effects on the flow regime from various wetland parameters like depth, bathymetry, and shape. The temporal hazard index demonstrated superior correlation to the effluent pollutant fraction predicted by a first order reduction implying the temporal hazard index could be the good predictor of treatment.

All three proposed indices overcame weaknesses inherent in the existing indices. The arbitrary truncation of data resulting from finite resources for data collection has no impact on any of the proposed indices. All the proposed indices had the ability to detect attenuation of residence time distributions.
These proposed indices should not immediately supplant existing indices but the findings do support further consideration of those proposed. Once a sound metric is established and its sensitivity verified, key wetland design parameters and management factors can be identified for input to a statistical model for predicting treatment. This type of model might be used to consider multiple factors simultaneously and identify the relative influence of the different factors affecting the hydraulic regime. The proposed indices could help identify key parameters that contribute to inefficiencies in constructed wetlands and aid in developing management and design strategies to minimize hydraulic inefficiencies.
Dedication

Dedicated to all the fallen soldiers, sailors, airmen, and marines whose contributions to science will go unrealized
Acknowledgements

The author thanks the The Ohio State University; Office of International Affairs, Department of Food, Agricultural, and Biological Engineering, the Ohio Agricultural Research and Development Center, College of Food, Agricultural, and Environmental Sciences; and the International Program for Water Management in Agriculture; the College of Water Resources and Hydropower at Wuhan University; the Guangxi Center Station of Irrigation and Drainage, Guangxi Province; the Tuanlin Experiment Station, Hubei Province; and the Chinese Ministry of Water Resources for support of this research.
Vita

February 2, 1978.......................... Born – Muncie, IN, USA

2001........................................... B.S., Civil Engineering
University of Dayton

2007-2009.................................... Graduate Research Associate, Department
of Food, Agricultural, and Biological
Engineering, The Ohio State University

2009-present............................... Graduate Teaching Associate, Department
of Food, Agricultural, and Biological
Engineering, The Ohio State University

Fields of Study

Major Field: Food, Agricultural, and Biological Engineering
# Table of Contents

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract .................................................................................................................. ii</td>
</tr>
<tr>
<td>Dedication ............................................................................................................... v</td>
</tr>
<tr>
<td>Acknowledgements .................................................................................................... vi</td>
</tr>
<tr>
<td>Vita ........................................................................................................................... vii</td>
</tr>
<tr>
<td>List of Tables ........................................................................................................... xii</td>
</tr>
<tr>
<td>List of Figures ......................................................................................................... xiii</td>
</tr>
<tr>
<td>Chapter 1  Introduction .............................................................................................. 1</td>
</tr>
<tr>
<td>1.1  Background ........................................................................................................ 1</td>
</tr>
<tr>
<td>1.1.1  Problem Identification .................................................................................... 2</td>
</tr>
<tr>
<td>1.1.2  Objective ....................................................................................................... 3</td>
</tr>
<tr>
<td>1.2  Methodology ...................................................................................................... 3</td>
</tr>
<tr>
<td>1.3  Citations ............................................................................................................ 8</td>
</tr>
<tr>
<td>Chapter 2  Relating Existing Hydraulic Indices to Wetland Treatment ..................... 9</td>
</tr>
<tr>
<td>Abstract ..................................................................................................................... 9</td>
</tr>
<tr>
<td>2.1  Introduction ..................................................................................................... 10</td>
</tr>
<tr>
<td>Section</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>2.1.1</td>
</tr>
<tr>
<td>2.1.2</td>
</tr>
<tr>
<td>2.1.2.1</td>
</tr>
<tr>
<td>2.1.2.2</td>
</tr>
<tr>
<td>2.1.2.3</td>
</tr>
<tr>
<td>2.1.3</td>
</tr>
<tr>
<td>2.2</td>
</tr>
<tr>
<td>2.3</td>
</tr>
<tr>
<td>2.3.1</td>
</tr>
<tr>
<td>2.3.2</td>
</tr>
<tr>
<td>2.4</td>
</tr>
<tr>
<td>2.5</td>
</tr>
<tr>
<td>Chapter 3</td>
</tr>
<tr>
<td>3.1</td>
</tr>
<tr>
<td>3.1.1</td>
</tr>
<tr>
<td>3.1.2</td>
</tr>
<tr>
<td>3.1.2.1</td>
</tr>
<tr>
<td>3.1.2.2</td>
</tr>
<tr>
<td>3.1.3</td>
</tr>
</tbody>
</table>
3.2 Methodology ................................................................................................................. 38

3.2.1 Measuring Residence Time ....................................................................................... 38

3.2.2 RTD Normalization ................................................................................................. 39

3.2.3 Moment Analysis ..................................................................................................... 41

3.2.4 Moment Index .......................................................................................................... 41

3.2.5 Pollutant Reduction ................................................................................................. 44

3.3 Results and Discussion ................................................................................................. 46

3.3.1 Comparison with Qualitative Analysis ................................................................. 46

3.3.2 Tail Effect ................................................................................................................ 48

3.3.3 Correlating Hydraulic Efficiency to Treatment ..................................................... 49

3.4 Summary ..................................................................................................................... 51

3.5 Citations ....................................................................................................................... 53

Chapter 4 Quantifying Hydraulic Performance with Failure Analysis .................. 55

Abstract ............................................................................................................................ 55

4.1 Introduction ................................................................................................................ 56

4.1.1 Problem Definition ............................................................................................... 56

4.1.2 Theoretical Background ....................................................................................... 58

4.1.2.1 Residence time distributions ............................................................................. 58

4.1.2.2 Hydraulic Indices ............................................................................................... 59

4.1.3 Objective ................................................................................................................ 61
4.2 Methodology ........................................................................................................62
4.2.1 RTD Normalization .........................................................................................62
4.2.2 Failure Analysis ..............................................................................................63
  4.2.2.1 Hazard Index .............................................................................................64
  4.2.2.2 Temporal Hazard Index .............................................................................66
4.2.3 Pollutant Reduction .........................................................................................67
4.3 Results and Discussion .......................................................................................68
  4.3.1 Comparison with Qualitative Analysis .........................................................68
  4.3.2 Correlation to Treatment ..............................................................................71
4.4 Summary ............................................................................................................74
4.5 Citations .............................................................................................................76

Chapter 5 Conclusions ............................................................................................78
  Abstract ................................................................................................................78
  5.1 Summary ..........................................................................................................79
  5.2 Limitations ........................................................................................................81
  5.3 Application of Results ......................................................................................82

References ..............................................................................................................84
List of Tables

Table 2.1 Various parameters related to hydraulic performance computed for the Tuanlin and Guilin sites. ................................................................. 21
List of Figures

Figure 1.1 Special cases showing hydraulic performance assessed qualitatively. ........... 5

Figure 1.2 Special cases with hydraulic performance assessed qualitatively and then ranked using various indices. Case 5 approximates ideal plug flow and Case 7 represents a completely mixed tank. Case 6 is somewhat intermediate and Case 8 demonstrates severe short-circuiting. .......................................................... 5

Figure 1.3 Residence time distributions of 42 hypothetical cases used for analysis of hydraulic indices. .......................................................... 7

Figure 2.1a) Conceptual effect of short-circuiting: b) Conceptual effect of mixing on residence time distribution. Mixing scale is represented by the number of continuously stirred tank reactors (CSTRs) in series (adapted from Holland et al., 2004). .......................................................... 14

Figure 2.2 For ideal plug flow, a tracer pulse introduced at the inlet is observed after one volume exchange at the outlet. Short-circuiting reduces the travel time while mixing attenuates the response at the outlet (adapted from Persson et al., 1999). 16

Figure 2.3 Residence time distributions of 42 hypothetical cases used for analysis of hydraulic indices. .......................................................... 18

Figure 2.4 Hydraulic index, $\lambda = t_p/t_n$, plotted vs. predicted effluent pollutant fraction, $X$, derived from Equation (2-3). .......................................................... 23
Figure 2.5  Hydraulic index, $\lambda = \bar{t}/t_n$, plotted vs. predicted effluent pollutant fraction, $X$, derived from Equation (2-3). ................................................................. 24

Figure 2.6  Hydraulic index, $\lambda = e(1 - 1/N)$, plotted vs. predicted effluent pollutant fraction, $X$, derived from Equation (2-3). ................................................................. 25

Figure 3.1a) Conceptual effect of short-circuiting (adapted from Holland et al., 2004):  b) Conceptual effect of mixing on residence time distribution (adapted from Holland et al., 2004). Mixing scale is represented by the number of continuously stirred tank reactors (CSTRs) in series................................................................. 33

Figure 3.2  For ideal plug flow, a tracer pulse introduced at the inlet is observed after one volume exchange at the outlet. Short-circuiting reduces the travel time while mixing attenuates the response at the outlet (adapted from Persson et al., 1999). 35

Figure 3.3  Residence time distribution represented as a probability density function with cumulative distribution function inset. ......................................................................................... 42

Figure 3.4  Residence time distribution showing pre-nominal and post-nominal components. ......................................................................................................................... 43

Figure 3.5  Residence time distributions of forty-two hypothetical cases used for analysis of hydraulic indices................................................................. 45

Figure 3.6  Special cases showing hydraulic performance assessed qualitatively and then ranked using various indices. Cases 2 and 3 are hydraulically very similar........ 47

Figure 3.7  Special cases with hydraulic performance assessed qualitatively and then ranked using various indices. Case 5 approximates ideal plug flow and Case 7 represents a completely mixed tank. Case 6 is somewhat intermediate and Case 8 demonstrates severe short-circuiting................................................................. 48
Figure 3.8 Illustration of truncation effects on the two hydraulic indices a) observed data from two field tracer studies in Hubei and Guangxi provinces of China b) truncated results from the Hubei and Guangxi studies.

Figure 3.9 Hydraulic indices plotted vs. effluent pollutant fraction, X, derived from Equation (3-16) for 42 residence time distributions. Regression lines are displayed with $R^2$ values for all four indices.

Figure 4.1a) Conceptual effect of short-circuiting: b) Conceptual effect of mixing on residence time distribution. Mixing scale is represented by the number of continuously stirred tank reactors (CSTRs) in series (adapted from Holland et al., 2004).

Figure 4.2 For ideal plug flow, a tracer pulse introduced at the inlet is observed after one volume exchange at the outlet. Short-circuiting reduces the travel time while mixing attenuates the response at the outlet (adapted from Persson et al., 1999).

Figure 4.3 Example of probability functions for a given residence time distribution; $f_\phi(x)$ is a probability density function, $F_\phi(x)$ is the cumulative distribution function representing probability of failure, $R_\phi(x)$ is the complement of the failure indicating reliability, $h(x)$ is a failure rate function known as the hazard function, and $H(x)$ is the cumulative hazard function.

Figure 4.4 The temporal hazard is the time, $\alpha$, required to reach the cumulative hazard, $H(x) = 0.75$. In this example $\alpha = 0.83$. 

Figure 4.5 Residence time distributions of forty-two hypothetical cases used for analysis of hydraulic indices.
Figure 4.6 Special cases showing hydraulic performance assessed qualitatively and then using various indices. Cases 2 and 3 are hydraulically very similar. .................. 69

Figure 4.7 More special cases with hydraulic performance assessed qualitatively and then ranked using various indices. Case 5 approximates ideal plug flow and Case 7 represents a completely mixed tank. Case 6 is somewhat intermediate and Case 8 demonstrates severe short-circuiting................................................................. 70

Figure 4.8 Cumulative hazard, \( H(t_n) \), plotted vs. predicted effluent pollutant fraction, \( X \), derived from Equation (4-13). ................................................................. 72

Figure 4.9 Hazard index, \( H'(t_n) \), plotted vs. predicted effluent pollutant fraction, \( X \), derived from Equation (4-13). ................................................................. 72

Figure 4.10 Temporal hazard index, \( t@H(x) = 0.75 \), plotted vs. predicted effluent pollutant fraction, \( X \), derived from Equation (4-13).................................. 73
Chapter 1  Introduction

Abstract

Conventional water treatment is typically not practical for addressing non-point source water pollution and can be cost prohibitive even for point sources. Constructed wetlands are becoming an increasingly common best management practice for reducing pollutants. Processes like rhizofiltration, settling of suspended particles, and degradation are all time dependent. These treatment mechanisms can be limited by hydraulic inefficiencies like short-circuiting in treatment wetlands. It is not known exactly what role such inefficiencies play in treatment but when expected water quality gains are not realized the adoption of treatment wetlands as a best management practice can be slowed. One reason the effects on treatment are not well understood is that hydraulic inefficiencies are difficult to quantify. The aim of this work was to develop a universally applicable means for quantifying the hydraulic performance of treatment wetlands.

