Ecological Engineering 61 (2013) 200–206

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

A correction coefficient for pollutant removal in free water surface wetlands using first-order modeling

Shang-Shu Shih[a,*], Pin-Han Kuo[b], Wei-Ta Fang[c], Ben A. LePage[d]

[a] Hydrotech Research Institute of National Taiwan University, Taiwan
[b] Department of Hydraulic and Ocean Engineering of National Cheng Kung University, Taiwan
[c] Graduate Institute of Environmental Education of National Taiwan Normal University, Taiwan
[d] Pacific Gas and Electric Company, USA

ARTICLE INFO

Article history:
Received 19 April 2013
Received in revised form 9 August 2013
Accepted 20 September 2013

Keywords:
Hydraulic retention time
Residence time distribution
Aspect ratio
Water depth
First-order model
Correction coefficient

ABSTRACT

Pollutant removal in free water surface wetlands (FWS) for practical purposes is calculated using the simplified hydraulic retention time (HRT) of the first-order model. Although the residence time distribution (RTD) represents the hydraulic conditions seen in natural wetlands better when compared to the HRT, the RTD is more difficult to calculate. It is crucial to determine the situations that the first-order model would have good performance and quantify the difference between HRT and RTD. In this study, the correction coefficient for the first-order model is presented and examined through 28 numerical experiments. The relationship between the correction coefficient and the related hydraulic efficiency is also established and discussed. The refining results show that the aspect ratio has a logarithmic trend while the water depth has turned an exponential trend with the variant correction coefficients. Higher aspect ratios or lower water depths can ensure better pollutant removal estimation by the first-order model. Both water depth and aspect ratio influence correction coefficients; however, water depth is the factor that has a greater impact. It is suggested that the first-order model is employed for shallow water wetlands with water depths lower than 0.8 m and narrow long wetlands with aspect ratios higher than 1.20 without modification. We also concluded that the first-order model could be more widely and adequately used for practical purposes after modification by the correction coefficients. Furthermore, increasing water depth and decreasing aspect ratio resulted in lower hydraulic efficiency. Wetland designers should avoid selecting a dysfunctional plan when designing deep water and low aspect ratio constructed wetlands.

1. Introduction

Free water surface (FWS) wetlands are a type of constructed wetland (CW) combining open-water areas of varying water depths, soil to support emergent vegetation, and a sub-surface barrier to prevent seepage (USEPA, 2000). CWs are designed to control water retention time and hydraulic pathways (Brix, 1993). The primary function of FWS wetlands is to treat wastewater by removing pollutants, such as biochemical oxygen demand (BOD) and nitrogen, using natural microbial, biological, physical, and chemical processes. Pollutant removal is an important metric used for evaluating the effectiveness of FWS wetlands for water quality improvement (Reed et al., 1995). Hsu et al. (2011) indicated that the Hsin-Hai II and the Daniaopi Constructed Wetlands achieved maximum functional performance in reducing the concentrations of total nitrogen, total phosphorus, loadings of biochemical oxygen demand (BOD), and chemical oxygen demand (COD) from municipal sewage.

The most common method to estimate pollutant removal in CWs is to use a first-order model that includes the hydraulic retention time (HRT) of the water flowing through the wetland (USEPA, 1988; Reed et al., 1995). The first-order model is deterministic in that it indicates the wetland output concentrations in response to input concentrations, flow discharge and detention volume (Kadlec, 2000). The HRT is calculated by assuming an aquatic system with uniform unrestricted water flow with no mixing and/or diffusion and a nominal retention time (Su et al., 2009). However, such conditions are rarely present in FWS wetlands because water flow through wetlands is not spatially and temporally uniform (Fisher, 1990; Urban, 1990; Stairs, 1993; Kadlec, 1994; Kadlec and Knight, 1995; Werner and Kadlec, 1996).

Constructed wetland parameters such as aspect, bottom topography, water depth, vegetation, obstructions, and inlet/outlet position all influence wetland hydrodynamics, which ultimately

* Corresponding author. Tel.: +886 2 33662624; fax: +886 2 33662624.
E-mail addresses: uptreeshih@ntu.edu.tw, uptreeshih@gmail.com (S.-S. Shih).

0925-8574/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecoleng.2013.09.054

determines the retention time and hydraulic and treatment efficiency (Thackston et al., 1987; Konyha et al., 1995; Shilton and Prasad, 1996; Ta and Brignal, 1998; Koskiaho, 2003; Su et al., 2009). Su et al. (2009) and Holland et al. (2004) indicated that the most influential parameters are aspect ratio and water depth. The residence time distribution (RTD) quantifies the distribution of retention time for a given wetland (Kadlec, 1994). The RTD approach considers the mixing, diffusion, and residence time distribution of fluids (Levenspiel, 1972; Kadlec, 2000), and is thus an advanced tool for science and engineering purposes (Holland et al., 2004). As such, the RTD represents the hydraulic conditions seen in natural wetland ecosystems better when compared to the HRT. Therefore, to model the water flow conditions in reaction vessels such as constructed wetlands more accurately and ultimately obtain a more realistic pollutant removal value, the RTD, rather than HRT is being used with scientific rigor (Werner and Kadlec, 1996; Kadlec, 2003; Su et al., 2009).

