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Effects of porosity on flow of free water surface constructed wetland in a physical model

Jih-Ming Chyan[a,*], Fibor Jacobe Tan[b], I-Ming Chen[a], Chien-Jung Lin[a], Delia Bantillo Senoro[b], Mario Paul Camino Luna[c]

[a]*Department of Environmental Resources Management, Chia Nan University of Pharmacy and Science, Tainan 717, Taiwan*
Tel. +886 6 266 4911 ext. 6320; Fax: +886 6 266 0266; email: mjmchyan@mail.chna.edu.tw
[b]*School of Civil, Environmental and Geological Engineering, Mapua Institute of Technology, Manila 1002, Philippines*
[c]*Office of Research and Extension, Universidad de Zamboanga, Zamboanga City 7000, Philippines*

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ABSTRACT

Despite the widespread use of constructed wetland, the parameters of its design and their operational related parameters have not yet been clearly defined. In free water surface (FWS) flow constructed wetland (CW), emergent vegetation is a primary component in pollutant removals that alters the porosity and flow pattern of water. Based on tracer experiments in a physical model, this study investigates how porosity affects hydraulic performance parameters. Experimental results indicate that, at a rather low hydraulic loading rate (*HLR*), the mean residence time (τ_m) decreases with decreasing porosity (ε). When the static and dynamic effects are balanced, the relation between ε and τ_m becomes neutral at a high *HLR*. However, the Reynolds number (N_R) can accurately predict τ_m. A rather high coefficient of multiple determination for the proposed model is 0.985. This study also investigates, how the number of tanks-in-series (*N*) under various porosities influences the flow pattern. When vegetation is lacking, *N* ranges from 1.27 to 1.94. With an increasing *HLR*, the flow pattern in CW changes from a completely stirred tank reactor to a plug flow reactor (PFR). However, when affected by porosity, the flow approaches PFR in a larger mode implying that porosity influences the flow pattern in FWS CW. The average hydraulic efficiencies without any porosity effect are approximately 0.2. In a poorly designed FWS CW, increasing *HLR* does not actively modify hydraulic efficiency. Moreover, reducing the porosity from 100 to 76% increases the mean hydraulic efficiency to 0.54. Two empirical equations for the relationships of τ_m and the actual hydraulic efficiency with N_R and the stem Reynolds number (N_{R^*}) give CW investigators or designers to have a deeper understanding of the mean residence time and the hydraulic efficiency by RTD, N_R, and N_{R^*}.

*Corresponding author.

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1. Introduction

A burgeoning population is severely straining the global water supply. Contamination by municipal, agricultural, and industrial waste degrades water resources such as rivers, oceans, and groundwater [1]. Polluted water resources can lead to a scarcity of potable water for humans, and the destruction of the aquatic ecosystem. Wastewater treatment technology can alleviate the problem of water pollution. Numerous wastewater treatment technologies are available, but they are selected according to their sustainability and reliability. Although land-intensive, constructed wetland technology is a well-established alternative for treating wastewater, especially in rural areas [2]; this technology is still mostly implemented in individual households.

Constructed wetlands (CWs) can eliminate various nutrients and pollutants (i.e. heavy metals, BOD, and toxic compounds) from contaminated waters at relatively low cost [3]. However, inadequately considering hydrological and hydraulic design requirements in the construction of wetlands could lead to problems of efficiency and operational problems since hydraulic control is a causal factor which significantly contributes to the poor performance of constructed ponds that serve as water pollution control facilities [4,5]. Many investigators have identified three hydraulic volumes or zones in wetlands: main channel, temporary storage zone (where water and constituents are exchanged with the main flow channel), and "dead water" volume since it is completely isolated [5–9]. The distributions and interactions between these zones influence the mass transportation of pollutants in CWs, which significantly contribute to pollution removal. They are connected with major mechanisms (i.e. microorganisms-degradation and plants-adsorption) for water treatment in CW [10]. Several studies have evaluated the hydraulic performance of CW using hydraulic parameters, as listed in Table 1.

