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Optimal design for hydraulic efficiency performance of free-water-surface constructed wetlands

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ABSTRACT

This study aims to provide the optimal design of different free-water-surface constructed wetlands (FWS CWs) according to hydraulic efficiency index (λ). This index is mainly determined by the position and distribution of the hydraulic retention time (HRT) curve of a wetland. HRT can be defined as the period during which each portion of fluid remains in the wetland under the influence of flow uniformity. Flow uniformity of a wetland is primarily affected by the aspect ratio of the wetland (AR_w), the inlet and outlet configuration, and the obstruction designation. The important findings about these three factors in this study are as follows:

1. When the AR_w is greater than 5, the λ will reach 0.9 or even higher. If the project site or field area cannot meet the theoretical standard, the recommended AR_w is higher than 1.88 so that the λ will be higher than 0.7.
2. The best configuration of inlet and outlet is uniform–midpoint. Meanwhile, midpoint–midpoint is preferable to corner–corner.
3. According to the multi-linear regression of numerical experiment results, it is suggested that the obstruction width-to-wetland width ratio (w_{ob}/w_w), rather than the amount of obstruction, is the most significant influential factor in the performance of hydraulic efficiency.

1. Introduction

Wetlands serve as both “nature’s supermarket” and “nature’s kidneys” and are found in all parts of the world (Mitsch and Gosselink, 2007). The protection, restoration, and creation of these water resources are essential for the sustainable support of nature and human culture alike (Mitsch, 2005). Therefore, several hundreds of marshes have now been built primarily for the purposes of water quality improvement (Kadlec, 1995). The research about using wetland macrophytes for wastewater treatment and horizontal sub-surface flow constructed wetlands (HF CWs) was started by Käthe Seidel in Germany in the 1960s and by Reinhold Kickuth in the 1970s (Vymazal, 2009). The CWs are effective natural systems for treating polluted water as discovered recently. The design parameters, removal mechanisms and treatment performance were cited from the review of Kadlec and Brix (1995) and Vymazal (2005).

Microorganisms-degradation and plants-adsorption are two major mechanisms found in CWs for polluted water treatment (Toet et al., 2005). Both are dependent on the retention time. Hydraulic retention time (HRT), which indicates how long the inflow is retained in the wetland, is a critical parameter for a CW design. HRT means the activity time for treating pollutants. Previous studies indicated that HRT has a significant influence on the pollutant removal ratio (Kadlec, 1994, 2003; Dierberg et al., 2005).

In practice, nominal retention time is often used as HRT. The nominal retention time is the time taken for flow to pass through a wetland uniformly, but this is not an appropriate index since flow is seldom uniform. Based on the concept of hydrodynamics mechanism, such as streamline, boundary layer, and turbulence effect, we illustrated the FWS CW’s flow condition in general as shown in Fig. 1. Because the inside fluid elements are hard to exchange with outside ones in low-velocity zone, the volume utilization would

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Nomenclature

CW	constructed wetland
HF CWs	horizontal sub-surface flow constructed wetlands
FWS CWs	free-water-surface constructed wetlands
HRT	hydraulic retention time
RTD	retention time distribution
AR_w	aspect ratio of wetland; wetland length/wetland width
AR_{ob}	aspect ratio of obstructions
n_{ob}	number of obstructions
w_{ob}	obstruction width
w_w	wetland width
C	concentration of pollutant
t	time
$E(\theta)$	normalized concentration
θ	normalized time
t_n	nominal retention time
t_m	mean retention time
e_v	effective volume ratio
N	number of tank-in-series
λ	hydraulic efficiency index
n	Manning's roughness coefficient
E	eddy viscosity
D	dispersion coefficient

decrease. The existence of low-velocity zone would reduce the treatment efficiency. Improving the treatment performance can be achieved by allowing the flow to pass through the wetland uniformly.