Despite the limitations and inadequacy of the HRT approach, the HRT is more widely applied than the RTD for practical purposes because it is much easier to calculate. However, few studies quantified the relationship between these two approaches. The objective of this study is to examine the difference between these two approaches and present the correction coefficients of the first-order model. The correction coefficient is defined as the pollutant removal calculated using the RTD approach divided by that found using the HRT approach under situations of different aspect ratios and water depths. The suitability of using the conditions of aspect ratio and water depth in the HRT method will also be discussed.

2. Materials and methods

2.1. Hydraulic retention time (HRT) approach

The following equation is a simplified HRT approach for calculating pollutant removal.

$$R_{\mathrm{HRT}} = 1 - \frac{C_e}{C_i} = 1 - e^{-K_t t_{\mathrm{HRT}}} \tag{1}$$

where, e is the exponential notation ≈ 2.718282; C_e is the effluent concentration, mg/L; C_i is the influent concentration, mg/L; k_t is the first-order rate constant = 0.3/day (Taiwan EPA, 2008); t_{HRT} is the retention time calculated by the HRT approach estimated from the volume of water divided by the daily discharge, days; and R_{HRT} is the calculated pollutant removal using the HRT approach.

Eq. (1) implies that the microbial and biochemical processes are synchronous. Therefore, pollutant removal is dependent on the k_t and t_{HRT}. A number of studies have indicated different values of k_t for local purposes (USEPA, 1988; Hammer, 1989; Cooper et al., 1996) and the k_t in this study was determined to be 0.3/day for both of the HRT and RTD approaches (Taiwan EPA, 2008).

2.2. Residence time distribution (RTD) approach

The RTD approach considers the mixing, diffusion, and residence time distribution of a fluid in a reactor vessel (Fig. 1) and models the flow conditions of fluids in a reactor better than the HRT method (Levenspiel, 1999). The simplest way to obtain the RTD of a reactor is by using a pulse experiment that evaluates RTD using a tracer test or numerical simulation (Su et al., 2009).

Using the RTD model the pollutant removal (R_{RTD}) is computed using the following equation:

$$R_{\mathrm{RTD}} = 1 - e^{-K_t t_{\mathrm{RTD}}} \tag{2}$$

where, e is the exponential notation ≈ 2.718282; k_t is the first-order rate constant = 0.3/day (Taiwan EPA, 2008); t_{RTD} is the residence time calculated by the RTD approach with the numerical model, TABS-2, days; and R_{RTD} is the calculated pollutant removal using the RTD approach.

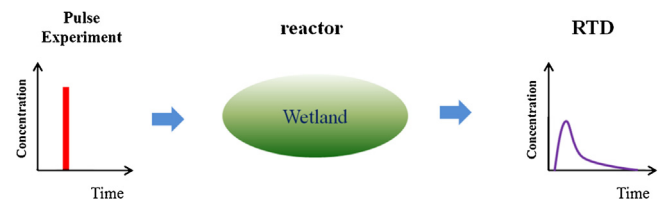

Fig. 1. Illustration of a pulse experiment in a constructed free water surface wetland where the wetland is a large reactor vessel. The RTD was used to calculate the real pollutant removal performance.

2.3. Correction coefficient for the first-order model

The correction coefficient (C_r) is defined as the pollutant removal calculated using the RTD approach divided by that found using the HRT approach. The C_r for the first-order model is calculated using Eq. (3) and the value of the C_r ranges from 0 to 1.

$$C_r = \frac{R_{\mathrm{RTD}}}{R_{\mathrm{HRT}}} = \frac{1 - e^{-K_t t_{\mathrm{RTD}}}}{1 - e^{-K_t t_{\mathrm{HRT}}}} \tag{3}$$

where, e is the exponential notation ≈ 2.718282; R_{HRT} is the calculated pollutant removal using the HRT approach; R_{RTD} is the calculated pollutant removal using the RTD approach; and C_r is the correction coefficient for the first-order model.

2.4. Hydraulic efficiency

The performance of wastewater treatment facilities such as constructed FWS wetlands is closely related to their hydraulic efficiency (Kadlec, 2000; Kadlec and Knight, 1995; Dal and Persson, 2000; Dierberg et al., 2005). The hydraulic efficiency is calculated as shown in the following equation (Persson et al., 1999):

$$\lambda = \frac{t_p}{t_n} \tag{4}$$

where, t_p is the time of pick outflow concentration, day; t_n is the nominal detention time, day; and λ is the hydraulic efficiency.