For a free water surface flow CW or a subsurface flow (SSF) CW, some spaces are always occupied by vegetation or media. Since the nominal hydraulic residence or detention time (HRT) implies that the particle mass theoretically spends in a constructed wetland, the determination of HRT is not only related to water volume and flow rate. A porosity induced by vegetation or media is also considered. HRT is defined by Eq. (1) in Table 1 [11]. HRT significantly affects the removal efficiency of CW [12,13]. However, in practice, the actual residence time of pollutants remaining in the CW, as defined in Eq. (2) in Table 1, is less than the nominal residence time [2]. For estimating the actual residence time, field tracer experiments are often conducted and tracer test data commonly utilized in combination with the moment method in order to estimate τ_m [8,14–16]. This approach is characterized by the ability to determine residence time distribution (RTD), subsequently allowing for a mean residence time to be obtained for a wetland to be determined. However, this approach is limited mainly in that the tracer experiments can only be conducted in an existing wetland when τ_m is required in the design stage of a constructed wetland. Therefore, considerable attention has been paid to develop numerical or simulation models that can provide valuable information regarding the design of a constructed wetland [17].

The RTD is not easily determined from the ideal flow equations that are based on a plug flow reactor (PFR) or a completely stirred tank reactor (CSTR). The movement and direction of contaminants, as well as nutrients in CWs are often modeled using PFR and CSTR [18] and made subsequent improvements [19] by using the tanks-in-series model which is characterized by several CSTRs in series and a gamma function for describing RTD [20]. According to Eq. (3) in Table 1, tanks-in-series number can be determined from nominal residence time and the variance of RTD [21]. A value of $N=1$ implies a totally mixed flow in CW and it becomes the plug flow when $N=\infty$ [11]. N also denotes the degree of mixing in a flow system [15]. Some studies have reported N values for SSF CW, $2<N<8$, implying that the flow is neither completely mixed flow nor plug flow [2,22].

Based on the peak time of the concentration distribution at the exit (τ_p) of the RTD and τ_n, another index (i.e. hydraulic efficiency) can be established for indicating the uniformity of fluid flow inside a wetland using Eq. (4) in Table 1. A previous study suggested some criteria in which a three group classification system for hydraulic efficiency performance is characterized as good ($\lambda>0.75$), satisfactory ($0.5<\lambda<0.75$), and poor ($\lambda<0.5$) [23]. The flow uniformity in CW is affected mainly by the aspect ratio of the wetland, inlet and outlet configuration, and obstruction designation [17,23–25]. Besides the

Table 1
Hydraulic parameters used to evaluate the flow status of CW

Definitions
(1) Hydraulic retention time (HRT) or nominal residence time (τ_n):
$\tau_n = \frac{\varepsilon V}{Q} = \frac{\varepsilon Ah}{Q} = \frac{\varepsilon h}{HLR}$ (1)
(2) Actual residence time or mean residence time (τ_m):
$\tau_m = \frac{\int_0^\infty tf(t)\mathrm{d}t}{\int_0^\infty f(t)\mathrm{d}t} \quad f(t) = \frac{QC(t)}{\int_0^\infty f(t)\mathrm{d}t}$ (2)
(3) Tanks-in-series number:
$N = \frac{\tau_n^2}{\sigma^2}, \quad \sigma^2 = \frac{\int_0^\infty (t-\tau_m)^2 f(t)\mathrm{d}t}{\int_0^\infty f(t)\mathrm{d}t}$ (3)
(4) Hydraulic efficiency (λ):
$\lambda = \frac{\tau_p}{\tau_n}$ (4)

mentioned factors influencing the flow uniformity and hydraulic efficiency, poorly designed wetlands with an inappropriate layout of wetland vegetation can significantly reduce the hydraulic efficiency of a wetland system [26]. For a more precise description, the porosity induced by vegetation affects the hydraulic performance and, ultimately, the removal efficiency of pollutants. However, to our knowledge, exactly how porosity and hydraulic performance parameters are related has not been fully discussed. Therefore, this study thoroughly elucidates how vegetation porosity influences mean residence time, tanks-in-series number, hydraulic efficiency, and corresponding empirical estimation equations of mean residence time and hydraulic efficiency. The study presents empirical equations for estimating mean residence time and hydraulic efficiency. Results of this study provide a valuable reference for CW investigators or designers attempting to qualitatively understand the hydraulic effects of wetland vegetation on the flow in a wetland system.