1.1  Background

World food demand is expected to continue increasing into the next decade driven in large part by developing countries (OECD, 2008). At the same time, biofuel production is expanding. Agriculture will continue to intensify with even greater use of chemicals and fertilizers to supply the increasing demand for both food and fuel. Such intensive agricultural practices can potentially impact water quality. Nitrogen contamination in drinking water in the form of nitrate can cause methemoglobinemia, a
potentially fatal disease in infants (Vigil et al., 1965). Coastal eutrophication, driven primarily by nitrogen, and sometimes phosphorus, results in harmful algal blooms and widespread hypoxia or anoxia (Howarth, 2008). This is a growing concern in the Great Lakes region of the United States as well as in the Gulf of Mexico, where hypoxia threatens to upset delicate food chains with potential impacts on commercial and recreational fishing industries.

Constructed wetlands are an increasingly common management practice for reducing nutrient loads (Brix, 1994). Wetlands utilize physical, chemical, and biological, processes to reduce residual chemicals and excess nutrients in drainage water. But wide scale implementation of a strategy which incorporates wetlands for the treatment of agricultural runoff is challenging. Historically wetlands were often drained to increase acreage and improve trafficability in areas with rain fed crops. Much of Ohio and many parts of the Midwestern United States are intensively drained (Zucker and Brown, 1998). Drained cropland has minimal detention storage and subsurface drains can discharge soluble nutrients to surface waters (Fausey et al., 1995).

1.1.1 Problem Identification

Time dependent treatment mechanisms can be limited by hydraulic inefficiencies like short-circuiting in treatment wetlands. It is not known exactly what role hydraulic efficiency plays treatment. Preliminary results summarized in Chapter 2 indicate that short-circuiting could reduce treatment by nearly two thirds of the theoretical maximum. When water quality gains go unrealized as a result of hydraulic inefficiencies this can slow the adoption of treatment wetlands as a best management practice.
One reason the effects on treatment are not well understood is that hydraulic inefficiencies are difficult to quantify. Numerous indices have been derived from parameters associated with residence time. The use of these hydraulic indices has strong theoretical basis (Fogler, 1992; Levenspiel, 1999) yet many practical limitations exist in characterizing actual physical systems (Teixeira and Siqueira, 2008). Methods for quantifying hydraulic efficiency based on hydraulic indices often demonstrate limited correlation to first-order pollutant reductions or poor sensitivity to variation from one residence time distribution to another.

1.1.2 Objective

The rationale for this work is that a measure of hydraulic performance that can be universally applied to produce uniform results is needed for the optimization of the design and management of treatment wetlands. The objective is to quantify hydraulic performance of wetlands by evaluating existing indices for their suitability and, if needed, propose a new index or composite of existing indices that can be used to determine what role hydraulic efficiency has in treatment. Such an index could help identify key parameters that contribute to inefficiencies in constructed wetlands used for water treatment. Suitability of an index for these purposes includes the ability to detect even slight variation in performance and correlation to treatment.

1.2 Methodology

Hydraulic performance and treatment are both closely related to residence time. Thus it is common to extract parameters from the residence time distribution (RTD) and use them to quantify hydraulic performance. Composite indices derived from RTD...
parameters are used to describe hydraulic characteristics like the degree of mixing or short-circuiting, or aggregated to quantify overall hydraulic efficiency in terms of departure from ideal uniform flow (Thackston et al., 1987). Measurable deviations from ideal conditions are useful for quantifying hydraulic efficiency (Werner and Kadlec, 1996). Deviations from ideal conditions are useful in helping quantify the degree of mixing, stagnation, and short circuiting within a wetland. Direct comparison is difficult when basin size, tracer mass, and flow rate differ. A dimensionless function developed from normalized data provides a means of comparing various loading rates or comparison with other wetland basins.

Indices were considered for suitability as a measure of hydraulic performance based on their sensitivity to RTD variations and demonstrated correlation to treatment. Both the existing and proposed indices were evaluated for their sensitivity to changes in the RTD. Slight deviations to substantial qualitative differences were considered. Hydraulic performance for each of the cases shown in Figure 1.1 and Figure 1.2 was ranked qualitatively according to deviations from ideal uniform flow. Various index values were computed from eight RTDs and those respective rankings were compared with the qualitative comparisons shown in the figures.
Figure 1.1 Special cases showing hydraulic performance assessed qualitatively.

Figure 1.2 Special cases with hydraulic performance assessed qualitatively and then ranked using various indices. Case 5 approximates ideal plug flow and Case 7 represents a completely mixed tank. Case 6 is somewhat intermediate and Case 8 demonstrates severe short-circuiting.
Correlation to treatment is the other criterion identified for selecting a superior hydraulic index. Treatment is approximated by calculating the effluent pollutant fraction as a time dependent first-order reaction using a generic rate constant as suggested by Kadlec and Knight (1996). For higher order reactions, the RTD alone is not sufficient for predicting pollutant reductions although the RTD still has use for supplying the bounds (Fogler, 1992).

Forty-two hypothetical RTDs were conceptualized to capture varying degrees of short-circuiting and mixing. Figure 1.3 illustrates the conceptual RTDs associated with each case plotted with respect to time on the x-axis where time is flow-weighted and expressed in units of volume exchanges. The time axis is flow-weighted to normalize for effects from wetland volume and hydraulic loading. Mixing scales ranging from a single completely mixed tank to a near approximation of plug flow were considered.

Various hydraulic indices were calculated for each of the 42 cases considered. Index values were plotted with respect to the effluent pollutant fraction computed using a first-order reduction. A linear regression was used to establish correlation. Strong correlation implies an index may be a good predictor of treatment.
A number of existing indices were considered for their suitability as a measure of hydraulic performance. Three common indices were the focus; a ratio of the mean-residence-time to the time-for-one-volume-exchange; a ratio of the time-to-peak to the time-for-one-volume-exchange; and a widely used composite efficiency index. Another index derived from residence time distribution theory was also developed and evaluated. Recognizing that a residence time distribution is closely related to a probability density function, a statistically based approach was used to develop two additional indices derived from probabilistic methods associated with failure and reliability. The three existing indices and the three proposed indices are evaluated in the following chapters.
1.3 Citations


Chapter 2  Relating Existing Hydraulic Indices to Wetland Treatment

Abstract

A hydraulic index demonstrating strong correlation to pollutant reduction is needed to identify the optimal wetland configuration for maximizing residence time. Such an index should be related to the various wetland parameters that influence the RTD. The index would not only be useful in quantifying the effects of vegetation, bathymetry, and wetland shape on residence time; it could then be used to supply the bounds for pollutant reduction. A number of existing hydraulic indices are evaluated for their ability to quantify hydraulic performance and to predict treatment. Three common hydraulic indices were evaluated for their suitability both as a measure of hydraulic performance and as a predictor of treatment. Of the three existing hydraulic indices evaluated, only one demonstrated strong correlation to the effluent pollutant fraction. However, that index could not detect variations among residence time distributions that had a common centroid implying the index could not detect attenuation of a time distribution. Other indices are needed to better quantify the influence that various wetland parameters have on residence time and develop predictive models for treatment.
2.1 Introduction

2.1.1 Problem Definition

Agricultural practices impact water quality as production intensifies through the use of chemical fertilizers and pesticides, in combination with intense drainage practices (Zucker and Brown, 1998). Drainage increases the amount of arable land and improves trafficability. Much of Ohio and many parts of the Midwestern United States are intensively subsurface drained (Fausey et al., 1995). Intensively drained cropland has reduced detention storage compared with undrained cropland. As a result more nutrients are flushed from the soil directly to surface waters (Hubbard et al., 2004). Nitrogen contamination in drinking water in the form of nitrate can cause methemoglobinemia, a potentially fatal disease in infants (Vigil et al., 1965). Coastal eutrophication, driven primarily by nitrogen, and sometimes phosphorus, results in harmful algal blooms and widespread hypoxia or anoxia (Howarth, 2008). This is a growing concern in the Great Lakes region of the United States, as well as in the Gulf of Mexico, where hypoxia threatens to upset delicate food chains with potential impacts on commercial and recreational fishing industries.

One strategy to improve public health, promote economic vitality, and preserve ecologic health is to reduce the amount of excess nutrients entering surface waters so that cumulative downstream concentrations are not excessive (Mitsch and Gosselink, 2007). Conventional water treatment processes used in point source applications are generally not practical or economical in agricultural settings where a large pollution component is from non-point sources. Constructed wetlands are useful as low-tech water treatment option in rural settings; particularly in an agricultural landscape where intensive farming
practices contribute to high nutrient and sediment loads in drainage water (Dong et al., 2009; Mao et al., 2009). With relatively low capital cost and minimal operational cost, constructed wetlands are an appropriate technology for water treatment in many parts of the world (Brix, 1994).

Wetlands provide considerable benefit and promote biodiversity by offering habitat for plants and animals (Mitsch and Gosselink, 2007). Wetlands provide hydrologic benefits through storm water capture and detention which can delay the onset and limit the severity of downstream flooding. Additionally, wetlands remove impurities through physical, chemical, and biological mechanisms (Mitsch and Gosselink, 2007). Consequently, constructed wetlands are an increasingly common best practice for reducing nutrient loads and other contaminants (Brix, 1994; Kadlec and Knight, 1996).

Wide-scale implementation of a strategy which incorporates constructed wetlands for the treatment of agricultural runoff is challenging. Competing cost and efficacy concerns must be balanced (Shields and Thackston, 1991). Wetlands require sufficient land area in order to handle a particular runoff volume, and in many cases that land could otherwise be used for generating revenue. Land cost along with lost revenue exerts pressure to minimize the size of these wetlands. However, undersized units will be ineffective at reducing nutrients. One challenge to achieving optimal wetland design and management is related to our ability to measure hydraulic performance. Metrics are needed that can reliably quantify hydraulic performance and then be used to predict time dependent treatment processes.
2.1.2 Theoretical Background

2.1.2.1 Residence time distributions

Wetlands act as nutrient sinks through processes including sedimentation, sorption, plant uptake, as well as chemical and biological reductions (Kadlec and Knight, 1996). These processes are all heavily time dependent so that pollutant reduction is closely related to the amount of time an individual pollutant resides in the wetland (Fogler, 1992; Kadlec and Knight, 1996). The more exposure pollutants have to these removal mechanisms the greater the likelihood for pollutant reduction. Currently it is extremely challenging to predict the effectiveness of a wetland design because of the uncertainty in predicting residence time.

Wetland residence time describes travel time from inlet to outlet. The term residence time is sometimes used interchangeably with hydraulic retention time (Persson et al., 1999; Su et al., 2009). For consistency and to avoid confusion with the hydrologic concept for routing storm water through retention/detention basins, the term residence time is preferred for this discussion.