2.5. Numerical experiments

To determine the impact of different physical aspects on residence time distribution and hydraulic efficiency we performed a series of numerical experiments. TABS-2 is a horizontal two-dimensional hydrodynamic and water quality transport model that can be used to simulate a tracer pulse experiment to obtain the RTD of a FWS wetland. It includes three modules: RMA2, RMA4, and SED-2D. The hydrodynamic model (RMA2) and water quality transport model (RMA4) were implemented in our numerical experiment. The RMA2 is the two-dimensional depth averaged finite element hydrodynamic model for computing water surface elevations and horizontal velocity components of the subcritical free-surface flow field which Froude number is lower than 1.0 (Donnell, 1997). The RMA4 is the finite element water quality transport model in which the depth concentration distribution is assumed uniform (King, 2003). The boundary conditions of the RMA2 model are the flow discharge in the inlet and the water level in the outlet; while the boundary condition of the RMA4 is pollutant concentration in the inlet. The water depth and water velocity simulated from the RMA2 model were input to the RMA4 model from time to time as a fundamental flow field at each time step.

Table 1
Calculated results of the pollutant removal performance of the HRT and RTD approaches and the related correction coefficients with water depth 0.7 m and different aspect ratios.

Example	Aspect ratio	t_{HRT} (day)	R_{HRT} (%)	t_{RTD} (day)	R_{RTD} (%)	C_r	λ	First-order model performance
1A	0.21	0.61	16.7	0.50	13.9	0.84	0.04	Poor
1B	0.30	0.61	16.7	0.51	14.3	0.86	0.06	Poor
1C	0.53	0.61	16.7	0.52	14.5	0.87	0.11	Poor
1D	0.83	0.61	16.7	0.53	14.8	0.89	0.26	Poor
1E	1.20	0.61	16.7	0.54	15.0	0.90	0.33	Satisfactory
1F	1.88	0.61	16.7	0.56	15.4	0.92	0.43	Satisfactory
1G	2.13	0.61	16.7	0.56	15.5	0.93	0.45	Satisfactory
1H	3.33	0.61	16.7	0.57	15.8	0.95	0.56	Satisfactory
1I	4.80	0.61	16.7	0.58	15.9	0.95	0.64	Satisfactory
1J	7.50	0.61	16.7	0.59	16.2	0.97	0.73	Satisfactory
1K	11.72	0.61	16.7	0.59	16.3	0.98	0.81	Good
1L	13.33	0.61	16.7	0.60	16.4	0.98	0.83	Good
1M	20.83	0.61	16.7	0.60	16.5	0.99	0.88	Good
1N	30.00	0.61	16.7	0.60	16.5	0.99	0.92	Good

The parameters of TABS-2 were set following those of Kuo et al. (2008) and Su et al. (2009), and include: 0.03 for Manning's roughness value; 25 °C for temperature; 50 (Pa s) for eddy viscosity; and 0.05 (m^2/s) for the diffusion coefficient.

Variations in aspect ratio and water depth were developed and investigated as follows:

(1) Aspect ratio

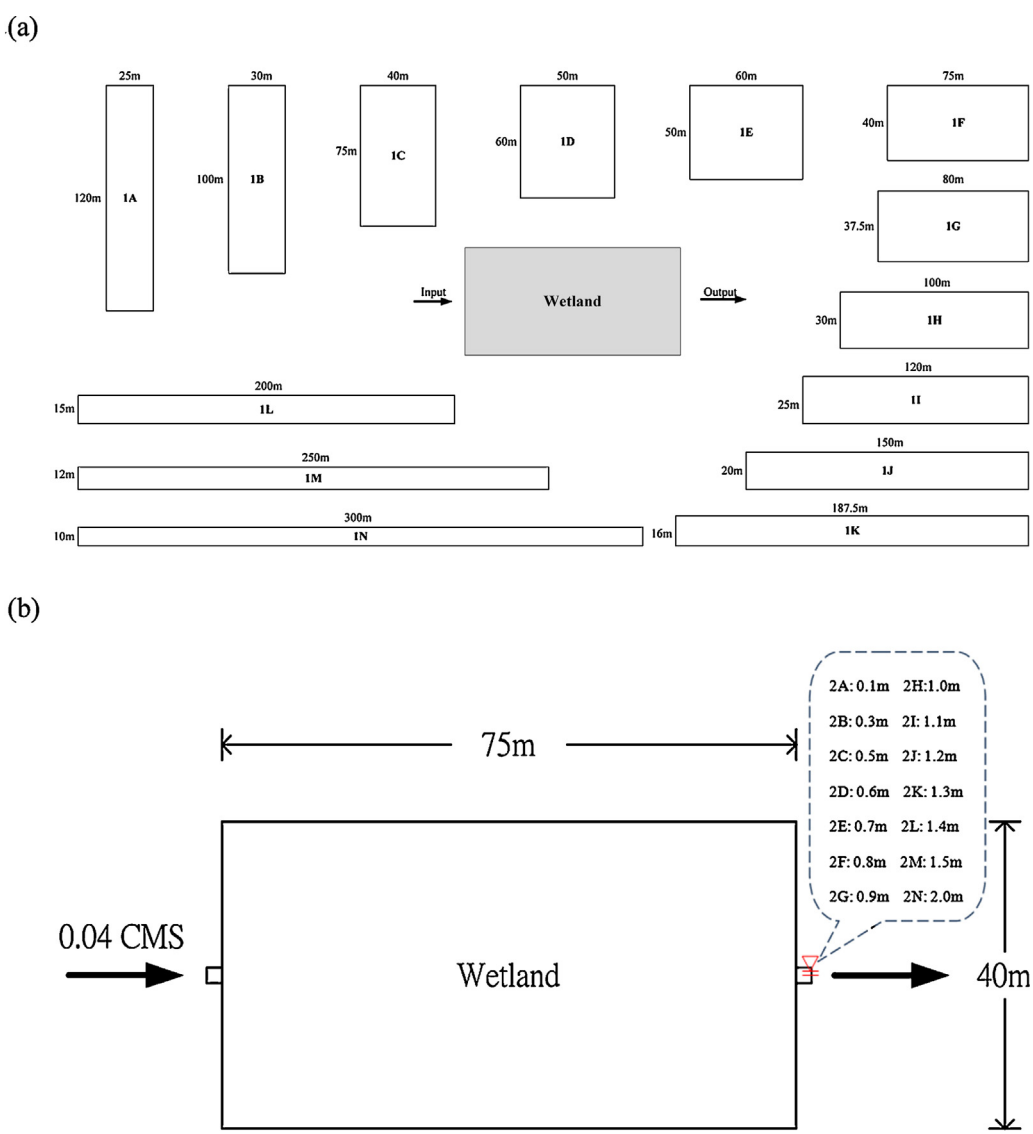

Fig. 2. Fig. 2a illustrates the fourteen reaction vessels with different aspect ratios. Fig. 2b illustrates a reaction vessel and the fourteen scenarios based on different water depths.

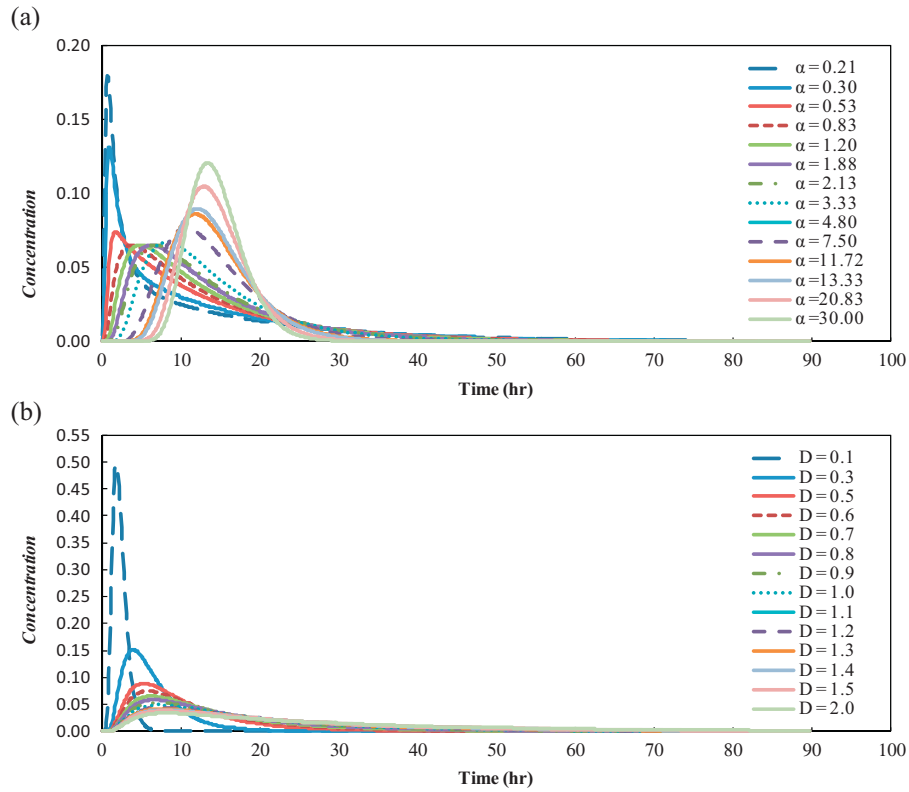

Fig. 3. Fig. 3a illustrates the RTDs of the fourteen modeled scenarios that were based on different aspect ratios. Fig. 3b illustrates the RTDs of the fourteen modeled scenarios that were based on different water depths.