2. Materials and methods

This study attempted to investigate how vegetation, i.e. porosity, affects hydraulic flow pattern in a FWS constructed wetland by installing an indoor laboratory experimental setup. According to Fig. 1, a clear tempered glass tank (T-1) was used as a CW tank with dimensions of 100 cm long, 30 cm width, and 30 cm high. The porosity induced by vegetation in a horizontal FWS CW was simulated by vertical plastic pipes. Water column in the reactor was maintained at 20 cm. Four sets of porosities were tested including 100% (no plants), 92%, 84%, and 76%, respectively [4,27,28]. Additionally, a constant head tank (T-2) was devised to provide constant volumetric flow of water for each *HLR* and porosity. Water was supplied from tank (T-3) to tank (T-2) by a pump. Tank (T-3) was refilled continuously with tap water from a water source. Samples were collected directly from the effluent pipe at T-4.

In the tracer experiments, a fluorescent dye (i.e. Rhodamine WT) was used as a tracer and injected in a pulse mode with an initial concentration of 100 ppm and a total volume of 10 mL. At the same moment, samples taken at the effluent were collected and analyzed immediately of tracer concentrations using Spectrofluorometer (Jasco, model no.: FP-750). To maintain data quality, all calibration curves between dye concentrations and measurement results from the Spectrofluorometer possessed coefficients of multiple

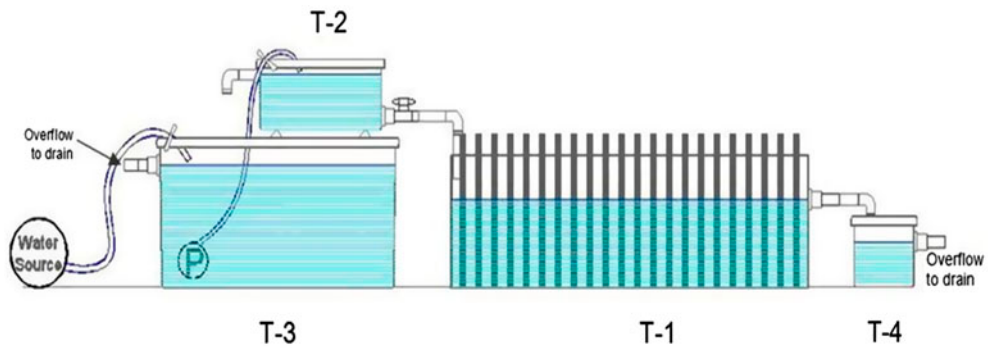

Fig. 1. Laboratory setup for simulating flow patterns induced by artificial vegetation.

determination (R^2) larger than 0.999. The mass recoveries of tracer for all tests were controlled to be larger than 90%. For every test run, large scale recirculation with various flow patterns may form, possibly resulting in different RTDs if the flow is not stable. These features influence the accuracy of the results of this study and can be avoided by a longer operational period before the tracer injection.