Residence time is often approximated as the time required for one complete volume exchange in the wetland, expressed nominally as:

\[ t_n = \frac{V}{Q} \]  

(2-1)

Where \( t_n \) is the nominal residence time, \( V \) is the wetland volume, and \( Q \) is the flow rate through the wetland. In practice, a single nominal residence time is inadequate. Each parcel of water may have a unique residence time affected by streamlines, boundary conditions, and turbulent effects (Su et al., 2009). Residence time can be considered a
random variable having some type of distribution known as the residence time
distribution (RTD) represented as a time dependent function, \( E(t) \). The shape and
position of an RTD can be qualitatively considered to indicate preferential flow,
stagnation, and mixing effects. A typical wetland contains some stagnant or slow moving
zones. Such underutilized components effectively reduce the basin volume, generating
preferential flow paths and shortening the average residence time. This shifts the RTD to
a position having shorter times as depicted in Figure 2.1a. Mixing tends to attenuate the
peak of the residence time distribution and increases the spread. Fogler (1992) and
Levenspiel (1999) describe treatment wetlands as reactors modeled by a sequence of
tanks-in-series. In a continuously stirred tank reactor (CSTR) all parcels have an equal
probability of leaving the basin at any given time. The RTD for a single CSTR is an
exponential function. As the number of CSTRs-in-series increases, the spread of the
RTD decreases. Figure 2.1b illustrates the effects of mixing scale on RTD using the
tanks-in-series approach.

RTDs are commonly assessed either with an analysis of measured residence
times or by plotting flow vectors (Somes et al., 1999). A plot of flow vectors can be
constructed from measured velocities or by numerical simulation. The vector plot can be
used to develop the RTD or a field tracer study might be conducted (Persson et al., 1999).
2.1.2.2 Pollutant Reduction

Kadlec and Knight (1996) suggest wetland treatment processes resemble a first-order rate function of the following form:

\[ X = e^{-kt} \]  (2-2)
where $X$ is the fraction of pollutant remaining over time depending on some rate constant $k_v$. For first order reactions it is possible to determine $X$ directly from the RTD:

$$X = \int_0^\infty E(t) e^{-k_v t} dt \quad (2-3)$$

For greater order reactions, the RTD alone is not sufficient for predicting pollutant reduction although the RTD still has utility in supplying bounds for the reduction (Fogler, 1992).

It may be desirable to manipulate the hydraulic regime to affect residence time in a manner favorable for treatment (Persson et al., 1999; Wang and Mitsch, 2000; Holland et al., 2004). Many factors influence travel time and will potentially affect the shape of a RTD. These include the inlet and outlet configuration, wetland shape, depth of water, basin bathymetry, length to width ratio, flow rate, and resistance to flow offered by vegetation (Persson et al., 1999). Equation (2-3) indicates that an optimally configured wetland managed to maximize residence time will generally provide better treatment.

2.1.2.3 Hydraulic Indices

Hydraulic indices are commonly extracted from the RTD and used to quantitatively assess hydraulic performance. Basic indices related to the position of the distribution along the x-axis are commonly classified as short-circuiting indices. These are derived from parameters related to leading edge, the time-to-peak, and centroid identified from the RTD. Other indices, often considered mixing indices, include measures related to the spread of the RTD or to the number of CSTRs derived from the tanks-in-series model. A composite index commonly known as hydraulic efficiency combines short-circuiting and mixing indices to describe hydraulic performance in terms of departure from ideal
uniform flow (Thackston et al., 1987). Figure 2.2 illustrates such a departure in terms of mixing and short-circuiting effects.

![Diagram](image)

Figure 2.2 For ideal plug flow, a tracer pulse introduced at the inlet is observed after one volume exchange at the outlet. Short-circuiting reduces the travel time while mixing attenuates the response at the outlet (adapted from Persson et al., 1999).

2.1.3 Objective

A hydraulic index demonstrating strong correlation to pollutant reduction is needed to identify the optimal wetland configuration for maximizing residence time. Such an index should be related to the various wetland parameters that influence the RTD. The index would not only be useful in quantifying the effects of vegetation, bathymetry, and wetland shape on residence time; it could then be used to supply the bounds for pollutant reduction. A number of existing hydraulic indices are evaluated for their ability to quantify hydraulic performance and to predict treatment.
2.2 Methodology

Existing hydraulic indices were evaluated for their suitability as both as a measure of hydraulic performance and as a predictor of treatment. Forty-two hypothetical residence time distributions were conceptualized to capture varying degrees of short-circuiting and mixing. Figure 2.3 illustrates the conceptual RTDs associated with each case plotted with respect to time on the x-axis where time is flow-weighted and expressed in units of volume exchanges. By flow-weighting the 42 cases, effects from wetland volume and hydraulic loading are normalized. Mixing scales ranging from a single completely mixed tank to a near approximation of plug flow are considered. The short-circuiting component is described by the effective volume. Effective volume \( e \) is defined by Thackston et al. (1987) as a ratio of mean residence time \( \bar{t} \) to nominal residence time \( t_n \):

\[
e = \frac{\bar{t}}{t_n}
\]  \hspace{1cm} (2-4)

Effective volumes for the 42 cases range from 0.25 to 1. Various existing hydraulic indices are computed for each of the 42 cases and then evaluated with respect to treatment considering the time dependent first-order pollutant reduction function shown in Equation (2-3).

Potential pollutant reductions are computed for each case according to the first-order reduction assuming a generic rate constant, \( k_v \), as the inverse of the nominal residence time, \( k_v = 1/t_n \), since time is expressed as a number of volume exchanges. The assumed \( k_v \) value is somewhat conservative since treatment wetlands are typically
sized according to an expected flow rate so that the nominal residence time will achieve a
desired level of treatment. While holding basin volume, hydraulic loading, and reduction
rates constant, the 42 hypothetical cases yield effluent pollutant fractions ranging from
0.33 to 0.77.

![Hypothetical Cases](image)

**Figure 2.3** Residence time distributions of 42 hypothetical cases used for analysis of hydraulic indices.

The computed pollutant fractions remaining are then compared with three
hydraulic indices commonly considered in wetland hydraulic analysis. One simplistic
hydraulic index considers a ratio of the time-to-peak ($t_p$) to the nominal residence time
(Persson et al., 1999):

$$\lambda = \frac{t_p}{t_n} \quad (2-5)$$

Another index considers the ratio of mean residence time to nominal residence time
similar to effective volume in Equation (2-4):

$$\bar{\lambda} = \frac{\bar{t}}{t_n} \quad (2-6)$$
A third often cited index combines a flow uniformity index \((I-I/N)\) and effective volume \((e)\) as:

\[
\lambda = e \left(1 - \frac{1}{N}\right)
\] (2-7)

where \(N\) is the number of CSTRs in series. Fogler (1992) considers \(N\) the inverse of the coefficient of variation squared:

\[
N = \left(\frac{\sigma}{\bar{t}}\right)^{-2}
\] (2-8)

2.3 Results and Discussion

2.3.1 Quantitative Analysis of Existing Hydraulic Indices

There is a need for consistency in reporting hydraulic efficiency in order for the term to be meaningful. Table 2.1 introduces a number of parameters commonly used to quantify hydraulic performance. The list is not intended to be exhaustive; instead it should provide the reader an appreciation for the diversity of existing approaches and illustrate some shortcomings. The parameters in Table 2.1 were calculated from residence time distributions measured at two wetlands in China. Values of hydraulic efficiency for the Tuanlin site in Hubei Province range from 0.32 to 0.98 depending on the method used to calculate hydraulic efficiency, \(\lambda\). Discrepancies arise due in part to ambiguity in defining related terms such as variance, number of tanks-in-series, and effective volume. Depending on whether hydraulic efficiency is referenced from the peak, the mean, or the median of the distribution has a substantial bearing on the calculation. Referencing any parameter to the peak can be problematic where a RTD has
multiple peaks, such as the example from the multi-celled wetland at the Guilin site in Guangxi Province. Additionally, long tails on the trailing limb of the RTD tend to skew the mean residence time, overestimating hydraulic efficiency. Equations (2-5), (2-15), (2-17) and are proposed improvements based on the $t_{50}$ value as better representations independent of influence from the tail or truncation effects, and less ambiguous than the time-to-peak.

Teixeira and Siqueira (2008) summarize several reported hydraulic indices. Most of the hydraulic indices could be categorized as either short-circuiting indices or mixing indices. Commonly, a single hydraulic efficiency index combines mixing and short-circuiting effects into one measure of hydraulic performance. Challenges persist in quantifying hydraulic efficiency. Numerous mixing and short-circuiting indices exist. Teixeira and Siqueira (2008) found most indices lacking in at least one of three areas: (1) the correlation of the index to the physical phenomenon it is said to represent; (2) the capability of the index to detect variation; and (3) statistical variability of the index. This evaluation of eight short-circuiting indices found only one index meeting all criteria while none of the six mixing indices fulfilled all requisites. An ideal index should quantify hydraulic performance in a manner consistent with qualitative analysis and should have enough sensitivity to consider slight variations. Since hydraulic performance has substantial bearing on treatment efficacy, the index should also demonstrate some correlation to pollutant reduction.
Table 2.1 Various parameters related to hydraulic performance computed for the Tuanlin and Guilin sites.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Tuanlin</th>
<th>Guilin</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variance</td>
<td>[\sigma^2 = M^2_2]</td>
<td>0.33</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>[\sigma^2 = \int_0^\infty (t - t_0)^2 E(t)dt]</td>
<td>0.33</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>[\sigma^2 = \left(\frac{1}{2} \left(\frac{t_{84} - t_{16}}{t_{50}}\right)^2\right)]</td>
<td>0.55</td>
<td>0.37</td>
</tr>
<tr>
<td>Number of CSTRs</td>
<td>[N = \frac{t_n}{t_n - t_{peak}}]</td>
<td>2.4</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>[N = \left(\frac{\sigma}{t_n}\right)^2]</td>
<td>1.8 - 3.0</td>
<td>0.7 - 7.8</td>
</tr>
<tr>
<td>Effective Volume Ratio</td>
<td>[e = \frac{t_{mean}}{t_n}]</td>
<td>0.98</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>[e = \frac{t_{50}}{t_n}]</td>
<td>0.71</td>
<td>0.58</td>
</tr>
<tr>
<td>Extent of short-circuiting</td>
<td>[s = \frac{t_{16}}{t_{84}}]</td>
<td>0.77</td>
<td>0.50</td>
</tr>
<tr>
<td>Hydraulic Efficiency</td>
<td>[\lambda = \frac{t_{mean}}{t_n}]</td>
<td>0.98</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>[\lambda = \frac{t_{50}}{t_n}]</td>
<td>0.71</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>[\lambda = \frac{t_{peak}}{t_n}]</td>
<td>0.58</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>[\lambda = e \left(1 - \frac{1}{N}\right)]</td>
<td>0.32 - 0.66</td>
<td>0.37 - 0.56</td>
</tr>
<tr>
<td></td>
<td>[\lambda = \left(\frac{t_{mean}}{t_n}\right) \left(1 - \frac{t_{mean} - t_{peak}}{t_{mean}}\right)]</td>
<td>0.58</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>[\lambda = \left(\frac{t_{50}}{t_n}\right) \left(1 - \frac{t_{50} - t_{peak}}{t_{50}}\right)]</td>
<td>0.58</td>
<td>-</td>
</tr>
</tbody>
</table>

Some values are reported as ranges since dependent variables may be calculated several different ways. Others are omitted since the values are indeterminate due to the existence of multiple single times-to-peak.
2.3.2 Correlation with Treatment

The hydraulic indices described above were calculated for each of the 42 cases considered. Index values were plotted with respect to the effluent pollutant fraction computed using a first-order reduction. A straight line was fit through the data points with the Coefficient of Determination, $R^2$, displayed. Strong correlation implies an index may be a good predictor of treatment. Correlation alone does not necessarily identify a good index. The index should also have the ability to meaningfully quantify the effects of wetland characteristics, such as bathymetry, configuration, shape, and the like.

Teixeira and Siqueira (2008) found most indices lacking in at least one of three areas: (1) the correlation of the index to the physical phenomenon it is said to represent; (2) the capability of the index to detect variation; and (3) statistical variability of the index.

