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### ESTABLISHING A RELATIONSHIP BETWEEN HYDRAULIC EFFICIENCY AND TREATMENT PERFORMANCE IN CONSTRUCTED WETLANDS

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**ABSTRACT** Best practices for managing drainage water quality include the use of constructed wetlands for reducing nutrient loads. Nutrient reduction can be related to the hydraulic performance of a wetland. Hydraulic indexes used for quantifying the hydraulic efficiency of a wetland have more value when they can be used to predict treatment ability. This paper evaluates a number of common indexes describing hydraulic efficiency and relates them to the expected treatment derived from time dependant first order nutrient reductions. There is a need for a hydraulic index demonstrating strong correlation to pollutant reduction in order to identify the optimal wetland configuration for maximizing residence time. Such an index should quantify the effects of the various wetland parameters that influence the residence time distribution and supply the bounds for pollutant reduction.

**Keywords:** Free-water-surface constructed wetland (FWS CW), Hydraulic efficiency, Residence time distribution (RTD), Retention time, Treatment wetlands.

#### INTRODUCTION

**Problem Definition** Agricultural practices are impacting water quality as production intensifies through the use of chemical fertilizers and pesticides, in combination with intense drainage practices. Drainage creates more arable land and improves trafficability. Much of Ohio and many parts of the Midwestern United States are intensively drained. Intensively drained land has minimal detention storage. 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 (Hubbard et al., 2004). 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 ecology is to reduce the amount of excess nutrients entering surface waters so that cumulative downstream concentrations are not excessive. 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 options in rural settings; particularly in an agricultural landscape where intensive farming practices contribute to high nutrient and sediment loads in drainage water. With relatively low capital cost and minimal operational cost, constructed wetlands are an appropriate technology for water treatment in many parts of the world.

The wetlands provide considerable benefit. They promote biodiversity by offering habitat for water loving plants and insects. 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 & Gosselink, 2007). Consequently, constructed wetlands are an increasingly common best practice for reducing nutrient loads and other pollutants (Brix, 1994; Kadlec & Knight, 1996).

Wide scale implementation of a strategy which incorporates wetlands for the treatment of agricultural runoff is challenging. Wetlands require sufficient land area in order to handle a particular volume of runoff. 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. Competing cost and efficacy concerns must be balanced.

### ***Theoretical Background***

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 & 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 residence time is highly uncertain.

Wetland residence time describes travel time from inlet to outlet. The term *residence time* is sometimes used interchangeably with *hydraulic retention time* (Su et al., 2009; Persson et al., 1999). 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:

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

[1]

In practice, a single nominal residence time is inadequate. Each parcel of water has 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:

$$RTD = E(t) \quad [2]$$

The shape and position of an RTD can be qualitatively considered to indicate 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 towards the origin as depicted in Figure 1a. Mixing tends to attenuate the peak of the residence time distribution and increases the spread. Levenspiel (1999) and Fogler (1992) 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,