The experiments were completed with 3 sets of *HLR*s whose averages are 98 cm/d for RUN A, 282 cm/d for RUB B, and 425 cm/d for RUN C. At each *HLR*, 4 sets of porosity models were carried out 100% (no plants), 92%, 84%, and 76%. To more thoroughly understand the FWS CW flow, Reynolds number and stem Reynolds number, $N_R = v \times h/\nu$ and $N_{R^*} = v \times D_S/\nu$, were introduced as control parameters. Where v, ν, and D_S denote the approaching velocity, kinematic viscosity, and stem diameter of the emergent vegetation, respectively. The approaching velocity is calculated by $v = [Q/(\varepsilon \times V/L)]$ where L represents the length of an experimental model. In most field situations, the Reynolds number of CW system is maintained at $1 < N_R < 100$, while the distribution range of stem Reynolds number vary from 5 to 20 [29]. In this study, for considerations of real actual flow conditions in field CW, the corresponding control hydraulic properties of the experiments; ε, τ_n, and Q, were set beforehand and the ranges of N_R and were arranged as 13.2–72.0 and 1.83–13.55, respectively. Table 2 summarizes those results of control hydraulic properties. The tracer experiments for each *HLR* and porosity were tested 2 to 3 times to ensure the acceptable reproducibility of the time series curves of tracer concentrations [$C(t)$]. Based on the concentration data of a complete tracer test run, the RTD function can be derived from Eq. (2) in Table 1. Then, by Eqs. (3) and (4), the flow characteristics in FWS CW under porosity effects can be investigated through N and λ.

3. Results and discussion

3.1. Porosity effects on mean residence time and its prediction

The experiments were conducted at 4 porosities, i.e. 76% 84%, 92%, and 100%, respectively. For a FWS CW in steady operation, the porosities range from 0.65 to 0.75 [4]. According to Table 2, all tracer mass recoveries are kept to be larger than 90%, which is important in controlling the quality of experimental data. Fig. 2 shows one of experimental results whose porosity is 100%. The three tracer concentration tests closely resemble each other. Flow stability in the experimental model is essential to ensure data quality. Owing the experimental model configuration is quite simple, only a single peak is found for all tracer concentration lines; this feature implies that the flow in the experimental model is in a simple mode [23]. After the peak tracer arrives at the exit, the tracer is diluted when moving in the circulation; in addition, the tracer concentration in the following effluent decreases gradually. Fig. 2 illustrates a long tail that is formed by the tracer.

By using Eq. (2), RTD and a mean residence time can be determined. Fig. 3 shows the relations between the mean residence time and porosity under different *HLR*. Eq. (1) implies that a nominal residence time decreases linearly with decreasing porosities for a specific *HLR* and mean water depth. For RUN A (average $HLR = 98$ cm/d), as shown in Fig. 3, the variations of mean residence time vary with porosity. When the porosity decreases 24% from 100% to 76%, according to Eq. (1), a comparable decrease shall occurs in the nominal residence time. However, an average decrease of 20.3% is found for the mean residence time of RUN A. According to results of RUN B in Fig. 3, an increasing *HLR* (282 cm/d) leads to a slighter decrease of mean residence time of 15.4%. For a higher *HLR* (425 cm/d), the porosity negligibly

Table 2
Hydraulic properties in tracer test runs

Runs	Porosity (%)	τ_n (min)	Q (mL/min)	HLR (cm/d)	Tracer mass recovery (%)	N_R	N_{R^*}
A	100	271	212	102	93	13.2	—
	92	251	211	101	92	14.3	1.83
	84	251	192	92	106	14.2	2.62
	76	214	204	98	104	16.7	3.02
B	100	99	580	278	92	36.1	—
	92	91	580	278	93	39.2	5.50
	84	82	590	283	93	43.7	7.88
	76	73	600	288	96	49.1	9.07
C	100	64	900	432	90	56.0	—
	92	61	870	418	94	58.8	8.25
	84	54	890	427	100	65.9	11.83
	76	50	880	422	102	72.0	13.55

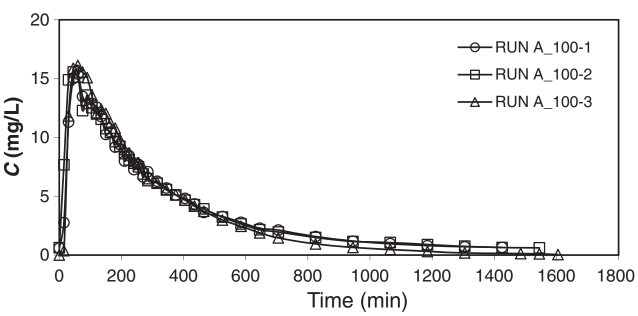

Fig. 2. Sample residence time distribution of fluorescent dye tracer concentration; (RUN A).