The ratio of time-to-peak to nominal residence time described in Equation (2-5) has limited value in relating basin parameters to treatment. As Figure 2.4 indicates, the $R^2$ value is 0.42. In addition, relating the hydraulic index to the time-to-peak can be problematic. When multiple preferential flow paths are present, the resulting RTD may have multiple peaks, which introduces some ambiguity when determining which peak to consider in the ratio.
The ratio of mean residence time to nominal residence time from Equation (2-6) shows considerably better correlation to treatment. An $R^2$ value of 0.91 is reported in Figure 2.5. Mean residence time is less ambiguous than the time-to-peak parameter. However, mean residence time will not detect variations in two or more RTDs having a common centroid. This limitation has serious implications when attempting to quantify the effects wetland parameters, like the configuration or the shape, have on the hydraulic performance. The index simply will not detect factors which contribute to mixing.
The third index, derived from Equation (2-7), is sensitive to both the position and the shape of the RTD. For this reason, it is widely cited as a hydraulic efficiency index (Holland et al., 2004; Dierberg et al., 2005; Kuo et al., 2008; Min and Wise, 2009; Su et al., 2009). The R-squared value of 0.41 in Figure 2.6 suggests that this index may not be reliable as a predictor of effluent pollutant fractions.

The reaction rate constant, \( k_v \), may not, in fact, remain constant for greater order reactions. For example temperature changes could cause the value of \( k_v \) to temporally change. This could have some effect on the correlation factors reported above. Sensitivity to changes in \( k_v \) values warrants further study.
2.4 Summary

Three existing hydraulic indices were evaluated for their suitability both as a measure of hydraulic performance and as a predictor of treatment. Index values were computed for a wide range of residence time distributions and compared with effluent pollutant fractions calculated for each of the RTDs based on a first-order time dependent reduction using a generic rate constant. Effluent pollutant fractions were found ranging from 0.33 to 0.77. This implies that a wetland operating at the optimal flow regime could remove nearly three times the pollutants of a severely short-circuited wetland of a similar size under the same loading conditions. The right hydraulic index could potentially be used to develop predictive models for optimizing the flow regime to improve treatment.

Of the three existing hydraulic indices evaluated, only the ratio of mean residence time to nominal residence time demonstrated strong correlation to the effluent pollutant
fraction. However, this index is insensitive to variations in RTD shape since the mean residence time parameter will not detect variations among RTDs having a common centroid. For example, positively and negatively skewed distributions having a common mean value are indistinguishable with this index. It will not detect attenuation of the RTD. Other indices are needed to better quantify the influence that various wetland parameters have on residence time and develop predictive models for treatment.
2.5 Citations


Chapter 3  Quantifying Hydraulic Performance with the Moment Index

Abstract

In this chapter, a new hydraulic index was derived using residence time distribution theory. The approach quantifies hydraulic inefficiencies according to the juxtaposition of the hold back parameter relative to the residence time distribution. The index was evaluated for its ability to detect variation, for conformity with qualitative assessments, and for correlation to effluent pollutant fractions in order to assess its suitability as a predictor of treatment.

The moment index overcomes many of the weaknesses inherent in other existing indices. The index can be computed from a dataset containing just one volume exchange so arbitrary truncation of data due to the finite nature of data collection has no impact on the moment index. The moment index appears to be more sensitive than existing indices in detecting attenuation of a residence time distribution as well. The new index demonstrated excellent correlation to the effluent pollutant fraction predicted by a first order reduction implying the index could be the good predictor of treatment. In addition to correlation with treatment, the moment index matched qualitative assessment precisely for the eight special cases considered.

The moment index could substantially aid in the design and management of treatment wetlands for balancing cost and efficacy by resolving some of the uncertainty associated with residence time. The index could be used to help identify the optimal
wetland configuration for maximizing residence time. Not only would it be useful in quantifying the effects of vegetation, bathymetry, and wetland shape on residence time; it could have utility in supplying the bounds for pollutant reduction.

3.1 Introduction

3.1.1 Problem Definition

Agricultural practices impact water quality as production intensifies through the use of chemical fertilizers and pesticides, in combination with intensive drainage practices (Zucker and Brown, 1998). Drainage increases the amount of arable land and improves trafficability. Much of Ohio and many parts of the Midwestern United States are intensively subsurface drained (Fausey et al., 1995). Intensively drained cropland has reduced detention storage compared with undrained cropland. As a result more nutrients are flushed from the soil and then accumulate in surface water (Hubbard et al., 2004). Nitrogen contamination in drinking water in the form of nitrate can cause methemoglobinemia, a potentially fatal disease in infants (Vigil et al., 1965). Coastal eutrophication driven, primarily by nitrogen, and sometimes phosphorus, results in harmful algal blooms and widespread hypoxia or anoxia (Howarth, 2008). This is a growing concern in the Great Lakes region of the United States, as well as in the Gulf of Mexico, where hypoxia threatens to upset delicate food chains with potential impacts on commercial and recreational fishing industries.

One strategy to protect public health, promote economic vitality, and improve ecological health is to reduce the amount of excess nutrients entering surface waters so that cumulative downstream concentrations are not excessive (Mitsch and Gosselink,
2007). Conventional water treatment processes used in point source applications are generally not practical in agricultural settings where a large pollution component is from non-point sources. Constructed wetlands are useful as low-tech water treatment option in rural settings; particularly in an agricultural landscape where intensive farming practices contribute to high nutrient and sediment loads in drainage water (Dong et al., 2009; Mao et al., 2009). With their low capital cost and minimal operational expense relative to convention water treatment, constructed wetlands are an appropriate water treatment technology in many parts of the world (Brix, 1994).

Wetlands provide considerable benefit and promote biodiversity by offering habitat for water loving plants and insects (Mitsch and Gosselink, 2007). Wetlands provide hydrologic benefits through storm water capture and detention which can delay the onset and limit the severity of downstream flooding. Additionally, wetlands remove impurities through physical, chemical, and biological mechanisms (Mitsch and Gosselink, 2007). Consequently, constructed wetlands are an increasingly common best practice for reducing nutrient loads and other pollutants (Brix, 1994; Kadlec and Knight, 1996).

Wide-scale implementation of a strategy which incorporates constructed wetlands for the treatment of agricultural runoff is challenging. Competing cost and efficacy concerns must be balanced (Shields and Thackston, 1991). Wetlands require sufficient land area in order to handle a particular runoff volume, and in many cases that land could otherwise be used for generating revenue. Land cost, along with lost revenue, exerts pressure to minimize the size of these wetlands. However, undersized units will be less effective at reducing nutrients. One challenge to achieving optimal wetland design and
management is related to our ability to measure hydraulic performance. Metrics are needed that can reliably quantify hydraulic performance and then be used to predict time-dependent treatment processes. A new index is proposed for quantifying hydraulic performance and its correlation to a first-order pollutant reduction is evaluated.

3.1.2 Theoretical Background

3.1.2.1 Hydraulic Residence Time

Constructed wetlands are an increasingly common best practice for reducing nutrient loads and other pollutants (Brix, 1994; Kadlec and Knight, 1996). Wetlands act as nutrient sinks through processes including sedimentation, sorption, plant uptake, and chemical or biological reductions. These processes are all heavily time dependent so that pollutant reduction is closely related to the amount of time an individual pollutant resides in the wetland (Fogler, 1992; Kadlec and Knight, 1996). The more contact time pollutants have to removal mechanisms the greater the likelihood for pollutant reduction. Management practices should aim to maximize wetland residence time to facilitate nutrient reductions.

Wetland residence time describes travel time from inlet to outlet. The term residence time is sometimes used interchangeably with hydraulic retention time (Persson et al., 1999; Su et al., 2009). For consistency and to avoid confusion with the hydrologic concept for storm water routing through retention/detention basins, the term residence time is preferred for this discussion. Residence time is dependent on the wetland volume and flow rate. Under uniform flow conditions, or plug flow, every parcel of water entering the inlet at \( t_0 \) reaches the outlet at precisely some nominal time \( t_n \) determined
as the time required for a complete volume exchange within the wetland (Kadlec and Knight, 1996; Persson et al., 1999), described as:

$$t_n = \frac{V}{Q}$$  \hspace{1cm} (3-1)

In practice, a single nominal residence time is inadequate. Each parcel of water may have a unique residence time affected by streamlines, boundary conditions, and turbulent effects (Su et al., 2009). Residence time can be considered a random variable having some type of distribution.

Residence time distributions (RTDs) are functions often described by their shape

Figure 3.1a) Conceptual effect of short-circuiting (adapted from Holland et al., 2004): b) Conceptual effect of mixing on residence time distribution (adapted from Holland et al., 2004). Mixing scale is represented by the number of continuously stirred tank reactors (CSTRs) in series.
and position relative to $t_n$. Stagnant or re-circulating zones reduce the effective volume of the wetland creating preferential flow paths that effectively shorten the average residence time. Short-circuiting tends to shift the center of the distribution below the theoretical residence time, $t_n$, as depicted in Figure 3.1a.

The shape of a RTD is generally related to the mixing. Principles of chemical reactor design can be used to quantify mixing effects. Fogler (1992) and Levenspiel (1999) describe treatment wetlands as reactors modeled by a sequence of tanks-in-series. In a continuously stirred tank reactor (CSTR) all parcels have an equal probability of leaving the basin at any given time. The RTD for a single CSTR is an exponential function. As the number of CSTRs-in-series increases, the spread of the RTD decreases. Deviations of ideal plug flow are described by the mixing scale. Mixing scale is the number of CSTRs required to approximate the actual residence time distribution. Figure 3.1b shows the effects of mixing scale on RTD using the tanks-in-series approach.

Direct comparison of RTDs is possible for assessing hydraulic performance only after normalizing for hydraulic loading, wetland size, and tracer mass. The area under the raw RTD represents tracer mass. Once normalization is performed, the RTD becomes a dimensionless function with flow-weighted time along the x-axis such that the area under curve is unity. The corrected, or normalized, RTD is a probability density function of residence time (Teixeira and Siqueira, 2008).

3.1.2.2 Hydraulic Efficiency

Treatment wetlands are frequently treated as chemical reactors (Kadlec and Knight, 1996). Plug flow assumes full utilization of the entire basin volume. However, a typical wetland contains some stagnant or slow moving zones. Such underutilized
components effectively reduce the basin volume generating preferential flow paths and shortening the average residence time. Additionally, exchanges occur between the preferential flow paths and stagnant zones due to recirculation, dispersion, and diffusion. In a free surface wetland mixing can also be turbulence induced as a result of wind shear and bioturbation (Werner and Kadlec, 2000). Mixing tends to attenuate the peak of the residence time distribution and increases the spread. Figure 3.2 shows the effects of short-circuiting and mixing on residence time distribution in relation to the ideal plug flow response.

\[
\text{mean residence time} = \frac{\bar{Q}}{\bar{V}}
\]

Figure 3.2 For ideal plug flow, a tracer pulse introduced at the inlet is observed after one volume exchange at the outlet. Short-circuiting reduces the travel time while mixing attenuates the response at the outlet (adapted from Persson et al., 1999).

The term *hydraulic efficiency* describes hydraulic performance in terms of departure from ideal plug flow (Thackston et al., 1987). Holland et al. (2004) interpret this as representative of the capacity of a wetland to effectively utilize the entire wetland volume by uniformly distributing flow to maximize residence time. Wetlands with comparable ratios of volume to flow rate will have similar nominal residence times but
may have very different measured residence times depending on hydraulic performance. This uncertainty poses challenges in predicting residence time as well as treatment performance.

Hydraulic indices are commonly extracted from a RTD and used to analyze hydraulic performance. Teixeira and Siqueira (2008) assessed several reported hydraulic indices. Most of the hydraulic indices could be categorized as either short-circuiting indices or mixing indices. They evaluated the indices on three criteria: (1) the correlation of the index to the physical phenomenon it is said to represent; (2) the capability of the index to detect variation; and (3) statistical variability of the index. The authors evaluated eight short-circuiting indices and found only one index meeting all criteria. None of the six mixing indices evaluated fulfilled every requisite.