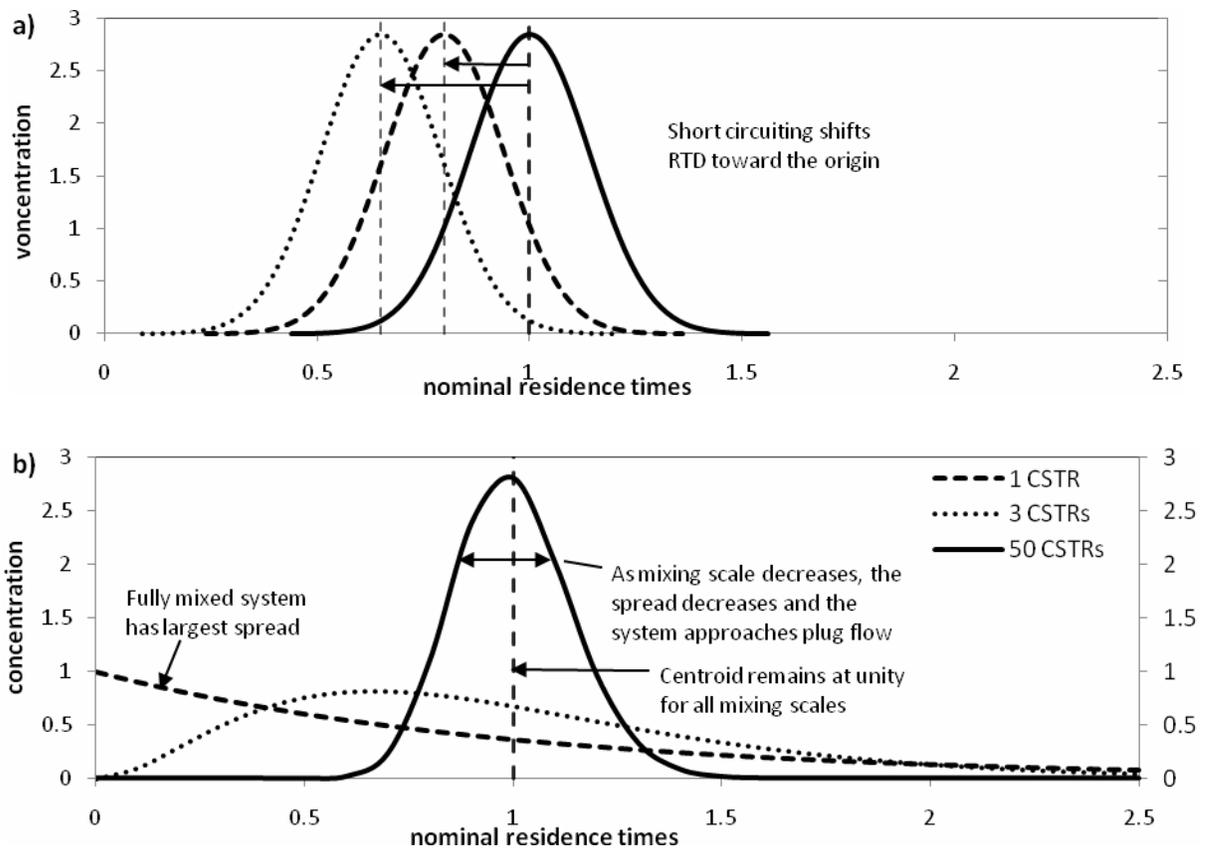


Figure 1. a) Conceptual effect of short-circuiting: b) Conceptual effect of mixing on residence time distribution. Mixing scale is represented by the number of continuously stirred tank reactors (CSTRs) in series (adapted from Holland, et al. 2004).

the spread of the RTD decreases. Figure 1b shows 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).

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

$$X = e^{-k_v t} \quad [3]$$

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:

$$X = \int_0^{\infty} E(t) e^{-k_v t} dt \quad [4]$$

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 (Wang & Mitsch, 2000; Persson et al., 1999; Holland et al., 2004). Many factors can affect the timing of a RTD including; 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 [4] indicates that an optimally configured wetland managed to maximize residence time will generally provide better treatment.

Hydraulic indexes Hydraulic indexes are commonly extracted from the RTD and used to quantitatively assess hydraulic performance. Basic indexes related to the position of the distribution are commonly classified as short-circuiting indexes. These are derived from parameters related to leading edge, the time-to-peak, and centroid identified from the RTD. Other indexes, often considered mixing indexes, include such 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 indexes to describe hydraulic performance in terms of departure from ideal uniform flow (Thackston et al., 1987). Figure 2 illustrates such a departure in terms of mixing and short-circuiting effects.