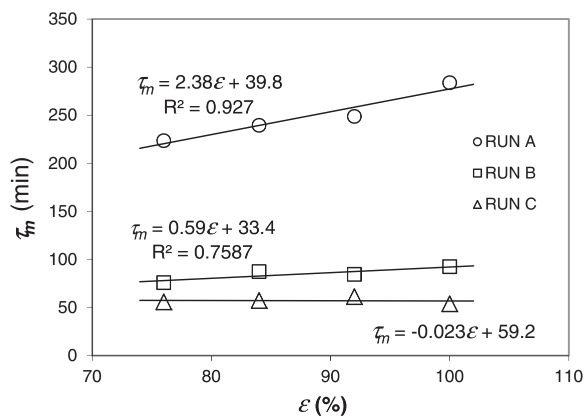

Fig. 3. Variations of mean residence time with porosities under various *HLR*s.

affects the mean residence time. As matter of fact, the slope in Fig. 3 is an index interpreting the effect of porosity on the mean residence time. The qualitative relation can also be derived from Eq. (1) and described as followed:

$$\frac{d\tau_n}{d\varepsilon} = \frac{h}{HLR} \tag{5}$$

For a given mean water depth, the variations of nominal residence time are not affected by the porosity when $HLR \fallingdotseq \infty$. Since τ_m is closely connected to τ_n, a similar feature is observed in RUN C when $HLR > 425$ cm/d and $N_R > 56$. At low Reynolds number, the fluid flows under a static condition. Additionally, a displacement of fluid mass induced by submerged vegetation accelerates the flow velocity, inevitably decreasing the mean residence time. However, with an increasing *HLR*, the flow in CW gradually transfers from a static condition to a dynamic one. The vegetation produces an additional drag force, subsequently forming an adverse effect on the variations of mean residence time. When static and dynamic effects are balanced, the porosity induced by vegetation negligibly affects the mean residence time [30].

A mean residence time represents an actual period of pollutant mass remaining in CW and is closely connected to the removal efficiency of pollutants. A better understanding for the variations of τ_m is very valuable for the applications of CW. Due to the flow patterns in CW plays an important role in the characteristics of τ_m, N_R is a dimensionless parameter widely used to describe the flow pattern. After closely examining the results of mean residence time, the results reveals a linear relation between the natural logarithms of N_R andτ_m. As shown in Fig. 4, the best fitting line can well interpret the relation of τ_m and N_R since the coefficient of multiple determination, R^2, is

0.9854. For a given design parameters, i.e. *HLR*, porosity, length of CW, water depth, and dynamic viscosity, N_R can be determined to estimate the corresponding τ_m using by Eq. (6).

$$\tau_m = e^{-0.99 \times \ln(N_R) + 8.15} \quad (6)$$

The above empirical equation well explains the relation of τ_m and N_R in the N_R range between 13.2 and 72. However, as N_R approaching 0, τ_m becomes a constant which is not a reasonable prediction. It implies that the relation between τ_m and N_R does not follow Eq. (6) at a lower N_R.

3.2. Porosity effects on flow patterns

To facilitate visualization of the curves at a common time parameter for comparisons, RTDs of the tracer experiments are normalized by mean residence time for the time axis and by peak concentration for tracer concentration. Fig. 5 shows the corresponding results. The RTDs under different experimental conditions exhibit various patterns. No similarity exists in the flow of FWS CW and an empirical prediction becomes a hard topic to overcome. According to the experimental results of RUN A in a considerably low *HLR*, the peak concentration of ε = 100%, occurs at the dimensionless peak time or actual hydraulic efficiency, t_p/τ_m, which is close to the origin. This feature suggests that the flow pattern is close to CSTR whose $t_p/\tau_m = 0$ [11]. Under this situation, all water parcels are almost completely mixed and have an equal probability of leaving the wetland at a given moment [8]. However, with a gradually decreasing porosity, t_p/τ_m moves away from the origin and the flow more closely resembles a plug flow. The porosity formed by vegetation not only changes the flow pattern in FWS CW but delays the dimensionless peak time. For a