Fourteen scenarios with different aspect ratios were modeled. The aspect ratio was calculated by the wetland length divided by wetland width. The wetland length and wetland width are defined as the lengths that are parallel and perpendicular to flow direction. Details of the dimensions and corresponding aspect ratios are provided in Table 1 and illustrated in Fig. 2a. The inlets and outlets are located at the midpoint–midpoint and the design parameters of each example were consistent: area 3000 m^2; water depth 0.7 m; inflow of 0.04 m^3/s; and an HRT of 0.61 days. We adopted example 1F from our previous study as the reference example (Su et al., 2009).

(2) Water depth

Fourteen scenarios with different water depths were modeled and the results are provided in Table 2 and illustrated in Fig. 2b. Water depths varied from 0.1 m to 2.0 m and the aspect ratio was set as 1.88 (reference example), which corresponds to a reaction vessel dimension of 75 m long and 40 m wide. Example 2E is used as the reference example for this model because examples 1F and 2E have the same dimensions with an aspect ratio of 1.88 and therefore, we can compare the influence and effectiveness of aspect ratio versus water depth on pollutant removal directly.

3. Results and discussion

The results of the modeled scenarios are provided in Tables 1 and 2. The RTD values are illustrated in Fig. 3 and demonstrate that water flow conditions and RTD values were strongly influenced by changes in the aspect ratio and water depth. Our results confirm those of Kuo et al. (2008) that indicate that pollutant removal is over-estimated when computed using the HRT

Table 2
Calculated results of pollutant removal performance of the HRT and RTD approaches and the related correction coefficients with aspect ratio 1.88 and different water depths.

Example	Water depth (m)	t_{HRT} (day)	R_{HRT} (%)	t_{RTD} (day)	R_{RTD} (%)	C_r	λ	First-order model performance
2A	0.1	0.09	2.6	0.09	2.6	1.00	0.86	Good
2B	0.3	0.26	7.5	0.26	7.5	1.00	0.62	Good
2C	0.5	0.43	12.2	0.42	11.9	0.97	0.50	Satisfactory
2D	0.6	0.52	14.5	0.49	13.7	0.95	0.46	Satisfactory
2E	0.7	0.61	16.7	0.56	15.4	0.92	0.42	Satisfactory
2F	0.8	0.69	18.8	0.62	17.0	0.90	0.39	Satisfactory
2G	0.9	0.78	20.9	0.67	18.2	0.87	0.36	Poor
2H	1.0	0.87	22.9	0.72	19.5	0.85	0.34	Poor
2I	1.1	0.96	24.9	0.76	20.5	0.82	0.32	Poor
2J	1.2	1.04	26.8	0.81	21.5	0.80	0.30	Poor
2K	1.3	1.13	28.7	0.85	22.4	0.78	0.28	Poor
2L	1.4	1.22	30.6	0.88	23.3	0.76	0.27	Poor
2M	1.5	1.30	32.3	0.91	24.0	0.74	0.25	Poor
2N	2.0	1.74	40.6	1.05	27.0	0.67	0.20	Poor

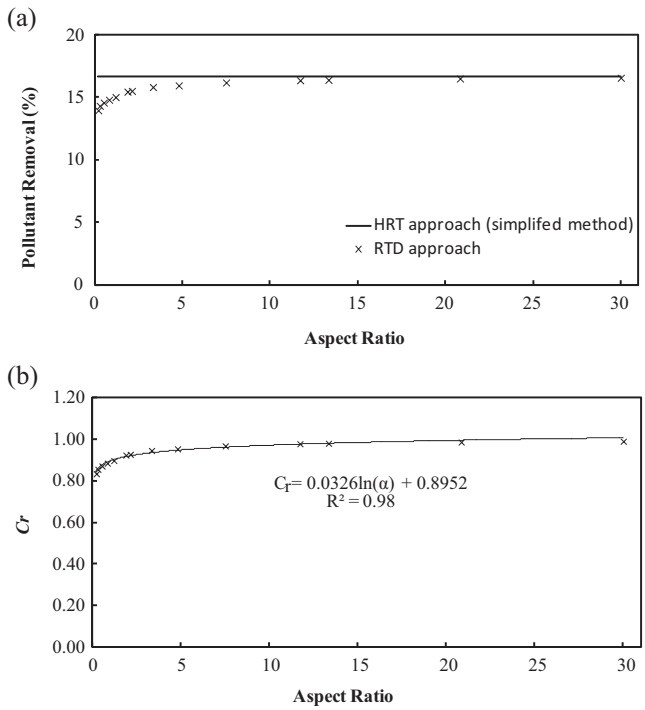

Fig. 4. Fig. 4a illustrates the pollutant removal performance of the fourteen modeled scenarios that were based on different aspect ratios. Fig. 4b illustrates the relationship between the correction coefficient (C_r) and aspect ratio (α). The C_r increases from 0.84 to 0.99 when the aspect ratio rises from 0.21 to 30.00.

