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Hydraulic Residence Time in a Prototype Free Water Surface Constructed Wetland

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ABSTRACT : A prototype surface flow constructed wetland was built in the upstream area of reclaimed tidal lands to improve the water quality of Lake Sihwa by treating severely polluted stream water. In this study, a tracer test using rhodamine-WT was performed to investigate the flow characteristics and to quantify the observed hydraulic residence time (HRT) for a high-lying cell in the Banwol wetland of the Sihwa constructed wetland. The tracer test indicated that even if flow was mainly observed in the open water area of the Banwol wetland, water flowed continuously in the vegetative area and there was no dead zone. The calculated HRT (51.3 hrs),calculated by dividing the wetland volume by the wetland inflow, exceeded the observed HRT (38.7 hrs), since the short-circuiting of flux resulting from irregular topography and vegetation was not reflected in the calculated HRT. The exit tracer concentration curves were reproduced well by both the plug flow with dispersion and tanks-in-series models, indicating that the performance of the Banwol wetland can be estimated accurately using these models.

Key words : Constructed wetland, hydraulic residence time, tracer test

INTRODUCTION

With the recognition of the beneficial functions of wetlands, such as in water purification, flood control, and their positive impact on biodiversity, significant efforts have been made to conserve, restore, and construct wetlands on a global basis[1)].

In general, there are two types of constructed wetlands: free water surface (FWS) and subsurface flow (SF)[2)]. The disadvantages of FWS wetlands include the requirement for a large area and relatively low treatment efficiency, while this method has the advantages that it is inexpensive in terms of maintenance and is effective for treating non-point source pollutants characterized by low concentrations and large quantities. In addition, wetland development restores ecosystems and provides wildlife habitat and recreational areas for residents[2)].

A constructed wetland system relies on physiochemical and biological mechanisms to remove pollutants from the water. Physiochemical processes include the settlement of suspended particulate matter, adsorption to soil particles, and volatilization, while biological processes remove pollutants through the metabolism of plants and microorganisms[3)]. Water purification processes are thus affected by many physical, chemical, and biological factors. The water movement patterns that result in the mixing and flow of influents, i.e., the hydraulic residence time in wetlands, are the principal factors determining the degree of wastewater purification[4)].

Urban[5)] used lithium as a tracer to measure the actual hydraulic residence time in the Des Plaines River wetland. Kadlec[6)] used the results of a tracer test to simulate water movement in a constructed wetland using three models: plug flow with dispersion, tanks-in-series, and a series-parallel network of tanks. Rhodamine-WT dye was used as a tracer to measure average flow velocities in a natural wetland located in Westchester, NY, USA[7)] and to determine the distribution of the hydraulic residence time

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within a constructed wetland[8].

The objectives of this thesis were to provide basic data on wetland design and operation by measuring the hydraulic residence time using a rhodamine-WT dye tracer test in the Sihwa FWS construceted wetland.

MATERIALS AND METHODS

Study site

The Sihwa constructed wetland was built at the confluence of the Banwol, Donghwa, and Samhwa streams in the upstream area of Lake Sihwa, which is located on reclaimed tidal lands near Ansan and Hwaseong, in Gyeonggi Province, Korea9). The watersheds drained by the Banwol, Donghwa, and Samhwa streams cover 40.9, 43.0, and 16.9 km2, respectively (Table 1). The percent run-off from the Banwol watershed (52.7%) is greater than that of the Donghwa watershed (41.1%), because the gates of many intake weirs in the latter are closed to provide water for irrigation, except during the rainy season. The percent run-off from the Samhwa watershed is only 36.6%.

Table 1. Drainage characteristics of the investigated watersheds

Stream	Banwol	Donghwa	Samhwa
Watershed Area (km^2)	40.9	43.0	16.9
Run-off (×106 m^3)	26.3	21.6	7.5
Percent Run-off (%)	52.7	41.1	36.6

The Sihwa wetland was constructed over a 75-ha area. Based on the geometry of the construction sites, the wetland was divided into low-lying cells, where the natural hydraulic gradient is the driving force of water flow, and high-lying cells, where mechanical pumps are used to supply water. The hydraulic residence time, which is one of the most important factors affecting the water purification mechanism, was measured in the high-lying Banwol wetland because a constant flow into the wetland was maintained with pumping (Fig. 1).