Hydrodynamics in a wetland is mainly influenced by the wetland's aspect ratio, the configuration of inlet and outlet, and the obstruction designation (Persson et al., 1999). The obstruction designation includes the determination of aspect ratio (AR_w), number, and location about designed obstructions. When there is no obstruction in a wetland, AR_w becomes the major factor affecting the hydraulic efficiency. Many studies have proposed different opinions about the AR_w by experience or data monitoring (Dinges, 1978; Stowell et al., 1986; Reed et al., 1995; USEPA, 2000). Nevertheless, due to the considerations of land expropriation, construction difficulties and landscape, it is often difficult to make a significant change on the AR_w. Land use is especially heavy and so the land required for a CW is scarce in Taiwan (Kuo et al., 2009). Therefore how to improve the hydraulic efficiency is critical.

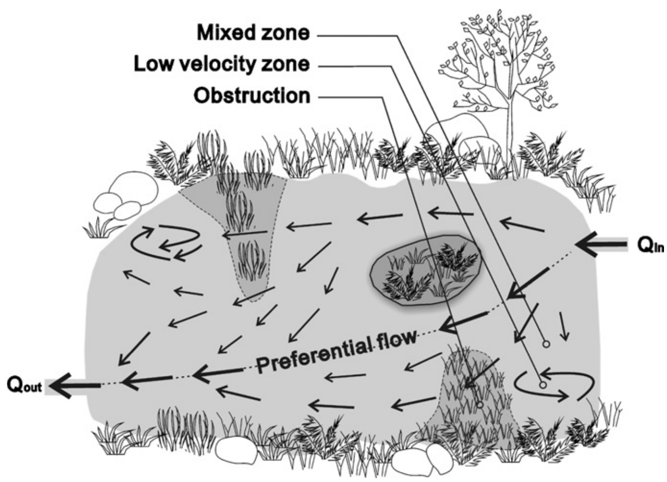

Fig. 1. Schematic plot of flow condition of a free-water-surface constructed wetland (FWS CW). Due to non-uniform flow, a FWS CW can be divided into preferential flow zone, mixed zone and low-velocity zone. The circulation occurs in low-velocity zone resulting from flow separation. Since the exchange of inside and outside fluid elements is minimal in low-velocity zone, hydraulic efficiency in the wetland would decrease.

Proper configuration of inlet and outlet structures can improve the hydraulic efficiency (Koskiaho, 2003). Obstructions, including terrain undulation, baffles, isles or mounds, also could improve hydraulic efficiency of the CW. This phenomenon has been reported and proved (Persson et al., 1999; Koskiaho, 2003; German et al., 2005). Previous studies of hydraulic efficiency of wetland examined the influential factors in general but did not focus namely on each of them. This study attempted to conduct the varied hydraulic efficiency of FWS CW with different AR_w, the configuration of inlet and outlet and the obstruction designation, respectively. The optimal design procedure of a FWS CW was also investigated.

2. Materials and methods

2.1. Tracer test

Levenspiel (1999) suggested treating the wetland as a great reactor, and conducted a pulse experiment at the inlet by adding a tracer such as rhodamine, bromide or chloride with a given concentration within a short time. Based on the tracer concentration measurement at the outlet of the wetland, the retention time distribution (RTD) curve was derived. The flow condition inside a wetland would be revealed by the position and distribution of a RTD curve. Fig. 2 shows the RTD curve of inflow and outflow developed from the pulse experiment.