**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.

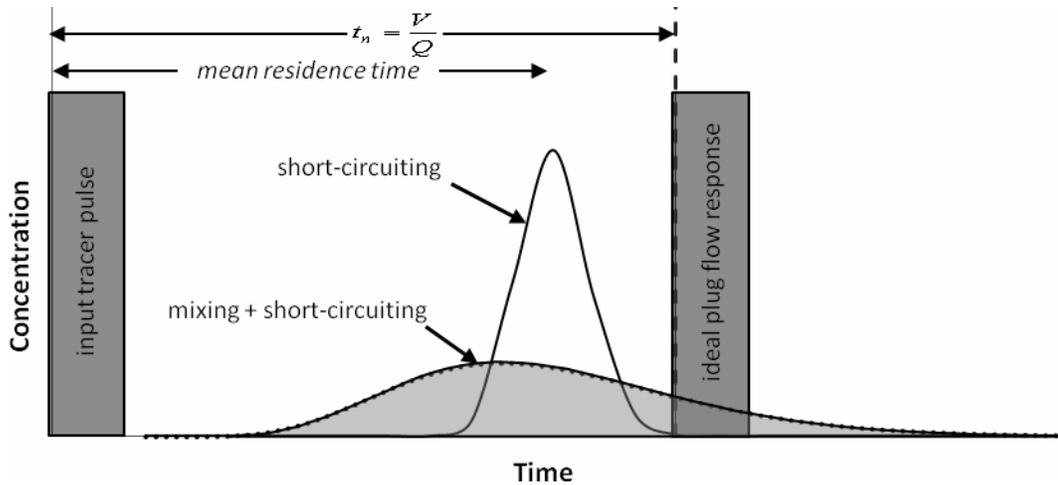


Figure 2. Effects of short-circuiting and mixing on residence time distribution (adapted from Persson, Somes, and Wong 1999)

**METHODOLOGY** Various hydraulic indexes are evaluated with respect to the first order pollutant reduction shown in Equation [4]. Residence time distributions derived from 42 hypothetical cases are considered with varying degrees of short-circuiting and mixing. Mixing scales ranging from a single completely mixed tank to a near approximation of plug flow are considered. The *effective volume* of the various cases ranges from 0.25 to 1 in order to consider the short-circuiting component. Effective volume is defined by Thackston et al. (1987) as a ratio of mean residence time ( $\bar{t}$ ) to nominal residence time:

$$e = \frac{\bar{t}}{t_n} \quad [5]$$

where  $\bar{t}$  is the mean residence time (Shields Jr. & Thackston, 1991). Figure 3 shows the RTDs associated with each case. The time axis is flow weighted so that it is expressed in units of volume exchanges.

Pollutant reductions are computed for each case using the first order equation shown with Equation [4]. A reaction constant,  $k_v$ , need not be known. Treatment wetlands are typically sized based on a nominal residence time. In other words, 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 ( $k_v = 1/t_n$ ) can be assumed since time is expressed as a number of volume exchanges. Even though all forty-two cases have the same nominal residence time, pollutant reductions will vary based on the shape of RTD.