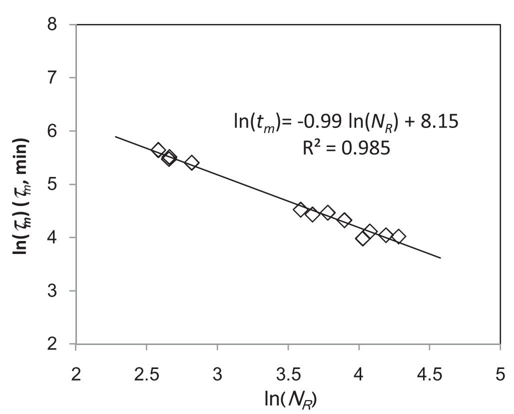

Fig. 4. Relations between Reynolds number and mean residence time.

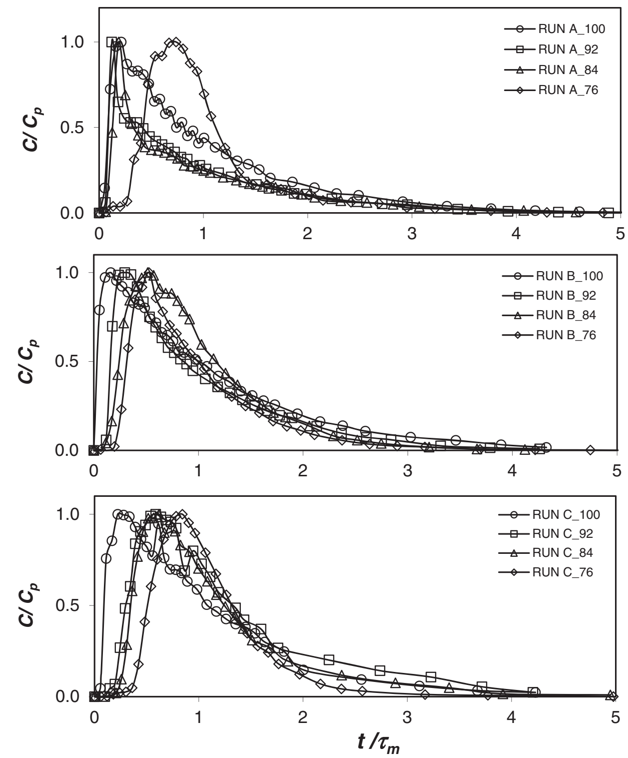

Fig. 5. Comparison of RTDs with porosities 76, 84, 93, and 100% at different *HLR*s.

given porosity (i.e. ε = 100%) t_p/τ_m also increases, and a higher *HLR* changes the flow pattern from CSTR to PFR. In this study, the *HLR* increases from 98 cm/d to 425 cm/d while the porosity decreases by 24%. Moreover, comparing the changes in t_p/τ_m reveals that porosity plays an significant role in turning the flow pattern in CW from CSTR towards PFR.

A similar conclusion can be also found in the results of number of tanks-in-series, as shown in Fig. 6. The plot of the number of tanks-in-series at different *HLR*s versus porosity indicates an increasing *N* with a decreasing porosity. As *N* represents the degree of mixing of tracer or pollutant as in the actual case, a higher *N* corresponds to a lower degree of dispersion. When $N = 1$, the flow is a CSTR; which becomes a PFR as $N = \infty$ [11]. The results of *N* in this experiment are consistent with those of actual wetlands. At higher porosities (i.e. 100% and 92%) the smallest *N* is 1.27, meanwhile at lower porosities (i.e. 84% and 76%), the highest *N* value is 4.9, which resembles the range, 2 to 5, of related research [11]. During investigation of the porosity effect, Fig. 6 reveals that, as the *HLR* increases from 98 to 425 cm/d, *N* increases from 1.27 to 1.94 when there is no effect of porosity (ε = 100%). For a given porosity of 100%, a higher *HLR* induces a larger *N*, which promotes the flow pattern toward PFR.