The position of the RTD curve can be represented as the mean retention time (t_m). In real situation, determining the ending time is difficult because there is an inevitable tail in the RTD curve. Sampling time in field is finite; hence there is no availability of complete RTD curve. Incomplete data cannot be used to calculate mean retention time accurately. As numerical model was used, the t_m can be evaluated by the entire RTD curve by applying Eq. (1) (Kadlec, 1994). When t_m is equal to t_n, this indicates that the flow passes uniformly through the wetland. Thackston et al. (1987) defined the ratio of t_m to t_n as the effective volume ratio (e_v):

$$t_m = \frac{\int_0^\infty tC\,dt}{\int_0^\infty C\,dt}; \quad e_V = \frac{t_m}{t_n} \tag{1}$$

Plug flow and mixed flow are two extreme conditions in the distribution of the RTD curve. Levenspiel (1999) applied the concept of continuous stirred tank reactor and tank-in-series to describe these two conditions simultaneously. Fig. 2 shows the RTD curve measured at the outlet actually changes with the different number of tank-in-series (N). The larger the N, the RTD curve concentrates on t_m. This implies that the flow is more uniform, and the t_m is closer to the t_n. The N is reciprocal of the variation (σ_θ^2), which can be calculated using the $E(\theta)$–θ curve (Fogler, 2006). Using Eqs. (2) and (3), the concentration–time curve can be normalized to $E(\theta)$–θ curve (Levenspiel, 1999). The N value is treated as an indicator of the RTD curve distribution:

$$\int_0^\infty \frac{E(\theta)}{t_m} dt = 1 \tag{2}$$

$$\theta = \frac{t}{t_m} \tag{3}$$

Persson et al. (1999) proposed the hydraulic efficiency index to identify the RTD curve position and distribution. The λ can be calculated using Eq. (4). The λ calculated from the RTD curve can provide an indication of the uniformity of fluid flow inside a wetland. When

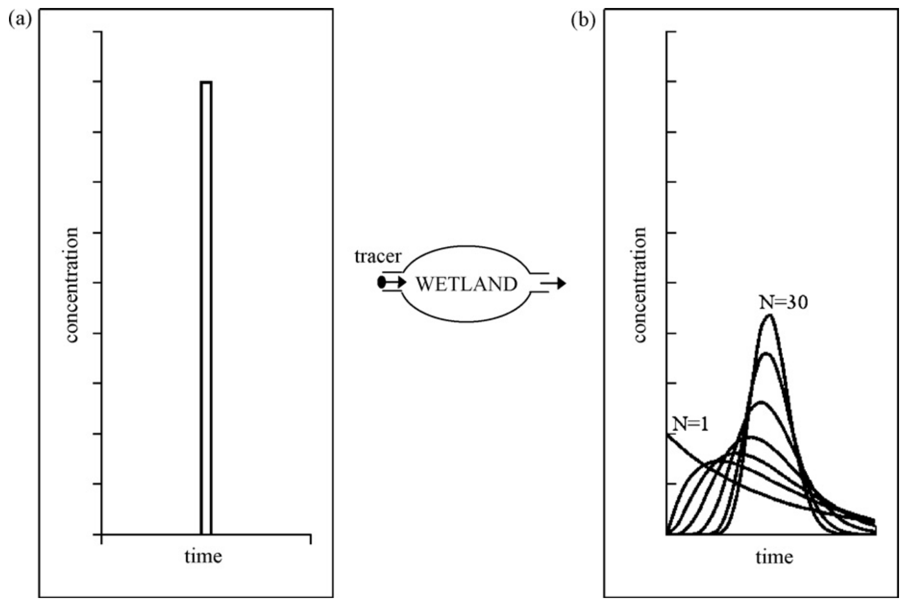

Fig. 2. RTD curve diagram of the tracer experiment. Based on the tracer concentration measurement at the outlet of the wetland, the RTD curve can be derived. (A) A pulse experiment of tracer infuses at inlet of the wetland; (B) the different tracer concentration curve is according to the different number of tank-in-series (N) at outlet of the wetland (redrawn from Levenspiel, 1999).

the λ is higher, hydraulic design of a wetland would be better and fluid flow is also uniform. Therefore, the λ is crucial in determining the AR_w, inlet and outlet configuration, and obstruction designation for optimal hydraulic design:

$$\lambda = e_v \left(1 - \frac{1}{N}\right) \quad (4)$$

2.2. Numerical experiment

2.2.1. Model parameters validation

As the water depth of a wetland is shallow (about 20–50 cm in general) and variation in the vertical direction can be omitted, a horizontal two-dimensional model, TABS-2, was chosen as the numerical experiment model. TABS-2, developed by the U.S. Army Corps of Engineers and Waterway Experiment Station, simulates tracer pulse experiment to understand the pollutant transmission in wetlands using hydrodynamic and water quality models without considering the tracer decay, extrinsic source or adsorption, rainfall and evaporation. Operation steps of the model were included in BYU-EMRL (2002).