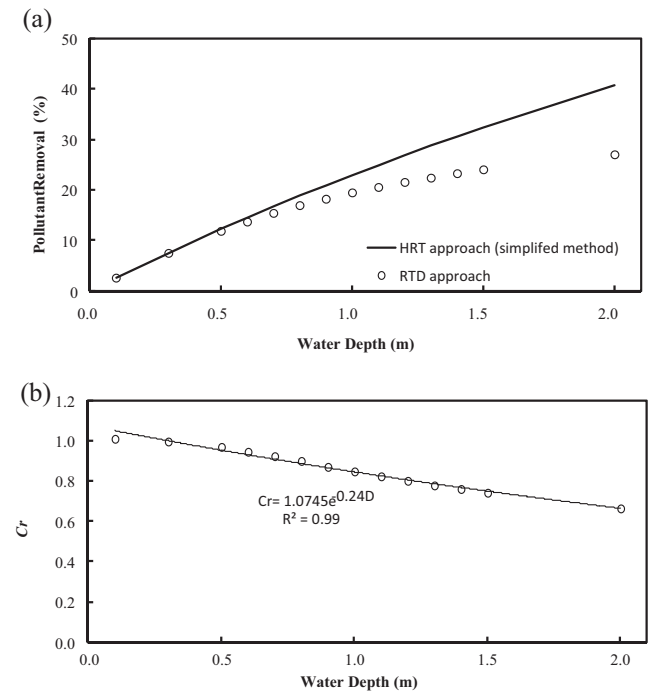

Fig. 5. Fig. 5a illustrates the pollutant removal performance of the fourteen modeled scenarios based on different water depths. Fig. 5b illustrates the relationship between correction coefficient (C_r) and water depth (D). The difference between R_{HRT} and R_{RTD} increases as water depth increases, while the C_r decreases from 1.00 to 0.67 as the water depth increased from 0.1 m to 2.0 m.

approach, especially when the aspect ratio was less than 5 and the water depth was greater than 0.5 m (Figs. 4a and 5a).

As the aspect ratio increases, the difference between the R_{HRT} and R_{RTD} values decreases and the C_r increases approaching 1.0 indicating optimal pollutant removal (Fig. 4b). Alternatively, as the water depth increases the difference between the R_{HRT} and R_{RTD} values increases and the C_r decreases indicating that optimal pollutant removal should occur when the wetland is shallow (Fig. 5b). The changes of the C_r are more noticeable with different water depths than with changing aspect ratios.

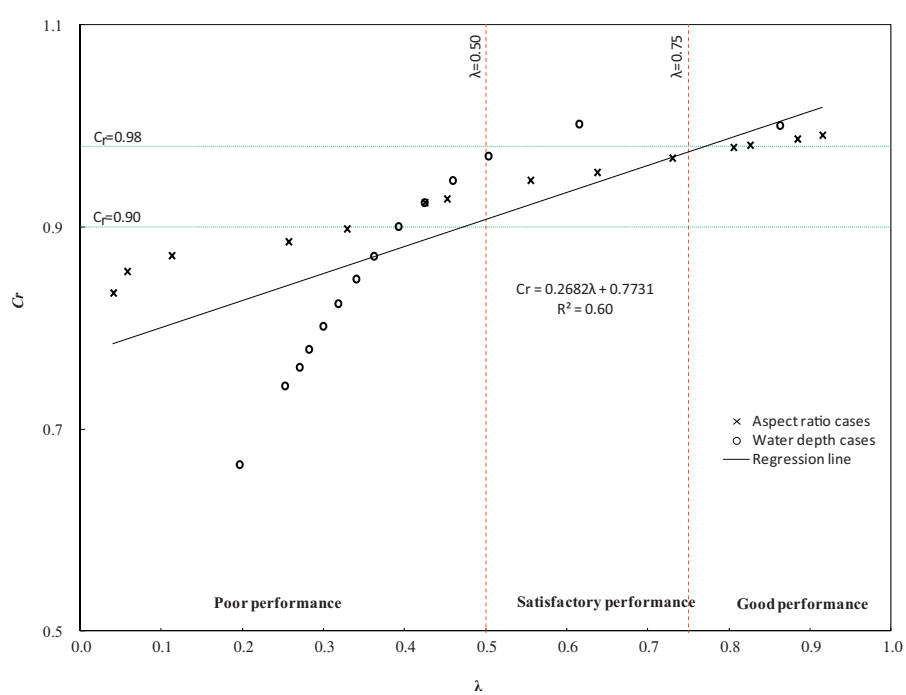

Fig. 6. The relationship between correction coefficient (C_r) and hydraulic efficiency (λ) indicates that higher λ leads to higher C_r. The hydraulic efficiency is satisfactory when the aspect ratio is greater than 1.20 or the water depth is less than 0.8 m. Furthermore, the C_r is greater than 0.98 in the good hydraulic efficiency zone and greater than 0.90 in the satisfactory hydraulic efficiency zone.