The high-lying cell in the Banwol wetland (BHC) consisted of upper and lower parts. The tracer test was conducted in the upper part of BHC, which covers 6 ha, consisting of 1.4 ha of open water and 4.6 ha of vegetative water area. The water depth was 40 cm during the test period.

Tracer test

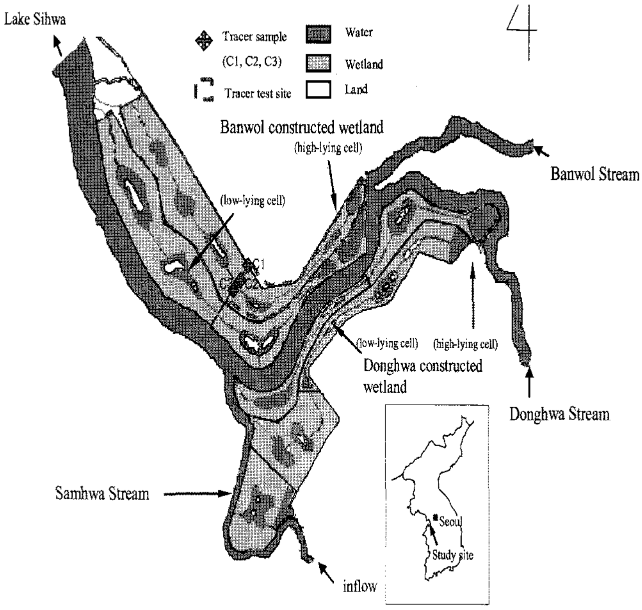

Fig. 1. Layout of the Sihwa constructed wetland and the locations of the sampling sites

Rhodamine-WT (FWT Red 50, Kingscote Chemicals) was selected as the tracer dye for measuring the hydraulic residence time. Rhodamine-WT is easily visible because of its red color, and its sorption to vegetation is relatively minor. In addition, its biological decay is believed to be negligible; therefore, it is the most common tracer used for measuring the hydraulic properties of wetlands[10,12]. However, tracer studies with rhodamine-WT that last longer than one week may need to consider photochemical decay[10,11] and the sorptive loss to sediments in shallow water is significant[11].

The tracer dye rhodamine-WT (41.7 kg) was diluted ten times with water and injected into the settling pond in the high-lying cell in the Banwol wetland on 13 October 2004. Water samples were captured in the middle of the high-lying cells in the Banwol wetland (C1, C2, C3) using auto-sampling equipment (Auto Sampler Model 6700, ISCO, USA) at 2-hour intervals (Fig. 1). A UV-spectrophotometer was used to measure the level of fluorescence in the water samples by sensing the maximum fluorescence emission at a wavelength of 560 nm. The volume of flow was calculated to estimate the mass of dye tracer at the sampling sites (C1, C2, and C3) after measuring the current speed using a current meter (Model 3000, B&P International, USA) from 10:00 until 18:00 at 2-hour intervals.

Hydraulic residence time calculation and distribution model

To describe the distribution of times that parcels of water spend in a constructed wetland, we adopted the residence time distribution for characterizing chemical reactors[5,6,13,14]. The residence time distribution function E(*t*) is determined by injecting tracer material into the wetland inlet and then measuring the tracer concentration as a function of time at the wetland outlet (Equation [1]).

$$E(t) = \frac{QC(t)}{\int_0^{\infty} QC(t)} = \frac{C(t)}{\int_0^{\infty} C(t)dt} \qquad \cdots(1)$$

Q: flow rate
C: concentration

The actual hydraulic residence time that a tracer particle spends in the wetland, is the first absolute moment of the residence time distribution function, as in Equation (2).

$$\tau = \int_0^{\infty} tE(t)dt \qquad \cdots(2)$$

The variance (2), which characterizes the spread of the tracer, is calculated from the second central moment (Equation [3]).