Three parameters, including Manning's roughness coefficient (n), eddy viscosity (E) and dispersion coefficient (D), have to be ascertained according to the condition of the wetlands. In this study, Manning's n of the wetland's bed is 0.035 because FWS CWs are mostly created by soil, with irregularity and obstructions (Cowan, 1956). On the other hand, since obstruction is usually a habitat for plants, the roughness is not only influenced by the wetland bed but also by the plant surface (Kadlec, 1990). Therefore, based on Woody's roughness coefficient table (Cowan, 1956), Manning's coefficient of the obstructions was set as 0.080. Besides, eddy viscosity was given as $20\,\mathrm{N\,m^{-2}\,s}$ considering the shallow and slow flow in wetlands (King, 2001a). King (2001b) meanwhile suggested that dispersion coefficient ranges from $0.0002\,\mathrm{m^2\,s^{-1}}$ to $0.001\,\mathrm{m^2\,s^{-1}}$. Due to the limitation of numerical simulation, the dispersion coefficient must be larger than $0.0008\,\mathrm{m^2\,s^{-1}}$ to avoid irrational results. According to suggestion of Thackston et al. (1987) and sensitivity analysis, the dispersion coefficient was given as $0.0008\,\mathrm{m^2\,s^{-1}}$. The relative errors of $D = 0.0008$ and 0.0010 are 27% and 33%, respectively (Fig. 3). The numerical simulation does not consider the influence of evaporation and infiltration, so there is almost no loss of tracer. Therefore, the recovery ratio of tracer is almost 100%. This is the reason the model results in Fig. 3 are slightly higher than Thackston's survey data.

Based on the general solution of one-dimensional convection–dispersion equation, Lin et al. (2003) suggested that in conducting a field experiment the tracer concentration should be higher than the environmental concentration by two times standard deviation when 95% of the tracer flows out. Though it is not necessary to take environmental concentration into consideration while conducting the numerical simulation, the dose adopted in the simulation should be similar to the field experiment in order to avoid distortion. Since parameters were validating, TABS-2 was employed to simulate the 1.44 g tracer test for the FWS CWs.

2.2.2. Cases setup description

This study adopted different setups of the FWS CWs to determine the influences of different factors on the hydraulic efficiency. Three factors, AR_{ob}, configuration of inlet and outlet and obstruc-

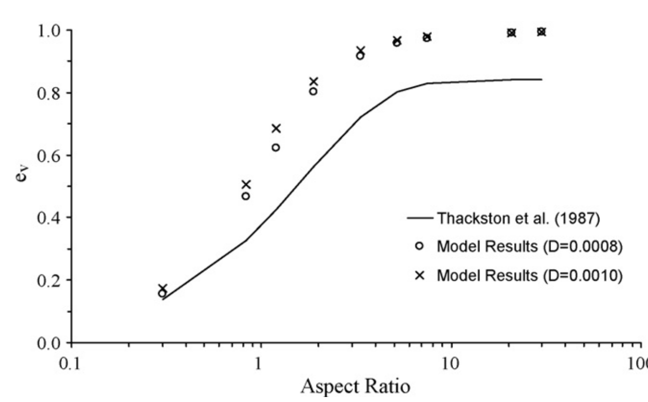

Fig. 3. Calibration of model parameters considering aspect ratio and effective volume ratio (e_v). The numerical simulation does not consider the influences of evaporation and infiltration so there is almost no loss of tracer. Therefore, the recovery ratio of tracer is almost 100%. This is the reason the model results are slightly higher than Thackston's survey data.