Persson et al. (1999) proposed the commonly used hydraulic efficiency index ($\lambda$) combining the flow uniformity index ($I - I/N$) and effective volume ($e$) as:

$$\lambda = e \left(1 - \frac{1}{N}\right)$$

(3-2)

where $e$ is defined by Thackston et al. (1987) as a ratio of mean residence time ($\bar{t}$) to nominal residence time:

$$e = \frac{\bar{t}}{t_n}$$

(3-3)

and $N$ is the number of CSTRs in series. Fogler (1992) considers $N$ the inverse of the coefficient of variation squared:

$$N = \left(\frac{\sigma}{\bar{t}}\right)^{-2}$$

(3-4)
Measured RTDs typically have a long drawn out tail that asymptotically approaches zero concentration since small quantities of tracer are trapped in stagnant or recirculation zones for extended periods of time. The point when data collection is terminated will determine the effective length of the tail and decide the overall influence on the distribution. Hydraulic indices based on mean residence time or variance are skewed by this tail effect. Incomplete data cannot accurately determine mean residence time (Su et al., 2009). Fogler (1992) suggests extrapolating the tail as an exponential decay function to avoid truncation error.

Challenges persist in quantifying hydraulic efficiency. The mere existence of so many hydraulic indices demonstrates a need for consistency in evaluating hydraulic performance (Min and Wise, 2009). Teixeira and Siqueira (2008) expose weaknesses inherent in many of these indices. Tail effects related to the arbitrary truncation of data as a result of the finite nature of the data collection also influence hydraulic efficiency calculations. A new index is put forth here to address these shortcomings.

3.1.3 Objective

A hydraulic index demonstrating strong correlation to pollutant reduction is needed to identify the optimal wetland configuration for maximizing residence time. Such an index should quantify the effects from various wetland parameters that influence the RTD to resolve some of the uncertainty associated with residence time. The index would not only be useful in quantifying the effects of vegetation, bathymetry, and wetland shape on residence time; it could have utility in supplying the bounds for pollutant reduction. Such an index could substantially aid in the design and management of treatment wetlands for balancing cost and efficacy.
3.2 Methodology

3.2.1 Measuring Residence Time

Wetland hydraulics are commonly assessed by plotting flow vectors or by an analysis of residence times (Somcs et al., 1999). A plot of flow vectors can be constructed from measured velocities or by numerical simulation. The vector plot can be used to quantify the RTD or a field tracer study might be conducted (Persson et al., 1999).

A field tracer study uses an inert tracer introduced at a single inlet with concentrations in the effluent stream measured as a function of time. Pulsed tracer studies were conducted to measure residence time distributions at wetlands located within rice paddy schemes in rural Hubei and Guangxi provinces, China. Rhodamine WT was selected as the tracer because it is non-toxic, receives minimal background interference, and has low adsorption and degradation rates (Holland et al., 2004). The tracer is considered conservative for up to five days in a wetland environment according to the manufacturer’s specifications.

Local irrigation canals supplied water continuously at the wetland inlet during the tracer studies while rhodamine concentrations were measured at a single outlet at various time intervals. Fluctuations in flow rates were unavoidable as a result of other paddy scheme demands on the water supply canal. After initiating flow at the inlet, a period of time was required to establish quasi-steady flow at the outlet. The delay allowed water temperature to stabilize minimizing thermal gradients. Flow rates were determined at the inlet and outlet by measuring the water depth over a broad-crested weir inside a portable sheet metal flume at both locations.
Once the flow rate and temperature at the outlet stabilized, a slug of tracer was introduced at the inlet. Rhodamine WT concentrations were measured with a YSI 600OMS V2 sonde equipped with a rhodamine probe, temperature sensor, and data recorder. Data were collected every five to ten minutes. Date (mo/day/year), time (hr:min:sec), temperature (°C), rhodamine concentration (µg/l), and battery voltage (volts) were recorded. The rhodamine probe range is 0-200 µg/l (detection limit 0.5µg/l, resolution 0.1 µg/l, and precision ±1µg/l or 5% of reading). Standard calibration performed on the probe before each tracer study did not consider turbidity or chlorophyll corrections.

3.2.2 RTD Normalization

Direct comparison of RTDs is not appropriate for basins having different volumes, tracer concentrations, flow rates, etc. A dimensionless function developed from normalized data provides a means of comparing wetlands of various sizes and flow rates. Hydraulic efficiency should be based on the normalized distribution for drawing meaningful comparisons with other RTDs.

Analytic challenges exist in applying residence time distribution theory to variable flow systems. Nauman (1969) describes two different residence times; the average residence time for particles entering a system and the average residence time for particles exiting the system. For unsteady flow conditions the entering and exiting residence times are not equal. Tracer pulses introduced during the same event may have different outlet tracer concentration profiles depending whether volumetric flow rate was increasing or decreasing.
Werner and Kadlec (1996) proposed the dimensionless flow-weighted time variable $\phi$ to account for unsteady flow with changing basin volume described as:

$$\phi = \int_{t_0}^{t} \frac{Q(t')}{V(t')} dt'$$  \hspace{1cm} (3-5)

where $t'$ represents a “dummy” variable of integration, $Q(t')$ represents the variable outflow rate, $V(t')$ represents a changing basin volume due to unsteady flow, and $t_0$ is the initial time of tracer delivery. The variable $\phi$ corresponds to a set amount of volume exiting the system “stretching” or “compressing” time into a dimensionless form (Werner and Kadlec, 1996). The theoretical residence time, or nominal residence time, is represented by $\phi$ equal to one. This value is comparable to the nominal residence time under steady state conditions from Eqn. (3-1) with basin volume divided by a constant flow rate.

Concentrations plotted on the y-axis become dimensionless by multiplying outflow concentration, $C(\phi)$, and volume, $V(\phi)$, at a given flow-weighted time and dividing by the total mass of the tracer:

$$C'(\phi) = \frac{C(\phi)V(\phi)}{M}$$  \hspace{1cm} (3-6)

where $C'(\phi)$ is the dimensionless function and M represents the total mass of tracer. The subsequent RTD with normalized concentration plotted with respect to flow weighted time results in a probability density function where the area below the function representing tracer mass equals one.
3.2.3 Moment Analysis

A moment analysis of the normalized RTD provides meaningful parameters for describing the distribution (Kadlec and Knight, 1996; Werner and Kadlec, 1996; Holland et al., 2004; Min and Wise, 2009). The zeroth moment \(M_0\) of the dimensionless RTD function about the origin provides the fraction of tracer mass recovered:

\[
M_0^* = \int_0^\infty C'(\phi) d\phi
\]  

(3-7)

The first moment \(M_1^*\) about the origin describes the centroid of the RTD function:

\[
M_1^* = \int_0^\infty \phi C'(\phi) d\phi
\]  

(3-8)

The second moment \(M_2^*\) represents variance which describes the spread of the function:

\[
M_2^* = \int_0^\infty (\phi - M_1^*)^2 C'(\phi) d\phi
\]  

(3-9)

An important check of the tracer mass balance is a zeroth moment equal to one. If substantially less is reported then the tracer may not be conserved. For ideal plug flow conditions the spread is zero while the recovery fraction and centroid are unity. Deviations from ideal conditions, \(M_0^* = M_1^* = 1\) and \(M_2^* = 0\), are useful for quantifying hydraulic efficiency (Werner and Kadlec, 1996; Holland et al., 2004).

3.2.4 Moment Index

The moment index provides a hydraulic efficiency index that avoids reliance on mixing and short-circuiting indices and operates independent of the influence from tail effects. This approach considers hydraulic efficiency relative to the fraction of tracer exiting prematurely as well as the juxtaposition of residence times about what is referred to as the nominal divide in Figure 3.3.
Figure 3.3 Residence time distribution represented as a probability density function with cumulative distribution function inset.

The method assumes that residence times of a completely efficient basin will meet or exceed the nominal residence time. The portion of tracer exiting the wetland prior to the nominal divide adversely impacts hydraulic efficiency. This segment of the probability density function prior to the nominal divide is considered inefficient with more weight assigned to the more severely premature residence times. If the bulk of tracer exiting has a close proximity to the nominal divide then hydraulic efficiency is high. As more tracer exits earlier, hydraulic efficiency approaches zero.

Thus when hydraulic efficiency decreases the magnitude of the moment about the nominal divide will increase proportionally. Assigning the direction of positive moment out of the page, the total moment about the nominal divide is as follows:

\[ M_{\text{divide}} = (t_n - \bar{t}) \times Mass_{\text{tracer}} \]  

\[ \text{Post-Nominal} \]

\[ \text{Pre-Nominal} \]

\[ \text{nominal divide} \]

\[ \text{mean residence time} \]

\[ A_{\text{total}} = 1 \]

\[ M_{\text{divide}} \]

\[ \phi \]

\[ \text{flow weighted time} \]

\[ \text{fraction recovered} \]

\[ \text{Tracer Recovery} \]

\[ Q \]

\[ V \]

\[ t_n \]

\[ \bar{t} \]

\[ Mass_{\text{tracer}} \]
After normalizing the RTD with respect to tracer mass, basin volume, and flow rate, the tracer mass represented by the area under the curve becomes unity and $t_n$ equals one.

Equation (3-10) then simplifies as:

$$ M_{divide} = (1 - \bar{\phi}) $$

(3-11)

Generally, the moment about the nominal divide for the normalized RTD is:

$$ M_{divide} = \int_0^\infty (1 - \phi)C'(\phi)d\phi $$

(3-12)

Residence times less than nominal are considered inefficient. Figure 3.4 shows the RTD divided into pre-nominal and post-nominal components. The pre-nominal area in the figure is what Stamou (1994) refers to as the hold back parameter (HBP). Only the inefficient pre-nominal portion of the distribution is counted against the computed hydraulic efficiency.

![Figure 3.4 Residence time distribution showing pre-nominal and post-nominal components.](image-url)
Using this approach, the pre-nominal moment about the nominal divide, \( M_{pre} \), is simply the moment bounded from zero to one as expressed below:

\[
M_{pre} = \int_0^1 (\phi - 1)C' (\phi) d\phi
\]

This pre-nominal moment is merely the HBP multiplied by the moment arm from the nominal divide to the centroid of the \( A_{pre} \) shown in Figure 3.4. The proposed \textit{moment index} is then the complement of the pre-nominal moment about the nominal divide:

\[
\text{moment index} = 1 - M_{pre}
\]

3.2.5 Pollutant Reduction

In order to function as a predictor of treatment, the index should not only quantify hydraulic performance, it should also demonstrate some correlation to treatment. Kadlec and Knight (1996) suggest wetland treatment processes resemble a first-order rate function of the following form:

\[
X = e^{-k_v t}
\]

where \( X \) is the fraction of pollutant remaining over time depending on some rate constant \( k_v \). For first order reactions it is possible to determine \( X \) directly from the RTD function, \( E(t) \):

\[
X = \int_0^\infty E(t) e^{-k_v t} dt
\]

For higher order reactions, the RTD alone is not sufficient for predicting pollutant reduction although the RTD still has utility in supplying bounds for the reduction (Fogler, 1992).
Forty-two hypothetical residence time distributions were conceptualized to capture varying degrees of short-circuiting and mixing. Figure 3.5 illustrates the conceptual RTDs with the time axis flow-weighted so that it is expressed in units of volume exchanges. Effects from wetland volume and hydraulic loading are normalized. Mixing scales ranging from a single completely mixed tank to a near approximation of plug flow are considered. The short-circuiting component is described by the ratio of mean residence time to nominal residence time ranging from 0.25 to 1.

![Hypothetical Cases](image)

Figure 3.5 Residence time distributions of forty-two hypothetical cases used for analysis of hydraulic indices.