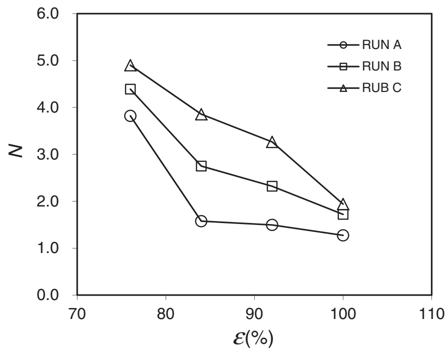

Fig. 6. Variations of number of tanks-in-series affected with different porosity.

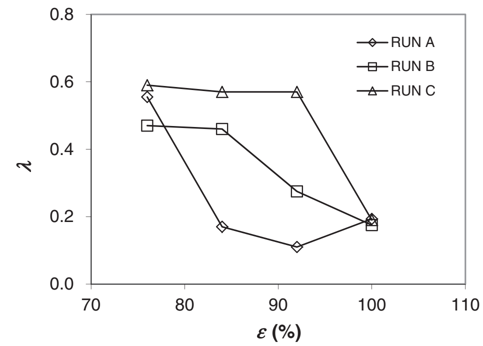

Fig. 7. Effects of porosity on hydraulic efficiencies of FWS CW at various *HLR*s.

However, *HLR* does not increase *N*, proportionally. For the porosity of 92%, a wider ranges of numbers of tanks-in-series, $1.50 \sim 3.24$, is observed than it acts in the porosity of 100%. When the porosity decreasing, the porosity induced by vegetation creates additional lateral mixing [29]. The porosity changes the flow pattern and increases the lateral mass transportation, subsequently facilitating the flow towards PFR. The porosity plays a more important role than *HLR* do in the change of the flow pattern in FWS CW.

3.3. Porosity effects on hydraulic efficiency and its prediction

Hydraulic efficiency plays a prominent role in the design of CW, especially if the problem of short-circuiting is of concern [15]. This study also examines the relation between porosity and hydraulic efficiency. Fig. 7 illustrates the variations of hydraulic efficiency under porosity effects. This figure reveals a general trend in which hydraulic increases with a decreasing porosity, which denotes an increase of vegetation. Experimental results indicate that time of peak concentration, τ_p, increases with a decreasing porosity. Since hydraulic efficiency is a function of the time of peak, the delay in the time of the maximum concentration increases the hydraulic efficiency. For the 100% porosity, at all 3 *HLR*s (RUN A, RUN B, and RUN C), the hydraulic efficiencies measured have similar values at around 0.20, which implying poor hydraulic efficiency. As a matter of fact, hydraulic efficiency is related to the aspect ratio of the wetland, inlet, and outlet configuration, and obstruction designation [17]. The configuration of the inlet and outlet in this study is horizontally point to point subsequently resulting in a poor hydraulic efficiency. *HLR* increasing by 4.34 times does not improve the hydraulic efficiency of a FWS CW with a poor design.

However, when vegetation is introduced, hydraulic efficiency of the different *HLRs* varies. At a lower *HLR* (i.e. RUN A), a drop in hydraulic efficiency at 92 and 84% porosities is due to the early peak attributed to short-circuiting. The stems function as preferred channels of flow considering that at this *HLR* (which is at low N_{R^*} values), the flow around the cylinder remains intact since no flow separation occurs [31]. However, at a porosity of 76%, N_{R^*} approaches 4.0 and the possibility of eddy formation may eliminate the preference for channeling. This feature increases the hydraulic efficiency. At higher *HLR*s (i.e. RUN B and RUN C), a decreasing porosity increases the hydraulic efficiency. At the lowest porosity (76%), the hydraulic efficiency is at its highest with an average of $\lambda = 0.54$ or 54%. Different *HLR* may induce specific flow patterns or organized structures whose influence on hydraulic efficiencies acts in different ways. But, there seems exist a limit in the hydraulic efficiency. An additional porosity induced by vegetation can improve hydraulic efficiency from 0.19 to 0.59.