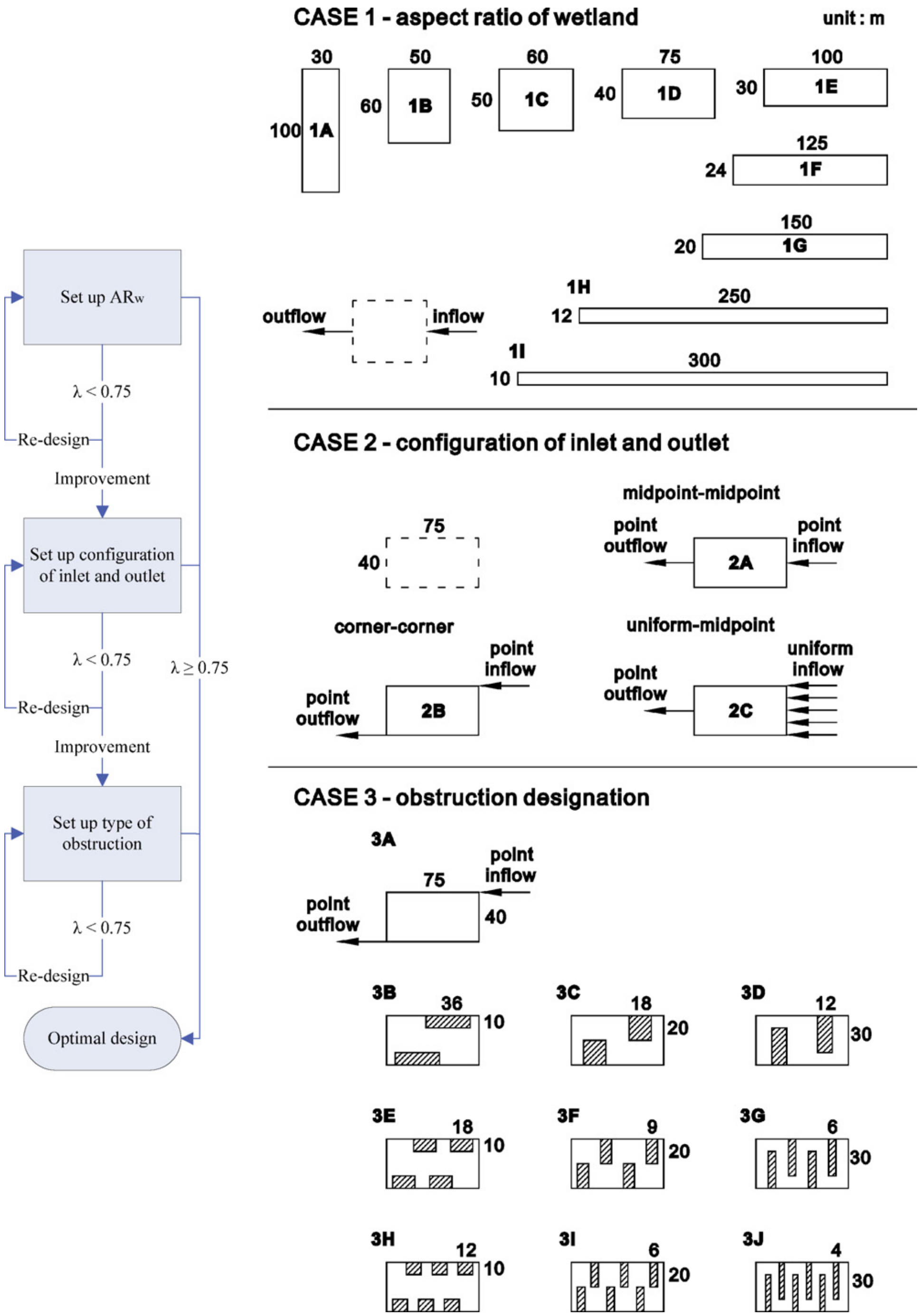

Fig. 4. Optimal design procedure and variant numerical cases, i.e. aspect ratio of wetland, configuration of inlet and outlet and obstruction designation.