$$\sigma^2 = \int_0^{\infty} (t-\tau)^2 E(t)dt \qquad \cdots(3)$$

Two types of model are often used to reproduce the residence time distribution: the plug flow with dispersion model (PFD) and the tank-in-series model (TIS)3). In the TIS model, a constructed wetland is partitioned into a number of equal-sized pieces (N), each of which is presumed to act as a continuous stirred tank reactor (CSTR). The number of reactors, N, is calculated from the actual hydraulic residence time divided into the variance. When a tracer impulse is added to the inlet of a wetland, the residence time distribution function of the outlet pulse for the TIS model is given by Equation (4).

$$E(t) = \frac{N}{(N-1)!}\left(N\frac{t}{\tau}\right)^{N-1} exp\left(-N\frac{t}{\tau}\right) \quad \cdots(4)$$

N: number of CSTRs

The conversion, i.e., dividing the removal concentration in the wetland into the inlet reactant concentration, is used to measure the wetland performance in a first-order reaction. Equation (5) represents the conversion for the TIS model for N tanks.

$$X = 1 - \frac{1}{\left(1 + \left(\frac{\tau}{N}\right)\right)^N} \qquad \cdots(5)$$

A PFD model that reproduces the dispersion process superimposed by mixing and turbulence can also be applied to describe the residence time distribution. In this study, the one-dimensional version was chosen because of the high area ratio and low water depth.

$$D\frac{\partial^2 C}{\partial x^2} - u\frac{\partial C}{\partial x} = \frac{\partial C}{\partial t} \qquad \cdots(6)$$

D: dispersion coefficient
u: velocity
x: distance

The appropriate wetland boundary conditions for this study were closed vessel boundary conditions, i.e., no tracer can diffuse back from the wetland into the inlet pumping pipe or flow backward from the exit structure at the wetland outlet. Equations (7) represent the conversion in the PFD model.

$$X = 1 - \frac{4b\ exp\left(\frac{Pe}{2}\right)}{(1+b)^2 exp\left(\frac{bPe}{2}\right) - (1-b)^2 exp\left(\frac{-bPe}{2}\right)} \qquad \cdots(7)$$

$$\left(b = \sqrt{1 + 4\frac{Da}{Pe}}\right)$$

Da: Damköhler number
Pe: Peclet number

RESULTS AND DISCUSSION

Flow observations and calculated hydraulic residence time

The tracer rhodamine-WT was injected in a settling pond located at the inlet of the Banwol high-lying wetland. The injected tracer was initially concentrated on the right side and slowly dispersed throughout the pond. With time, the tracer concentration on the right side decreased rapidly, while stagnation of the tracer was observed in the middle and left side of the wetland. Accordingly, the right side of the settling pond was considered the main flow path. Once the tracer dye left the settling pond, the main tracer flow was observed in the open water area, rather than the vegetated area. The plants in the vegetated area appeared to hinder the water flow. However, some of the tracer was found along the edges of the wetland, where plant growth was dense and no water appeared to flow.

The concentrations of the tracer dye from sampling locations C1, C2, and C3 are shown in Fig. 2. The tracer was first detected at C2 14 hours after injection. The overall tracer concentration at C2 was higher than at C1 and C3.

This may have been because C2 was located in the middle of the wetland, which was mainly open water, so that less vegetation hindered the water flow. The breakthrough pattern of the tracer at C3 was similar to that at C2. The arrival and breakthrough times at C1 were greater than at C2 and C3, which may have been caused by the location of site C1 in the wetland, at a hydraulic stagnant point. In addition, the dense vegetative zone near C1 may have delayed the water flow further as the water approached this site. The total mass of recovered tracer was calculated by multiplying the tracer concentration by the flow rate. As a result, 16.6 kg of tracer were recovered from a total injected mass of 41.7 kg (recovery ratio: 40%).

A previous study reported a recovery ratio of 29% for tracer applied to a 7.2-ha constructed wetland[8].

Fig. 3 shows the tracer recovery at each sampling location. The mean residence time and variance were calculated using Equations (2) and (3), respectively. The corresponding values were 38.7 hr and 296.3 hr2. The theoretical residence time was also calculated by dividing the volume of the wetland by the inflow rate. The measured mean residence time was smaller than the theoretical residence time of 52.1 hr. These results are consistent with previous studies[5,8].