In this study, we developed three regression models (Eqs. (5)–(7)) for the correction coefficients (C_r) with wetland aspect ratio (α), water depth (D) and hydraulic efficiency (λ). The aspect ratio has a logarithmic trend while the water depth has turned an exponential trend with the variant correction coefficients. Both these two aspect ratio and water depth are strongly correlated with the correction coefficient value. We further tested the relationship of hydraulic efficiency and correction coefficient with logarithmic, exponential, and linear regression models to find the linear regression model has owned the best-predicted results that best fits the data (see also Fig. 6).

$$C_r = 0.0326\ln(\alpha) + 0.8952, \quad R^2 = 0.98 \tag{5}$$

$$C_r = 1.0745e^{-0.24D}, \quad R^2 = 0.99 \tag{6}$$

$$C_r = 0.2682\lambda + 0.7731, \quad R^2 = 0.60 \tag{7}$$

Compared with the classification of Persson et al. (1999), the hydraulic efficiency of our reaction vessels ranges from the "Satisfactory" to "Good" classes when the aspect ratio is greater than 1.20 or the water depth is less than 0.8 m. Our results indicate that increasing water depth and decreasing aspect ratio resulted in lower hydraulic efficiency. Holland et al. (2004) also showed that increasing water depth resulted in noticeably lower hydraulic efficiency. We propose a classification system for first-order model performance based on C_r values as follows and illustrated in Fig. 6: (1) $C_r > 0.98$ good; (2) $0.90 > C_r < 0.98$ satisfactory; and (3) $C_r < 0.90$ poor.

The use of the HRT for a first-order model is recommended only when the modeled results fall into the "Good" and "Satisfactory" classes. It is recommended that the simplified HRT is used for shallow water wetlands with water depths lower than 0.8 m and narrow long wetlands with aspect ratios higher than 1.20. The first-order model can be more widely and adequately used for practical purposes after modification by the correction coefficients. We reasoned that wetland engineers, designers, and scientists should avoid designing deep and low aspect ratio constructed wetlands.

4. Conclusion and suggestions for future study

The numerical model TABS-2 was used to examine more realistic water flow conditions to obtain RTD and related hydraulic efficiency. The pollutant removal performance can be enhanced by applying a correction coefficient value (C_r) to modify the HRT for the first-order model. Twenty-eight scenarios were modeled to determine the influence of aspect ratio and water depth on C_r. A higher C_r implies that the pollutant removal computed by HRT, R_{HRT}, tends toward the pollutant removal computed by RTD, R_{RTD}, and the pollutant removal performance is not seriously hampered by short-circuit or backwater effects.

The use of the simplified HRT method is suggested only for situations where the water depth is lower than 0.8 m and the aspect ratio is higher than 1.20, otherwise the pollutant removal calculation is poor. Both the water depth and aspect ratio influence correction coefficients while the influence of water depth is more important. The results indicate that the HRT approach is suitable for estimating pollutant removal of shallow water wetlands and narrow long wetlands. The regression models of the correction coefficients provided by this study can be used to revise the HRT estimation for practical purposes. Given the choice between controlling the aspect ratio or water depth, our results suggest that water depth is a more important characteristic than the aspect ratio of the wetland. This study separately examined the aspect ratio that ranges from 0.21 to 30.00 and the water depth that ranges from 0.1 m to 2.0 m. They are well-designed experiments with numerical model. The applications of the derived regression models may be limited for broad practices. The future study is thus recommended to be collected more information and to be detected by using real field data.

Acknowledgements

We would like to thank the National Science Council of Taiwan for the founding supports under grant No. NSC 102-2218-E-002-008, NSC 102-2119-M-003-006, and NSC 100-2628-H-003-161-MY2. The useful suggestions from two anonymous reviews have been incorporated into the manuscript.