tion designation, are shown in Fig. 4. The flow chart of optimal design procedure is shown in left hand side of Fig. 4 as well. Firstly, the designer should determine the AR_W and the inlet and outlet configuration of the wetland and calculate the λ, based on the current wetland. If the value is lower than the threshold, modification of the wetland is required. Persson et al. (1999) suggest a three-group classification system for hydraulic efficiency performance: (1) good ($\lambda > 0.75$); (2) satisfactory ($0.5 < \lambda < 0.75$); (3) poor ($\lambda < 0.5$). The threshold λ was given as 0.75 in this study. In the design process, the AR_W is first adjusted to improve the λ. After adjusting the AR_W, the designer should modify the configuration of inlet and outlet to improve the flow uniformity and to increase the λ. If a change of inlet and outlet configuration is not able to satisfy the threshold λ, the designer should consider installing obstructions in the wetland to improve the λ. The cases of these three factors are discussed below:

(1) Aspect ratio variations

This study examines the impact of different AR_W by conducting simulation on nine FWS CWs. Shown as case 1 in Fig. 4, the dimension of these FWS CWs are 30 m × 100 m (1A), 50 m × 60 m (1B), 60 m × 50 m (1C), 75 m × 40 m (1D), 100 m × 30 m (1E), 125 m × 24 m (1F), 150 m × 20 m (1G), 250 m × 12 m (1H), 300 m × 10 m (1I), and the corresponding

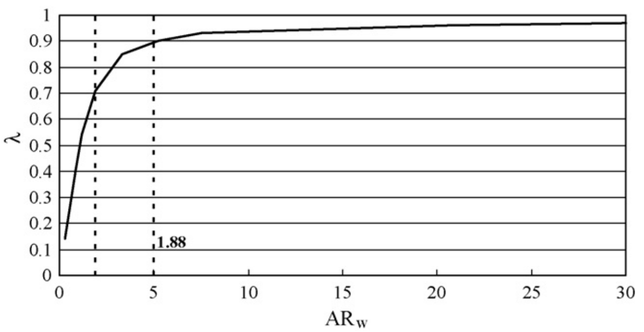

Fig. 5. Relationship between the hydraulic efficiency and the aspect ratio of wetlands. The hydraulic efficiency increases with the aspect ratio. On the other hand, the hydraulic efficiency of the wetlands significantly improves significantly when the aspect ratio is smaller than 5.