For a CW investigator or designer, hydraulic efficiency plays a major role when considering the problem of short-circuiting. According to Eq. (4), hydraulic efficiency is defined by the ratio of the peak time and nominal residence time which is easily calculated. However, τ_n always differs from mean residence time or actual residence time. It makes variations of λ cannot show a real situation in CW. A new parameter showing the characteristic of hydraulic efficiency close to a more real situation in CW is needed. An actual hydraulic efficiency under various porosities, λ_m, is defined as the ratio of peak time to mean residence time. This study develops an empirical equation, Eq. (6), of mean residence time. Of priority concern in CW design is to develop another empirical prediction equation of actual hydraulic efficiency. Due to the vegetation in FWS CW affects the variation of λ,

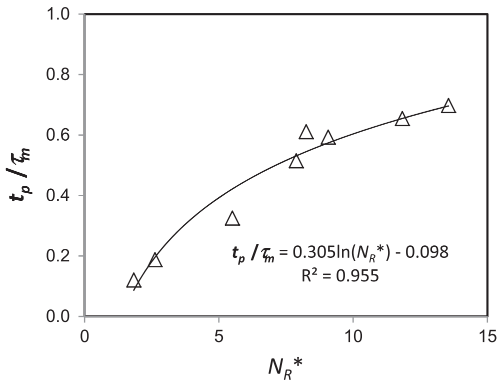

Fig. 8. Relations between the stem Reynolds number and actual hydraulic efficiency.

a new Reynolds number based on the stem diameter is introduced to establish an empirical relation. As shown in Fig. 8, the actual hydraulic efficient is closely related to the stem Reynolds number and the coefficient of multiple determination of the best fitting equation is 0.955. The proposed empirical equation is expressed as follows:

$$\lambda_m = \frac{t_p}{\tau_m} = 0.305 \times \ln(N_{R^*}) - 0.098 \tag{7}$$

Based on Eqs. (6) and (7), the mean residence time, actual hydraulic efficiency, and peak time are mutually correlated. The hydraulic efficiency can then be estimated and compared with the criterion normally used in the related studies. However, although the mean residence time and actual hydraulic efficiency by Eqs. (6) and (7), these relations are established in a small physical model with a simple configuration. We suggest that, in the actual design of FWS CW, these empirical equations shall be applied with caution.

4. Conclusions

This study thoroughly elucidates how porosity affects the flow in FWS CW. Experimental results based a small physical model indicate that τ_m decreases with a decreasing ε at a low *HLR*. Additionally, the relation between τ_m and ε becomes neutral at a higher *HLR*. However, the variations of τ_m is closely related to N_R, and a satisfactory empirical equation is proposed with a rather high coefficient of multiple determination, 0.985. Moreover, an increasing *HLR* or velocity transforms the flow pattern in CW from CSTR towards PFR. Experimental results further indicate that porosity plays a more active role in this process. Furthermore, porosity increases hydraulic efficiency of FWS CW. This study also develops two empirical equations that allow the estimate of the mean residence time, the actual hydraulic efficiency, and the hydraulic efficiency by RTD, N_R, and N_{R^*}. These empirical equations significantly contribute to understand the effects of porosity on the hydraulic characteristic of a FWS CW.

Acknowledgments

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Nomenclature

τ_n	—	nominal residence time, min
V	—	volume of water without vegetation in the wetland, cm^3
ε	—	water volume fraction in a water column or porosity[=(V-V_S)/V], cm^3/cm^3, V_S: vegetation volume under water surface
C(t)	—	exit tracer concentration, mg/L
f(t)	—	residence time distribution (RTD), 1/min
N	—	tanks-in-series number
τ_p	—	peak time of the concentration distribution at the exit, min
Q	—	flow rate, L/min
A	—	wetland area (wetted land area), cm^2
HLR	—	hydraulic loading rate (=Q/A), cm/d
h	—	mean water depth, cm
τ_m	—	actual residence time, min
t	—	time, min
λ	—	hydraulic efficiency

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