Potential effluent pollutant fractions are computed with RTDs from the 42 hypothetical cases according to the first-order reduction shown with Equation (3-16) assuming a generic rate constant, $k_v$, as the inverse of the nominal residence time, $(k_v = 1/t_n)$, since time is expressed as a number of volume exchanges. The assumed $k_v$ value is conservative since treatment wetlands are typically sized according to an expected flow rate so that the nominal residence time will achieve a desired level of
treatment. While holding basin volume, hydraulic loading, and the rate constant fixed, the 42 hypothetical cases yield effluent pollutant fractions ranging from 0.33 to 0.77.

3.3 Results and Discussion

3.3.1 Comparison with Qualitative Analysis

A hydraulic index should effectively quantify hydraulic performance in a manner consistent with qualitative analysis. Figure 3.6 compares RTDs from four special cases and displays rankings of hydraulic performance based on a qualitative assessment, then ranks them according to the proposed moment index, and finally according to three commonly reported indices. The qualitative analysis considers Case 1 the most favorable since dispersion is moderate and the peak is somewhat delayed. Case 4 is least favorable because short-circuiting is severe. Intermediate Case 3 and Case 4 are qualitatively very similar while Case 2 is perhaps slightly more favorable. The moment index is in good agreement with the qualitative assessment for all four cases. The time-to-peak ratio made more distinction between Cases 2 and 3 than between Cases 3 and 4. The effective volume parameter noticed little distinction among the first three cases while the hydraulic efficiency index recognized a substantial difference between the qualitatively similar Cases 2 and 3.
Figure 3.6 Special cases showing hydraulic performance assessed qualitatively and then ranked using various indices. Cases 2 and 3 are hydraulically very similar.

Figure 3.7 displays four additional special cases. Case 5 is an approximation of ideal flow whereas Case 8 is severely short-circuited. Case 7 is characteristic of a completely stirred tank and Case 6 is somewhat intermediate. The qualitative comparison and the moment index agreed. The time-to-peak parameter gave substantially different results. The effective volume parameter treated the fully mixed condition, Case 7, as if it were ideal whereas the hydraulic efficiency index scored Case 7 as the absolute worst.
3.3.2 Tail Effect

Measured RTDs typically have a long drawn out tail that asymptotically approaches zero concentration since small quantities of tracer are trapped in stagnant or recirculation zones for extended periods of time. At some point data collection must be terminated for practical considerations; typically three mean detention times is enough to characterize the distribution (Levenspiel, 1999). The end point when data collection is terminated will determine the effective length of the tail and decide its overall influence on the distribution. Hydraulic indices can be affected by this tail effect when parameters susceptible to influence from the tail are used such as mean residence time or variance. Incomplete data cannot accurately determine mean residence time (Su et al., 2009). Fogler (1992) suggests extrapolating the tail as an exponential decay function to avoid...

Figure 3.7 Special cases with hydraulic performance assessed qualitatively and then ranked using various indices. Case 5 approximates ideal plug flow and Case 7 represents a completely mixed tank. Case 6 is somewhat intermediate and Case 8 demonstrates severe short-circuiting.
truncation error. The proposed moment index is independent of any tail effects so tail extrapolation is not a concern.

Figure 3.8a displays actual normalized residence time distributions measured at each paddy scheme wetland in China and includes all recorded measurements from the two field studies. Figure 3.8b) considers data from the same studies only the tails are truncated sooner. In the Guilin example truncation had minimal affect on hydraulic efficiency. The tail effect is greater in the Tuanlin case where truncation changed the hydraulic index value given by Eqn. (3-2) from 0.64 to 0.56. The tail effect has no influence on values determined with the moment method because it is derived only from the pronominal portion of the RTD.

3.3.3 Correlating Hydraulic Efficiency to Treatment

Wang and Mitsch (2000) suggest that treatment can be improved by manipulating the hydraulic regime to improve hydraulic efficiency. Factors that can affect the
hydraulic regime are inlet and outlet configuration, shape of the wetland, depth of water, length to width ratio, flow rate, and resistance to flow such as that provided by vegetation (Persson et al., 1999). For such an approach to be effective there must be a strong correlation between hydraulic efficiency and pollutant reduction.

Strong correlation of an index to pollutant reduction implies the index may be a good predictor of treatment. Hazard indices determined from the 42 hypothetical cases described previously are compared with effluent pollutant fractions computed for each case using the first order approach presented in Equation (3-16). A generic rate constant of the inverse of the nominal residence time \( k_v = 1/t_n \) is assumed. This \( k_v \) value is not precise but we can be confident that it is of the right order of magnitude for a properly sized treatment wetland.

The moment index is plotted with respect to the effluent pollutant fraction for each of the 42 cases in Figure 3.9. A straight line is fit through the data points with the Coefficient of Determination, \( R^2 \), displayed. As indicated in the figure, the \( R^2 \) value is 0.94 for the index. Compare the value below with \( R^2 \) values of 0.41 for the hydraulic efficiency index, \( e(1 - 1/N) \), and 0.42 for the ratio of time-to-peak to nominal residence time. The effective volume parameter does demonstrate good correlation to treatment as well with an \( R^2 \) value of 0.91. However, this parameter is highly susceptible to influence from the tail effect and will not detect variations among RTDs having a common centroid. For example, positively and negatively skewed distributions having a common mean value are indistinguishable with this index. This is why there are inconsistencies with this parameter relative to the qualitative assessments in Figure 3.6 and Figure 3.7.
3.4 Summary

Uncertainty poses challenges in predicting residence time as well as treatment efficacy. Expected treatment based on nominal or mean residence time tends to overestimate actual pollutant reductions because of flow non-uniformity. This non-uniformity penalty is difficult to predict. A hydraulic index demonstrating strong correlation to pollutant reduction is needed to help identify the optimal wetland configuration for maximizing residence time. Such an index should be related to the various wetland parameters that influence the RTD. The index would not only be useful in quantifying the effects of vegetation, bathymetry, wetland shape, etc., on residence time; it could also be used to supply the bounds for pollutant reduction.

Figure 3.9 Hydraulic indices plotted vs. effluent pollutant fraction, X, derived from Equation (3-16) for 42 residence time distributions. Regression lines are displayed with $R^2$ values for all four indices.
A new hydraulic index was evaluated for its suitability as both a measure of hydraulic performance and as a predictor of treatment. The index addresses several of the weaknesses inherent in other indices. Experimental constraints resulting in the arbitrary truncation of data have no impact on the moment index value. The index can be computed from a dataset containing just one volume exchange although a more fully developed RTD function should be captured to verify the tracer recovery fraction approaches one. The moment index avoids reliance on parameters like the mean residence time, time-to-peak, or variance which are often limited in their ability to represent physical phenomena as well as in their ability to distinguish variation. This new index shows strong correlation with pollutant reduction so it may be used for predicting treatment or optimizing wetland configuration. Correlation to treatment alone does not necessarily indicate a good hydraulic index. The index should quantify hydraulic performance in a manner consistent with qualitative analyses and should have enough sensitivity to consider slight variations. The moment index matched qualitative results well for the eight special cases considered here. These results should be verified with actual field data.
3.5 Citations


Chapter 4  Quantifying Hydraulic Performance with Failure Analysis

Abstract

In this chapter, a statistical approach was used to derive two new hydraulic indices. Recognizing the close relationship between the residence time distribution and a probability density function, an approach typically associated with failure analysis was used to develop the two new indices. Indices were evaluated for their ability to detect variation, for conformity with qualitative assessments, and for correlation to effluent pollutant fractions in order to assess their suitability as a predictor of treatment.

The indices overcome several of the weaknesses inherent in other indices. Experimental constraints resulting in the arbitrary truncation of data have no impact on the values of either index. The temporal hazard index could be computed from a dataset limited to approximately one volume exchange. Both indices are sensitive to residence time distribution attenuation. The hazard index demonstrated superior agreement with qualitative assessments implying this index could be useful for characterizing the effects on the flow regime from various wetland parameters like depth, bathymetry, and shape. The temporal hazard index demonstrated superior correlation to the effluent pollutant fraction predicted by a first order reduction implying the temporal hazard index could be the better predictor of treatment.
4.1 Introduction

4.1.1 Problem Definition

Agricultural practices impact water quality as production intensifies through the use of chemical fertilizers and pesticides, in combination with intense drainage practices (Zucker and Brown, 1998). Drainage increases the amount of arable land and improves trafficability. Much of Ohio and many parts of the Midwestern United States are intensively subsurface drained (Fausey et al., 1995). Intensively drained cropland has reduced detention storage compared with undrained cropland. As a result more nutrients are flushed from the soil and then accumulate in surface water (Hubbard et al., 2004). Nitrogen contamination in drinking water in the form of nitrate can cause methemoglobinemia, a potentially fatal disease in infants (Vigil et al., 1965). Coastal eutrophication, driven primarily by nitrogen, and sometimes phosphorus, results in harmful algal blooms and widespread hypoxia or anoxia (Howarth, 2008). This is a growing concern in the Great Lakes region of the United States, as well as in the Gulf of Mexico, where hypoxia threatens to upset delicate food chains with potential impacts on commercial and recreational fishing industries.

One strategy to protect public health, promote economic vitality, and improve ecological health is to reduce the amount of excess nutrients entering surface waters so that cumulative downstream concentrations are not excessive (Mitsch and Gosselink, 2007). Conventional water treatment processes used in point source applications are generally not practical in agricultural settings where a large pollution component is from non-point sources. Constructed wetlands are useful as low-tech water treatment option in
rural settings; particularly in an agricultural landscape where intensive farming practices contribute to high nutrient and sediment loads in drainage water (Dong et al., 2009; Mao et al., 2009). With relatively low capital cost and minimal operational cost, constructed wetlands are an appropriate technology for water treatment in many parts of the world (Brix, 1994).

Wetlands provide considerable benefit and promote biodiversity by offering habitat for water loving plants and insects (Mitsch and Gosselink, 2007). Wetlands provide hydrologic benefits through storm water capture and detention which can delay the onset and limit the severity of downstream flooding. Additionally, wetlands remove impurities through physical, chemical, and biological mechanisms (Mitsch and Gosselink, 2007). Consequently, constructed wetlands are an increasingly common best practice for reducing nutrient loads and other pollutants (Brix, 1994; Kadlec and Knight, 1996).

Wide-scale implementation of a strategy which incorporates constructed wetlands for the treatment of agricultural runoff is challenging. Competing cost and efficacy concerns must be balanced (Shields and Thackston, 1991). Wetlands require sufficient land area in order to handle a particular runoff volume, and in many cases that land could otherwise be used for generating revenue. Land cost, along with lost revenue, exerts pressure to minimize the size of these wetlands. However, undersized units will be less effective at reducing nutrients. One challenge to achieving optimal wetland design and management is related to our ability to measure hydraulic performance. Metrics are needed that can reliably quantify hydraulic performance and then be used to predict time-dependent treatment processes. Two new indices are proposed for quantifying hydraulic
performance and their correlations to a first-order pollutant reduction are evaluated. The proposed indices are derived from probability functions related to failure analysis.

4.1.2 Theoretical Background

4.1.2.1 Residence time distributions

Wetlands act as nutrient sinks through processes including; sedimentation, sorption, plant uptake, as well as chemical and biological reductions. These processes are all heavily time dependent so that pollutant reduction is closely related to the amount of time an individual pollutant resides in the wetland (Fogler, 1992; Kadlec and Knight, 1996). The more contact time pollutants have to removal mechanisms the greater the likelihood for pollutant reduction. Currently it is extremely challenging to predict the effectiveness of a wetland design because of the uncertainty in predicting residence time.

Wetland residence time describes travel time from inlet to outlet. The term residence time is sometimes used interchangeably with hydraulic retention time (Persson et al., 1999; Su et al., 2009). For consistency and to avoid confusion with the hydrologic concept for routing stormwater through retention/detention basins, the term residence time is preferred for this discussion.