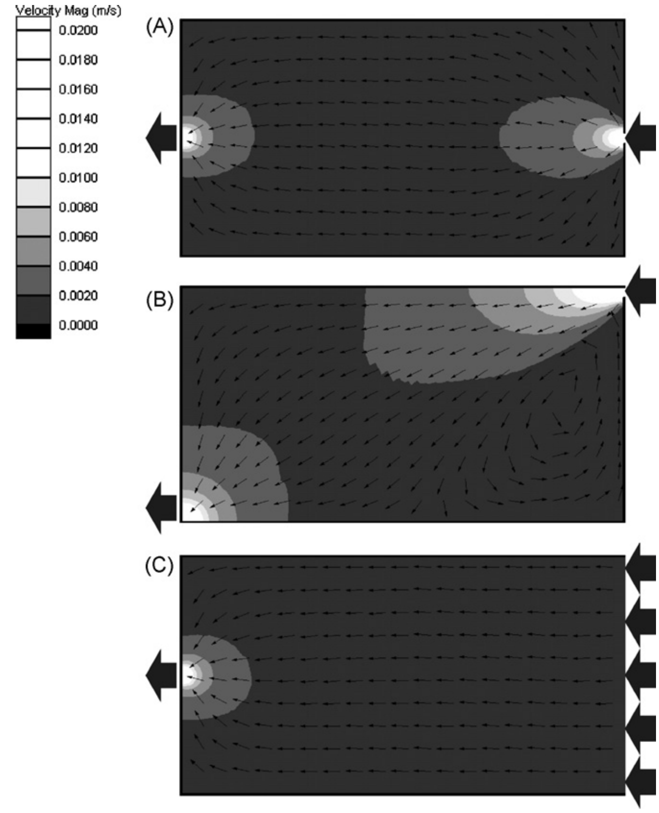

Fig. 6. Flow conditions with the velocity magnitude and direction for different cases of the inlet and outlet configuration: midpoint–midpoint (2A); corner–corner (2B); uniform–midpoint (2C).

AR_w are 0.30, 0.83, 1.20, 1.88, 3.33, 5.21, 7.50, 20.83, 30.00, respectively. Case 1D was set up as the referred case so as to compare the hydraulic efficiency performance with other cases.

(2) Configurations of inlet and outlet

The influence of the inlet and outlet configuration for hydraulic efficiency performance is examined in case 2. The dimension of the CWs was set at 75 m × 40 m and its AR_w was 1.88. Three configuration designations were evaluated, i.e. midpoint–midpoint, corner–corner and uniform–midpoint.

(3) Obstruction designations

Setup of the different obstructions is shown as case 3 in Fig. 4. Nine scenarios were investigated in this study. Obstructions are lower than the water surface of FWS CWs by 0.1 m; and bed elevation is lower by 0.7 m. The AR_w of this case is 1.88 with a corner–corner configuration.

3. Results and discussion

3.1. Aspect ratio variation

Nine FWS CWs with different AR_w were studied and the results are shown in Table 1. The results show that the AR_w is one of the main factors which influence the λ. The t_m approaches to t_n while the AR_w increases. This phenomenon implies that the fluid passes through the wetland more uniformly. Further, the AR_w increases monotonically with the effective volume ratio and hydraulic efficiency.

Fig. 5 shows the relationship between the AR_w and λ. As mentioned previously the λ increases with the AR_w but the increasing rate of the λ obviously decreases while the AR_w is greater than 5. The average increasing rate of the λ is equal to 0.274 when the AR_w is smaller than 5 and 0.003 when the AR_w is larger than 5. The increasing rate of the AR_w does not have obvious influence on the λ when the AR_w is higher than 5. Therefore, if the field condition permits, we suggest that the AR_w should be larger than 5 because the λ can reach 0.9 or even higher. On the contrary, if the field condition is not conducive, the AR_w should still be kept larger than 1.88. By doing so, the λ that can be achieved would still be higher than 0.7.

3.2. Configuration of inlet and outlet

Table 2 shows the simulation results of three different cases of the inlet and outlet configuration. The wetland volume was 2100.0 m^3, and the t_n was 14.60 h. The results show that uniform–midpoint can achieve the best λ, 0.88, and the corner–corner fared the worst one at 0.65. Fig. 6 displays the flow field of the three different cases of inlet and outlet. The first figure shows the flow velocity for the midpoint–midpoint case. For this case, four small low-velocity zones were found at the four corners. The second figure shows the flow velocity for the corner–corner case. A large low-velocity zone appeared at the opposite corner that is neither inlet nor outlet. The third figure shows that the flow uniformly passed through the wetland, and therefore raises the performance of the hydraulic efficiency. The hydraulic efficiency performance of inlet and outlet configuration can be sorted as: uniform–midpoint, midpoint–midpoint, and corner–corner. Without any obstruction, uniform–midpoint is the best configuration to improve the λ and to ensure that the fluid runs uniformly.