References

Brix, H., 1993. Wastewater treatment in constructed wetlands: system design, removal processes and treatment performance. In: Moshiri, G.A. (Ed.), Constructed Wetlands for Water Quality Improvement. Lewis Publisher, Boca Raton/Ann Arbor/London/Tokyo, pp. 9–22.
Cooper, P.F., Job, G.D., Green, M.B., Shutes, R.B.E., 1996. Reed Beds and Constructed Wetlands for Wastewater Treatment. WRc Publications, Medmenham, Marlow, UK.
Dal, C.L., Persson, J., 2000. The influence of vegetation on hydraulic performance in a surface flow wetland. In: Reddy, K.R., Kadlec, R.H. (Eds.), Proceedings of the Seventh International Conference on Wetland Systems for Water Pollution Control, vol. 2. Lake Buena, Vista, FL, pp. 539–546.
Dierberg, F.E., Juston, J.J., DeBusk, T.A., Pietro, K., Gu, B., 2005. Relationship between hydraulic efficiency and phosphorus removal in a submerged aquatic vegetation – dominated treatment wetland. Ecol. Eng. 25, 9–23.
Donnell, B.P., 1997. Users Guide to RMA2 Version 4.3. US Army Corps of Engineer-Waterways Experiment Station Hydraulics Laboratory. WexTech Systems, Inc., New York.
Fisher, P.J., 1990. Hydraulic characteristics of constructed wetlands at Richmond, NSW, Australia. In: Cooper, P.F., Findlater, B.C. (Eds.), Constructed Wetlands in Water Pollution Control. Pergamon, Oxford, pp. 21–31.
Hammer, D.A., 1989. Constructed Wetlands for Wastewater Treatment: Municipal Industrial and Agricultural. Lewis Publishers, Chelsea, MI.
Holland, J.F., Martin, J.F., Granata, T., Bouchard, V., Quigley, M., Brown, L., 2004. Effects of wetland depth and flow rate on residence time distribution characteristics. Ecol. Eng. 23 (3), 189–203.
Hsu, C.B., Hsieh, H.L., Yang, L., Wu, S.H., Chang, J.S., Hsiao, S.C., Su, H.C., Yeh, C.H., Ho, Y.S., Lin, H.J., 2011. Biodiversity of constructed wetlands for wastewater treatment. Ecol. Eng. 37 (10), 1533–1545.
Kadlec, R.H., 1994. Detention and mixing in free-water wetlands. Ecol. Eng. 3 (4), 345–380.
Kadlec, R.H., 2000. The inadequacy of first-order treatment wetland models. Ecol. Eng. 15 (1/2), 105–119.
Kadlec, R.H., 2003. Effects of pollutant speciation in treatment wetlands design. Ecol. Eng. 20 (1), 1–16.
Kadlec, R.H., Knight, R.L., 1995. Treatment Wetlands. Lewis Publishers, Boca Raton/New York/London/Tokyo.
King, I., 2003. Users Guide to RMA4. Version 4.5, US Army, Engineer Research and Development Center Waterways Experiment Station Coastal and Hydraulics Laboratory. WexTech Systems, Inc., New York.
Konyha, K.D., Shaw, D.T., Weiler, K.W., 1995. Hydrologic design of a wetland – advantages of continuous modeling. Ecol. Eng. 4 (2), 99–116.
Koskiaho, J., 2003. Flow velocity retardation and sediment retention in two constructed wetland-ponds. Ecol. Eng. 19 (5), 325–337.
Kuo, P.H., Shih, S.S., Lee, H.Y., 2008. The water depth criteria on detention wetland. In: Proceedings of 11th International Conference on Wetland Systems for Water Pollution Control, Ujjain/Indore, India, pp. 427–435.
Levenspiel, O., 1999. Chemical Reaction Engineering, 3rd ed. John Wiley & Sons, New York.
Levenspiel, O., 1972. Chemical Reaction Engineering, 2nd ed. John Wiley & Sons, New York.
Persson, J., Somes, N.L.G., Wong, T.H.F., 1999. Hydraulics efficiency of constructed wetlands and ponds. Water Sci. Technol. 40 (3), 291–300.
Reed, S.C., Crites, R.W., Middlebrooks, E.J., 1995. Natural Systems for Waste Management and Treatment. McGraw-Hill, New York.
Shilton, A.N., Prasad, J.N., 1996. Tracer studies of a gravel bed wetland. Water Sci. Technol. 34 (3/4), 421–425.
Stairs, D.B., 1993. Flow Characteristics of Constructed Wetlands: Tracer Studies of the Hydraulic Regime. Oregon State University, Corvallis, OR, USA (M.S. Thesis).
Su, T.M., Yang, S.C., Shih, S.S., Lee, H.Y., 2009. Optimal-design for hydraulic efficiency performance of free-water constructed wetlands. Ecol. Eng. 35 (8), 1200–1207.
Ta, C.T., Brignal, W.J., 1998. Application of computational fluid dynamics technique to storage reservoir studies. Water Sci. Technol. 37 (2), 219–226.
Thackston, E.L., Shields, F.D., Schroeder, P.R., 1987. Residence time distributions of shallow basins. J. Environ. Eng. ASCE 113 (6), 1319–1332.

Taiwan Environmental Protection Agency, 2008. Manual: Engineering of Constructed Wetlands. Taiwan EPA, Taipei.
Urban, D.T., 1990. Methods of Determining Retention Time Distributions in a Reconstructed Wetland. Illinois Institute of Technology, Chicago, IL (M.S. Thesis).
US Environmental Protection Agency, 1988. Design Manual for Constructed Wetlands and Floating Aquatic Systems for Municipal Wastewater. US EPA Office of Research and Development, Cincinnati, OH.
US Environmental Protection Agency, 2000. Manual: Constructed Wetlands Treatment of Municipal Wastewaters. US EPA Office of Research and Development, Cincinnati, OH.
Werner, T.M., Kadlec, R.H., 1996. Application of retention time distribution to stormwater treatment systems. Ecol. Eng. 7 (3), 213–234.