Residence time is often approximated as the time required for one complete volume exchange in the wetland expressed nominally as:

$$t_n = \frac{V}{Q}$$  

(4-1)

In practice, a single nominal residence time does not adequately describe the contact time for a pollutant within a wetland. Residence time is better characterized as some distribution of times since each parcel of water may have a unique residence time.
affected by streamlines, boundary conditions, and turbulent effects (Su et al., 2009). For this reason, residence time can be considered a continuous random variable, \( X \), with some type the probability density function (PDF) derived from the residence time distribution (RTD):

\[
P[a < X < b] = \int_{a}^{b} f(t) \, dt \quad (4-2)
\]

The RTD allows for a comparison of wetland basins made qualitatively. The shape and position of an RTD are indicators of certain hydraulic phenomena like preferential flow, stagnation, and mixing effects. A typical wetland contains some stagnant or slow moving zones. Such underutilized components effectively reduce the basin volume generating preferential flow paths and shortening the average residence time. This shifts the RTD along the x-axis towards the origin as depicted in Figure 4.1a. Mixing tends to attenuate the peak of the residence time distribution increasing the spread. Fogler (1992) and Levenspiel (1999) describe treatment wetlands as reactors modeled by a sequence of tanks-in-series. In a continuously stirred tank reactor (CSTR) all parcels have an equal probability of leaving the basin at any given time. The RTD for a single CSTR is an exponential function. As the number of CSTRs-in-series increases, the spread of the RTD decreases. Figure 4.1b shows the effects on the RTD considering the tanks-in-series approach.

4.1.2.2 Hydraulic Indices

Parameters such as average residence time, time-to-peak, or the spread of the distribution are commonly extracted from the RTD and used quantify hydraulic performance. Composite indices derived from RTD parameters are used to describe
hydraulic characteristics like the degree of mixing or short-circuiting or aggregated to quantify overall hydraulic efficiency in terms of departure from ideal uniform flow (Thackston et al., 1987). Figure 4.2 illustrates the departure from plug flow. An ideal index should quantify hydraulic performance in a manner consistent with qualitative analysis and should have enough sensitivity to consider slight variations. Since hydraulic performance has substantial bearing on treatment efficacy, the index should also demonstrate some correlation to pollutant reduction.

Figure 4.2a) Conceptual effect of short-circuiting: b) Conceptual effect of mixing on residence time distribution. Mixing scale is represented by the number of continuously stirred tank reactors (CSTRs) in series (adapted from Holland et al., 2004).
Challenges persist in quantifying hydraulic performance. Teixeira and Siqueira (2008) found most indices lacking in at least one of three areas: (1) the correlation of the index to the physical phenomenon it is said to represent; (2) the capability of the index to detect variation; and (3) statistical variability of the index. Since many indices already abound, there is a need for consistency in reporting hydraulic performance (Min and Wise, 2009).

![Diagram of Concentration vs Time](image)

Figure 4.2 For ideal plug flow, a tracer pulse introduced at the inlet is observed after one volume exchange at the outlet. Short-circuiting reduces the travel time while mixing attenuates the response at the outlet (adapted from Persson et al., 1999).

4.1.3 Objective

In this chapter a statistical approach is used to identify indices capable of characterizing hydraulic performance and demonstrating promise as predictors of treatment. An approach typically associated with failure analysis was used to derive two new indices from the residence time distribution. Indices were evaluated for their ability to detect variation, for conformity with qualitative assessments, and for correlation to...
effluent pollutant fractions. Suitable indices could be used in quantifying the effects of vegetation, bathymetry, and wetland shape on residence time and could ultimately be used for supplying the bounds for pollutant reduction. Such indices could substantially aid in the design and management of treatment wetlands for balancing cost and efficacy.

4.2 Methodology

4.2.1 RTD Normalization

A residence time distribution is commonly assessed either with an analysis of measured residence times or by plotting flow vectors (Somes et al., 1999). A plot of flow vectors can be constructed from measured velocities or by numerical simulation. The vector plot can be used to develop the RTD or a field tracer study might be conducted (Persson et al., 1999).

A dimensionless probability density function (PDF) is derived from the RTD by normalizing the distribution with respect to volume, flow rate, and tracer mass. Unsteady flow conditions require special treatment since the mean residence time mean of inflow is not equal to that of the outflow (Nauman, 1969). In effect, two tracer pulses introduced during the same event may have different tracer concentration profiles at the outlet depending whether the change in storage volume was increasing or decreasing when the pulse was introduced. After normalization the two distributions are identical. Werner and Kadlec (1996) propose the dimensionless flow-weighted time variable \( \phi \) to account for unsteady flow with changing basin volume described as:

\[
\phi = \int_{t_0}^{t} \frac{Q(t')}{V(t')} dt'
\]

(4-3)
where \( t' \) represents a “dummy” variable of integration, \( Q(t') \) represents the variable outflow rate, \( V(t') \) represents a changing basin volume due to unsteady flow, and \( t_0 \) is the initial time of tracer delivery. The variable \( \phi \) corresponds to a set amount of volume exiting the system “stretching” or “compressing” time into a dimensionless form (Werner and Kadlec, 1996). The theoretical residence time, or nominal residence time, represents the time for one volume exchange. This flow-weighted time, \( \phi \), is comparable to the nominal residence time under steady state conditions from Eqn. (4-1) where basin volume is divided by a constant flow rate.

Concentrations plotted on the y-axis become dimensionless by multiplying outflow concentration, \( C(\phi) \), and volume, \( V(\phi) \), at a given flow-weighted time and dividing by the total mass of the tracer:

\[
C'(\phi) = \frac{C(\phi)V(\phi)}{M} \tag{4-4}
\]

where \( C'(\phi) \) is the dimensionless function and \( M \) represents the total mass of tracer. The subsequent RTD with normalized concentration plotted with respect to flow weighted time results in a probability density function where the area below the function representing tracer mass equals one.

4.2.2 Failure Analysis

Trivedi (1982) describes probability functions for reliability and failure that can be applied to the continuous random variable \( \phi \) which represents flow-weighted time. We can consider it the purpose of the wetland to retain pollutants. The probability of a pollutant leaving represents the probability of failure:
For the probability density function, \( f_\phi(x) \), some cumulative distribution function, \( F_\phi(x) \), exists. The two are related as follows:

\[
P[a < \phi < b] = \int_a^b f_\phi(x) dx
\]  

(4-5)

\( F_\phi(x) \) represents the probability of failure for a given flow-weighted time. The reliability function, \( R_\phi(x) \), is simply the complement of failure:

\[
R(x) = 1 - F_\phi(x)
\]  

(4-7)

A failure rate function, known as the hazard function, is given by:

\[
h(x) = \frac{f_\phi(x)}{R(x)}
\]  

(4-8)

Finally, a cumulative hazard function is expressed as:

\[
H(x) = \int_0^x h(x) dx = -\ln R_\phi(x)
\]  

(4-9)

4.2.2.1 Hazard Index

The cumulative hazard function provides another means for characterizing hydraulic performance since each unique RTD provides a correspondingly unique hazard function. Hydraulic indices extracted from the cumulative hazard function are used here to relate hydraulic performance to the probability of a pollutant being reduced. Cumulative hazard may be determined at any flow weighted time whenever the RTD is known.

The cumulative hazard at one nominal residence time, \( H(1) \), is proposed as an index. Notice that in Figure 4.3 the cumulative hazard function, \( H(x) \), asymptotically
approaches some total hazard as $\phi$ increases. This upper limit varies according to the original probability density function. In order to compare various RTDs the index should be normalized by dividing by the upper limit to give the hazard index, $H'(1)$, within a range from zero to one:

$$hazard\ index = \frac{H(1)}{\lim_{x \to \infty} H(x)}$$  \hspace{1cm} (4-10)
4.2.2.2 Temporal Hazard Index

Another proposed index considers the time, $\alpha$, required to reach a specified cumulative hazard, $\beta$, as described in the following relationship:

$$\text{when } H(x) = \beta, \text{then } x = \alpha$$

(4-11)

The temporal hazard index $\alpha$, is based on a fixed cumulative hazard, $\beta = 0.75$ throughout this discussion. For example, consider Figure 4.4 where the cumulative hazard is $H(x) = 0.75$. The temporal hazard index, $\alpha$, is the corresponding value on the x-axis equal to 0.83.

Figure 4.4 The temporal hazard is the time, $\alpha$, required to reach the cumulative hazard, $H(x) = 0.75$. In this example $\alpha = 0.83$. 

66
4.2.3 Pollutant Reduction

Such indices should not only quantitatively perform hydraulic functions, they should also demonstrate some correlation to treatment. Kadlec and Knight (1996) suggest wetland treatment processes resemble a first-order rate function of the following form:

\[ X = e^{-k_v t} \]  

where \( X \) is the fraction of pollutant remaining over time depending on some rate constant \( k_v \). For first order reactions it is possible to determine \( X \) directly from the RTD:

\[ X = \int_0^\infty E(t) e^{-k_v t} \, dt \]  

(4-13)

For higher order reactions, the RTD alone is not sufficient for predicting pollutant reduction although the RTD still has utility in supplying bounds for the reduction (Fogler, 1992).

Forty-two hypothetical residence time distributions were conceptualized to capture varying degrees of short-circuiting and mixing. Figure 4.5 illustrates the conceptual RTDs with the time axis flow-weighted so that it is expressed in units of volume exchanges. Effects from wetland volume and hydraulic loading are normalized. Mixing scales ranging from a single completely mixed tank to a near approximation of plug flow are considered. The short-circuiting component is described by the ratio of mean residence time to nominal residence time ranging from 0.25 to 1.
Effluent pollutant fractions are computed with RTDs from 42 hypothetical cases using the first order equation shown with Equation (4-13). A reaction constant, $k_v$, need not be known. Treatment wetlands are typically sized based on a nominal residence time or rather the wetland is sized according to an expected flow rate so that an acceptable level of treatment is achieved. The reaction constant is generally known, or estimated, based on the persistence of the pollutant being targeted. A generic rate constant of one over the nominal residence time ($k_v = 1/t_n$) is assumed since time is expressed as a number of volume exchanges.

4.3 Results and Discussion

4.3.1 Comparison with Qualitative Analysis

A hydraulic index should effectively quantify hydraulic performance in a manner consistent with qualitative analysis. Figure 4.6 compares RTDs from four special cases and displays rankings of hydraulic performance based on a qualitative assessment, then
ranks them according to the two proposed hazard function indices, and finally according to two widely used indices. The qualitative analysis considers Case 1 the most favorable since dispersion is moderate and the peak is somewhat delayed. Case 4 is least favorable because short-circuiting is severe. Intermediate Case 2 and Case 3 are qualitatively very similar while Case 2 is perhaps slightly more favorable for treatment. The hazard index was in good agreement for with the qualitative assessment for all four cases. The temporal hazard index made little distinction among the first three cases. The effective volume parameter showed results similar to the temporal hazard index while the hydraulic efficiency index recognized a substantial difference between the qualitatively similar Cases 2 and 3.

Figure 4.6 Special cases showing hydraulic performance assessed qualitatively and then using various indices. Cases 2 and 3 are hydraulically very similar.
Figure 4.7 displays four more special cases. Case 5 is an approximation of ideal flow whereas Case 8 is severely short-circuited. Case 7 is characteristic of a completely stirred tank and Case 6 is somewhat intermediate. The qualitative comparison and the two hazard indices all agreed on the general order however some detect smaller differences than others. The effective volume parameter treated the fully mixed condition, Case 7, as if it were ideal whereas the hydraulic efficiency index scored Case 7 as the absolute worst.

Figure 4.7 More special cases with hydraulic performance assessed qualitatively and then ranked using various indices. Case 5 approximates ideal plug flow and Case 7 represents a completely mixed tank. Case 6 is somewhat intermediate and Case 8 demonstrates severe short-circuiting.