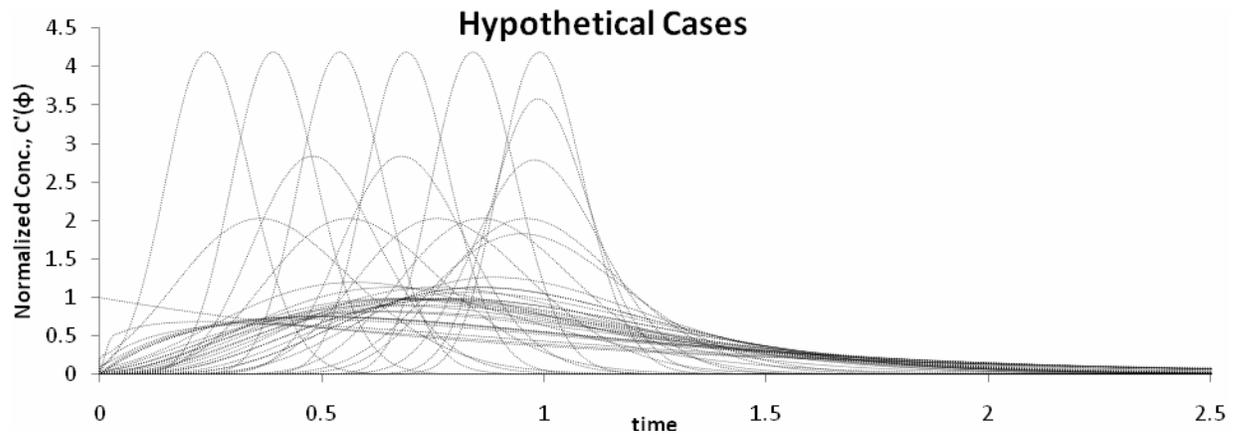


Figure 3. Residence time distributions of 42 hypothetical cases used for analysis of hydraulic indexes

The computed pollutant fractions remaining are then compared with three hydraulic indexes 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):

$$\lambda = \frac{t_p}{t_n} \quad [6]$$

Another index considers the ratio of mean residence time to nominal similar to effective volume in Equation [5]:

$$\lambda = \frac{\bar{t}}{t_n} \quad [7]$$

A third often cited index combines a flow uniformity index ( $1-1/N$ ) and effective volume ( $e$ ) as:

$$\lambda = e \left(1 - \frac{1}{N}\right) \quad [8]$$

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

$$N = \left(\frac{\sigma}{\bar{t}}\right)^{-2} \quad [9]$$

**RESULTS AND DISCUSSION** The hydraulic indexes described above are calculated for each of the 42 cases considered. Index values are plotted with respect to the effluent pollutant fraction computed using a first order reduction. A straight line is 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 effects of wetland characteristics such as bathymetry, configuration, shape, and the like. Teixeira and Siqueira (2008) found most indexes 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 [6] has limited value in relating basin parameters to treatment. As Figure 4 indicates, the  $R^2$  value is just 0.42. In addition, relating the hydraulic index to the time-to-peak can be problematic. When multiple preferential flow paths are present, the actual RTD may have multiple peaks. This results in some ambiguity when deciding which peak to consider in the ratio.

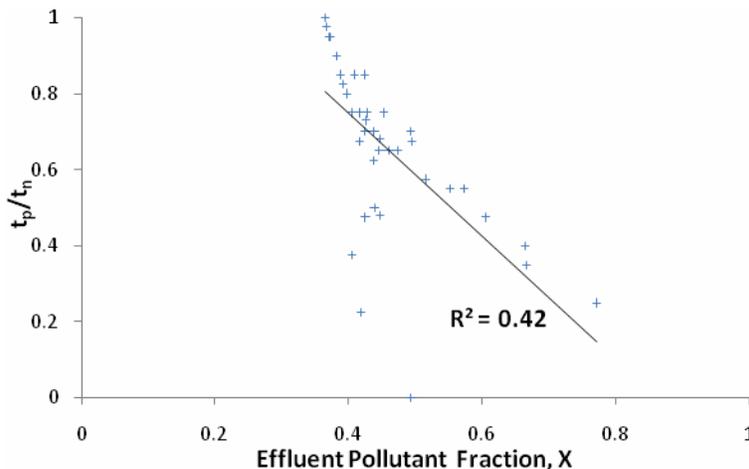


Figure 4. Hydraulic index,  $\lambda = \frac{t_p}{t_n}$ , plotted vs. effluent pollutant fraction, X

The ratio of mean residence time to nominal residence time from Equation [7] shows considerably better correlation to treatment. An  $R^2$  value of 0.91 is reported in Figure 4. 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 of the wetland. The index simply will not detect factors which contribute to increasing the spread of the RTD.