The hydraulic residence time is the principal factor in wetland design, and treatment efficiency is commonly estimated using the theoretical residence time. However, we found that the actual hydraulic residence time was shorter than the theoretical one. This might be because the water flow was not uniform throughout the wetland owing to the various hydraulic conditions, as well as the vegetative zone[3], and it was concentrated in a preferential flow path (short-circuit) where hydraulic resistance was low.

Application of a hydraulic residence time distribution model

The distribution of the HRTs within the wetland was simulated using a TIS model and the results of the tracer test. Using Equation (4), the estimated number of reactors for the Banwol high-lying wetland was five (HRT: 38.7 hr, variance: 296.3 hr^{2}). Therefore, the assumption that the experimental wetland cell consisted of five continuous reactors in series was used for the TIS model simulations. The simulated distribution of HRT was similar to the HRT measured in the tracer test (Fig. 4). The values of N estimated from the tracer test results for FWS constructed wetlands range from 2 to 5, where N= 1 indicates that the entire wetland is mixed uniformly, while greater values indicate less mixing within the wetland. As N approaches infinity, there is no mixing process; this is termed plug flow[3]. The distribution of the HRTs in the wetland was also simulated using the PFD model. The results showed that the simulated distribution agreed with the measured values (Fig. 4).

The dispersion number, which indicates the spread of the tracer, can be expressed in terms of the dispersion coefficient (D), mean velocity (u), and wetland length (L). A value greater than 0.01 represents great spread; subsequently, the response curve would be skewed to the right. Dispersion numbers for constructed wetlands commonly

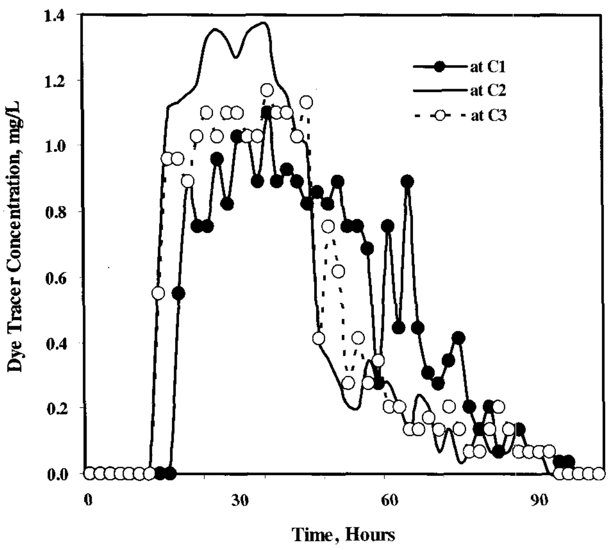

Fig. 2. Tracer concentrations at C1, C2, and C3 in the high-lying cell in the Banwol wetland

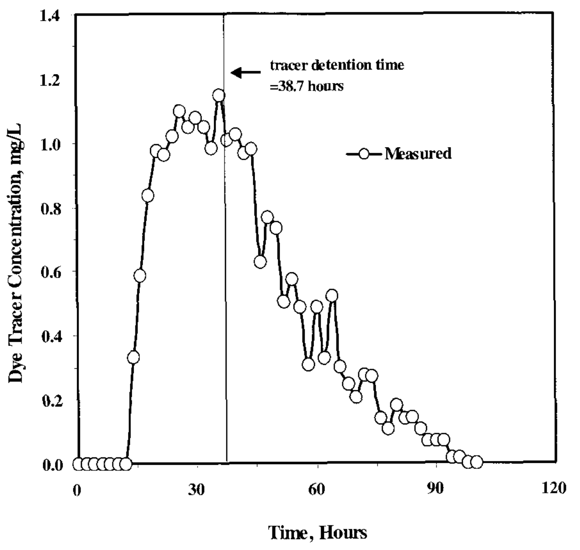

Fig. 3. Total tracer concentration curve for the high-lying cell in the Banwol wetland

range from 0.07 to 0.33[3]. The estimated dispersion number for the study wetland was 0.11

Constructed wetlands have been designed based on the assumption that the water flow in the wetland represents an ideal plug flow[15]. However, Urban[5] and Kadlec[6] indicated that this assumption is inappropriate. Assuming an ideal plug flow and using the TIS and PFD models, the first-order reaction rates (conversion rates) of pollutants for the Banwol high-lying wetland were estimated as follows:

PFR:

$$X = 1 - exp^{-38.7k} \quad \cdots (8)$$

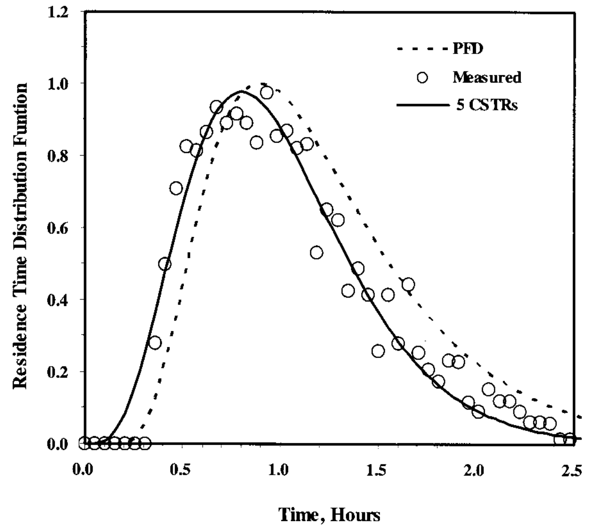

Fig. 4. Comparison of measured tracer data with the simulated residence time using the tank-in-series and plug flow with dispersion models

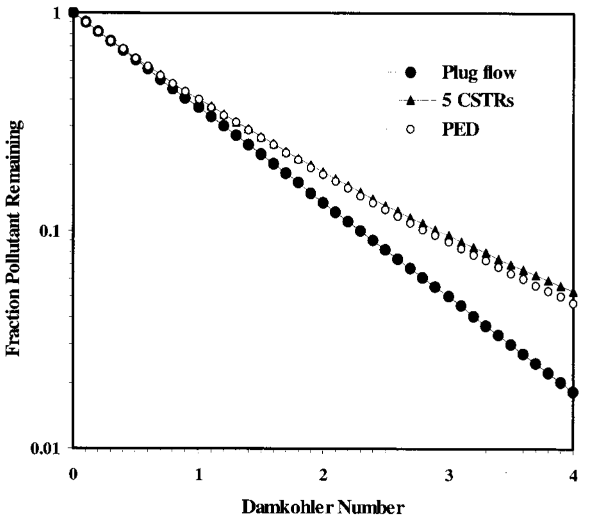

Fig. 5. Comparison of the conversion rates for the plug flow, tank-in-series, and plug flow with dispersion models

TIS model:

$$X = 1 - \frac{1}{(1+7.74k)^5} \quad ..(9)$$

PFD model:

$$X = 1 - \frac{342.5b}{(1+b)^2 exp(4.45b) - (1-b)^2 exp(-4.45b)} \quad (10)$$

$$(b = \sqrt{1+17.2k})$$

As shown in Fig. 5, the conversion rate estimated from the plug flow assumption was greater than that from the actual flow conditions. This implies that an ideal flow assumption can overestimate the pollutant-removal efficiency. It is unlikely that the water flow in a wetland represents an ideal plug flow owing to mixture4). Therefore, the HRTs in wetlands need to be characterized in order to evaluate the water purification performance of wetlands. The results presented here showed that the combination of the HRT measurement with use of the TIS and PFD models is useful for evaluating wetland performance and designing constructed wetlands. The conversion rate is also a useful parameter for optimal control of the inflow rate to increase wetland performance.

SUMMARY

A rhodamine-WT dye tracer test was used to observe the flow characteristics and to calculate the HRT of the high-lying cell in the Banwol wetland. The experiment demonstrated that water flowed continuously through the vegetated area without dead zone though the flow was mainly examined in the open water area. It was found the theoretical HRT (51.3 hrs) exceeded the observed one (38.7 hrs) due to short-circuiting of flux resulting from the irregular topography and vegetation. The simulation indicated that the simulated exit tracer concentration curves with both PFD and TIS models matched well with the observed ones. The results showed that the combination of the HRT measurement with use of these models would be useful for evaluating wetland performance.

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