Measured RTDs typically have a long drawn out tail that asymptotically approaches zero concentration since small quantities of tracer are trapped in stagnant or re-circulating zones for extended periods of time. At some point data collection must be terminated for practical considerations; typically three mean detention times is enough to
recover most of the tracer (Levenspiel, 1999). The end point when data collection is terminated will determine the effective length of the tail and decide its overall influence on the distribution. Hydraulic indices can be affected by this tail effect when parameters susceptible to influence from the tail are used such as mean residence time or variance. Incomplete data cannot accurately determine mean residence time (Su et al., 2009). Fogler (1992) suggests extrapolating the tail as an exponential decay function to avoid truncation error. The two proposed hazard indices are independent of any tail effects so tail extrapolation is not a concern. Computationally, the temporal hazard index is less involved requiring treatment only until the specified cumulative hazard is reached; in our case the specified cumulative hazard is 0.75. The normalized H'(x) index requires a maximum cumulative hazard be found.

4.3.2 Correlation to Treatment

Strong correlation of an index to pollutant reduction implies the index may be a good predictor of treatment. Hazard indices determined from the 42 hypothetical cases are compared with effluent pollutant fractions computed for each case using the first order approach presented in Equation (4-13). A generic rate constant of one over the nominal residence time ($k_v = 1/t_n$) is assumed. This $k_v$ value is not precise but we can be confident that it is of the proper order of magnitude for an optimally sized treatment wetland.

Cumulative hazard at one nominal residence time is plotted with respect to the effluent pollutant fraction in Figure 4.8. A straight line is fit through the data points with the Coefficient of Determination, $R^2$, displayed. As indicated in the figure, the $R^2$ value
is an unimpressive 0.59. Though we see in Figure 4.9 that the normalized hazard index, $H'(t_n)$, shows substantially better correlation with an $R^2$ value of 0.84. The reference nominal residence time, $t_n$, is selected arbitrarily. Correlation could be adjusted somewhat by using another reference for the index.

**Figure 4.8** Cumulative hazard, $H(t_n)$, plotted vs. predicted effluent pollutant fraction, $X$, derived from Equation (4-13).

**Figure 4.9** Hazard index, $H'(t_n)$, plotted vs. predicted effluent pollutant fraction, $X$, derived from Equation (4-13).
A similar plot is provided in Figure 4.10 to consider the temporal hazard index with respect to effluent pollutant fractions. This figure shows excellent correlation between the index and pollutant reduction with and $R^2$ value displayed of 0.985. Again for this index, the reference $\beta = 0.75$ is fairly arbitrary and could be adjusted.

Compare the values reported above with $R^2$ values of 0.41 for the hydraulic efficiency index, $e(1 - 1/N)$, and 0.42 for the ratio of time-to-peak to nominal residence time. The effective volume parameter does demonstrate good correlation to treatment with an $R^2$ value of 0.91. However, this parameter is highly susceptible to being influenced by tail effects. We see inconsistencies with this parameter and the qualitative analyses Figure 4.6 and Figure 4.7.

![Temporal Hazard Index](image)

**Figure 4.10** Temporal hazard index, $t_{@H(x)=0.75}$, plotted vs. predicted effluent pollutant fraction, $X$, derived from Equation (4-13).

Effluent pollutant fractions reported here are based on a generic first-order rate reduction coefficient with a time base corresponding to a single volume exchange.
Multiple pollutants are often targeted making it impossible to size the wetland for just one rate constant. In addition, the $k_v$ value is not necessarily constant for greater order reactions influenced by temperature or certain limiting reactants. Predictions regarding treatment based on these indices will be less certain when the rate constant no longer corresponds to the wetland volume exchange rate. In that case, the hazard and temporal hazard indices could be calibrated by adjusting their reference values. Additionally, the 42 hypothetical cases considered here were selected to capture the full range of mixing and short-circuiting effects. This may be too broad. Kadlec and Knight (1996) suggest most wetlands can be modeled with mixing scales ranging from 2 to 5 continuously stirred tanks in series. Reference values for the hazard and temporal hazard indices might again be adjusted to improve correlation within a specific range of observed levels of mixing and short-circuiting.

4.4 Summary

Uncertainty poses challenges in predicting residence time as well as treatment efficacy. Expected treatment based on nominal or mean residence time tends to overestimate actual pollutant reductions because of flow non-uniformity. This non-uniformity penalty is difficult to predict. A hydraulic index demonstrating strong correlation to pollutant reduction is needed to help identify the optimal wetland configuration for maximizing residence time. Such an index should be related to the various wetland parameters that influence the RTD. The index would not only be useful in quantifying the effects of vegetation, bathymetry, wetland shape, etc., on residence time; it could also be used to supply the bounds for pollutant reduction.
Two new hydraulic indices were derived and evaluated for their suitability as both a measure of hydraulic performance and as a predictor of treatment. Both indices are derived from the residence time distribution using probability functions associated with failure analysis. The indices deal with several of the weaknesses inherent in other indices. Experimental constraints resulting in the arbitrary truncation of data have no impact on the values of either index. The temporal hazard index could be computed from a dataset limited to approximately one volume exchange although a more fully developed RTD function should be captured to verify the tracer recovery fraction. Both indices avoid reliance on parameters like the mean residence time, time-to-peak, or variance which are often limited in their ability to represent physical phenomena as well as in their ability to distinguish variation. The hazard index demonstrated superior agreement with qualitative assessment implying this index should be useful for characterizing the effects on the flow regime from various wetland parameters like depth, bathymetry, and shape. The temporal hazard index demonstrated superior correlation to the effluent pollutant fraction predicted by a first order reduction. This implies the temporal hazard index could be the better predictor of treatment. These results should be verified with more field studies by measuring actual residence times and effluent pollutant fractions.
4.5 Citations


Abstract

The objective of this work was to quantify hydraulic performance of wetlands by evaluating existing indices for their suitability and, if needed, propose a new index that could be used to establish the role of hydraulic efficiency in treatment. Three commonly reported hydraulic indices were evaluated for suitability as a measure of hydraulic performance and as predictors of treatment. None of the existing indices evaluated demonstrated both strong correlation to treatment and sensitivity to slight variations in residence time distributions.

Three new hydraulic indices were proposed and then evaluated for suitability with the same criteria. These indices address several of the weaknesses inherent in existing indices. The arbitrary truncation of data resulting from finite resources for data collection has no impact on any of the proposed indices. All the proposed indices had the ability to detect attenuation of residence time distributions. These proposed indices should not immediately supplant existing indices but the findings do support further consideration of those proposed. Once a sound metric is established and its sensitivity verified, key wetland design parameters and management factors can be identified for input to a statistical model for predicting treatment. This type of model might be used to consider multiple factors simultaneously and identify the relative influence of the different factors affecting the hydraulic regime. The proposed indices could help identify key parameters...
that contribute to inefficiencies in constructed wetlands and aid in developing management and design strategies to minimize hydraulic inefficiencies.

5.1 Summary

The rationale for this work was that a measure of hydraulic performance which can be applied universally is needed for the optimization of the design and management of treatment wetlands. The objective was to quantify hydraulic performance of wetlands by evaluating existing indices for their suitability and, if needed, propose a new index or composite of existing indices that can be used to determine what role hydraulic efficiency has in treatment.

Three of the most common hydraulic indices were evaluated for their suitability both as a measure of hydraulic performance and as a predictor of treatment. Of these existing hydraulic indices evaluated, only the ratio of mean-residence-time to nominal-residence-time demonstrated strong correlation to the effluent pollutant fraction. However, this index proved insensitive to some variations in residence time distribution meaning it is unable to distinguish between residence time distributions sharing a common centroid. This particular index will not detect attenuation of the RTD. Other indices are needed to better quantify the influence that various wetland parameters have on residence time and develop predictive models for treatment.

Three new hydraulic indices were evaluated for their suitability as both a measure of hydraulic performance and as a predictor of treatment. These indices address several of the weaknesses inherent in existing indices. The arbitrary truncation of data resulting from finite resources for data collection has no impact on any of the proposed indices.
Two of the three can be computed from a dataset limited to approximately one volume exchange. None of the indices rely on parameters like the mean residence time, time-to-peak, or variance which are often limited in their ability to represent physical phenomena as well as in their sensitivity to variation.

The proposed moment index shows strong correlation with expected effluent pollutant fractions indicating it may be useful for predicting treatment and optimizing wetland configuration. Correlation to treatment alone does not necessarily indicate a good hydraulic index. Moment index results were also consistent with qualitative assessments indicating superb sensitivity to even slight variation.

Unlike the moment index which has a strong basis in residence time distribution theory, the other two proposed indices were derived using probability functions typically associated with failure analysis. These statistically based indices also outperformed the three existing indices with respect to sensitivity and correlation to treatment. The hazard index demonstrated excellent agreement with qualitative assessment implying good sensitivity. Unlike the other two proposed indices, the hazard index requires a fairly complete residence time distribution in order to be computed. The temporal hazard index demonstrated superior correlation to the effluent pollutant fraction predicted by a first order reduction implying the temporal hazard index could be the better predictor of treatment. Overall, the moment index appears to be most versatile since it scored exceptionally well in both sensitivity and correlation with expected treatment.
5.2 Limitations

These findings do support further evaluation of the proposed indices but are not meant to supplant existing indices here. While all three proposed indices are promising as predictors of treatment, they have not been tested on a robust set of actual field data. Although the moment index and the temporal hazard index can both be computed from a dataset limited to only one volume exchange, a more fully developed residence time distribution function should be captured to verify the tracer recovery fraction approaches one. While such indices may not spare investigators from substantial data collection, these two indices are particularly immune from distortion associated with the long tail typically associated with a residence time distribution. Some might argue that this results in some information loss. These preliminary findings seem to indicate that the contribution to treatment from the relatively small portion of the residence time distribution associated with the tail is minimal and should rightfully be weighted less.

It is also important to note that residence time, not necessarily hydraulic efficiency, determines treatment. A wetland with excellent hydraulic efficiency may experience inadequate treatment if the wetland is undersized or overloaded such that residence time is insufficient. A wetland with poor hydraulic efficiency may adequately treat pollutants as long as residence time is sufficient for treatment. Poor hydraulic efficiency simply indicates potential for extending residence time without expanding the size of the wetland. It is not thought that any hydraulic index alone could predict treatment but it is thought that it could be one of several important factors. In fact, the role hydraulic efficiency plays in treatment is not well established although preliminary indications are that hydraulic efficiency could be substantial.
5.3 Application of Results

Since various wetland parameters and management practices influence the hydraulic regime of a wetland, quantification of hydraulic performance is essential for a better understanding of the relative influence on the hydraulic regime from each of those various factors. It is imperative that the metric used have a strong correlation to treatment in order to optimize the wetland. Once a sound metric is established and its sensitivity verified with actual robust field data, key wetland design parameters and management factors can be identified for input to a statistical model for predicting treatment. Such a model might be used to consider interactions of multiple variables simultaneously and identify the relative influence of the different factors affecting the hydraulic regime. The proposed indices could help identify key parameters that contribute to inefficiencies in constructed wetlands used for water treatment. We could minimize hydraulic inefficiencies by identifying which management practices and design parameters most strongly influence the hydraulic regime. Knowledge gained directly from this work can help identify the optimal applications for treatment wetlands and ensure proper implementation so that our water supply is protected, aquatic habitat is preserved, and economic opportunities can be sustained.

Knowledge gained from the model can be applied to configure wetlands for optimal treatment. This would provide wetland designers a useful design tool. The empirical model can also be used to predict hydraulic inefficiencies based on the current or proposed configuration of a wetland. Indirectly the wetland configuration can be used to predict the effluent pollutant fraction without the need to physically measure residence time. Not only will this work support the development of appropriate technologies for
promoting agricultural production through the sustainable management of natural resources, it could also be used in rhizofiltration and chemical reactor design.
References