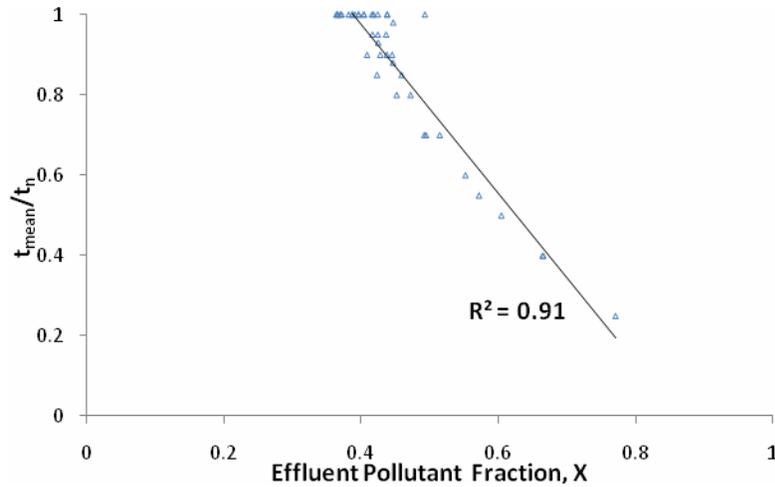


Figure 5 Hydraulic index,  $t_{\text{mean}}/t_r$ , plotted vs. effluent pollutant fraction, X

The third index derived from Equation [8] 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 & Wise, 2009; Su et al., 2009). As the R-squared value of 0.41 in Figure 6 suggests that this index may not be reliable as a predictor of effluent pollutant fractions.

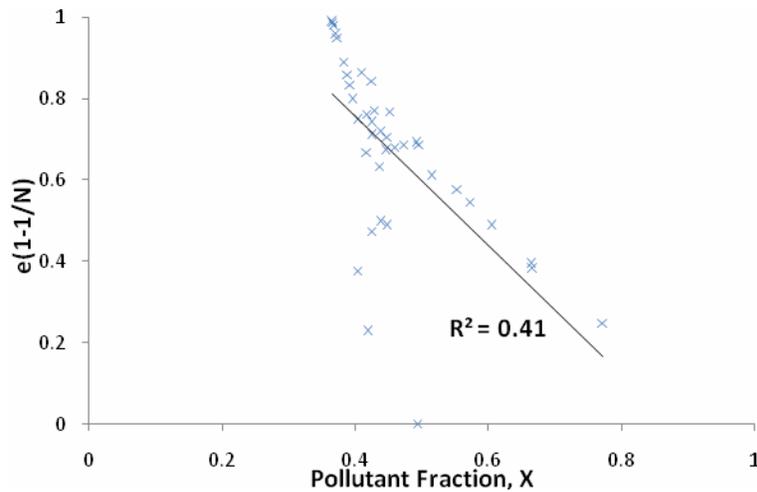


Figure 6 Hydraulic index,  $e^{(1-1/N)}$ , plotted vs. effluent pollutant fraction, X

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 warrant further study.

**SUMMARY** Treatment wetlands are increasingly used as a best management practice for mitigating human impacts on the environment. With relatively low cost, constructed wetlands are an effective low-tech water treatment option in rural areas. Poor hydraulic performance can shorten residence time in wetlands and limit treatment processes. It may be desirable to manipulate the hydraulic regime to increase hydraulic efficiency in order to improve effluent water quality (Wang & Mitsch, 2000; Persson et al., 1999; Holland et al., 2004).

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. 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, and wetland shape on residence time; it could then be used to supply the bounds for pollutant reduction.

Common hydraulic efficiency indexes combine mixing and short-circuiting indexes. The use of these hydraulic indexes has strong theoretical basis (Fogler, 1992; Levenspiel, 1999) yet many practical limitations exist in characterizing actual physical systems (Teixeira & Siqueira, 2008). Methods for quantifying hydraulic efficiency based on hydraulic indexes demonstrate limited correlation to first order pollutant reductions. Of the three hydraulic indexes evaluated, only the ratio of mean residence time to nominal residence time demonstrated strong correlation to improved effluent water quality. However, this index may lack sensitivity to residence time variation affected by the hydraulic regime. Other indexes are needed in order to better quantify the influence various wetland parameters have on residence time and then relate the quantity to pollutant reductions.

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