3.3. Obstruction designation

Objects that affect and change the flow direction are known as obstructions. The obstructions can be baffles, isles or jetties. The obstruction under the water surface not only provides growing habitat for emergent aquatic plants, but also allows the creatures to rest and for forage. In this case, the AR_w was set as 1.88, and the wetland volume was 2100.0 m^3. Because the λ when configuration of inlet and outlet was midpoint–midpoint or corner–corner was smaller than the threshold λ, the constructed design had to be improved. The inlet and outlet configuration of referred case was set as corner–corner. The height of the obstructions was set to be 0.1 m below the water surface (the water depth of wetland is 0.7 m), and the volume of the obstructions is about 432 m^3.

Table 3shows the simulation results of obstruction and Fig. 7 shows the flow condition with the velocity magnitude and direction of different cases. For case 3A, which is without obstruction and set as referred case, there is significant circulation resulting from flow separation in right bottom corner causing the λ to be only

Table 1
Simulated results of the different aspect ratios of the wetlands.

Case	Dimension (m × m)	AR_w	Ω (m^3)	t_n (h)	t_m (h)	e_v	$e_v \times \Omega$ (m^3)	N	λ	Note
1A	(30,100)	0.30	2100.0	14.60	2.15	0.15	310.8	19.00	0.14	Poor
1B	(50,60)	0.83	2100.0	14.60	5.82	0.40	837.9	55.36	0.39	Poor
1C	(60,50)	1.20	2100.0	14.60	7.92	0.54	1138.2	72.41	0.54	Satisfactory
1D	(75,40)	1.88	2100.0	14.60	10.54	0.72	1514.1	85.14	0.71	Satisfactory; referred case
1E	(100,30)	3.33	2100.0	14.60	12.50	0.86	1797.6	77.92	0.85	Good
1F	(125,24)	5.21	2100.0	14.60	13.38	0.92	1923.6	63.17	0.90	Good
1G	(150,20)	7.50	2100.0	14.60	13.84	0.95	1990.8	53.14	0.93	Good
1H	(250,12)	20.83	2100.0	14.60	14.35	0.98	2064.3	36.06	0.96	Good
1I	(300,10)	30.00	2100.0	14.60	14.60	1.00	2097.9	34.24	0.97	Good

Table 2
Simulated results for different configurations of inlet and outlet.

Case	Configuration of inlet and outlet	Ω (m^3)	t_n (h)	t_m (h)	e_v	$e_v \times \Omega$ (m^3)	N	λ	Note
2A	Midpoint–midpoint	2100.0	14.60	10.54	0.72	1512.0	85.14	0.71	Satisfactory; referred case
2B	Corner–corner	2100.0	14.60	9.57	0.66	1386.0	98.11	0.65	Satisfactory
2C	Uniform–midpoint	2100.0	14.58	12.97	0.89	1869.0	71.20	0.88	Good

AR_w = 1.88.

0.65. Case 3B has obstruction designation, and this increases the λ from 0.65 to 0.93. Because obstruction improves flow uniformity, the circulation disappears and the fluid passes through the wetland more uniformly and effectively. For case 3C and case 3D, we kept the obstruction numbers the same (n_{ob} = 2), but changed the aspect ratio of obstructions. With the increase of obstruction width (w_{ob}), the low-velocity area behind the obstruction will decrease and the λ can increase to 0.93 or even higher. On the other hand, the obstruction widths of case 3E and case 3H are the same, but the obstruction numbers are different (n_{ob} = 4 and n_{ob} = 6). The flow conditions of case 3B, case 3E and case 3H reveal low-velocity area will appear behind the obstruction and preferential flow in the wetland becomes evident with the increase of obstruction number (Fig. 7). Moreover, the streamline, with the decrease of obstruction width, became short. Therefore, the hydraulic efficiencies of case 3E and case 3H are lower than other cases. The λ of case 3E only increases up to 0.79 and the λ of case 3H is 0.71. On the other hand, because case 3D, case 3F, case 3G, case 3I, and case 3J are longer obstruction width, the hydraulic efficiencies are all larger than 0.90.

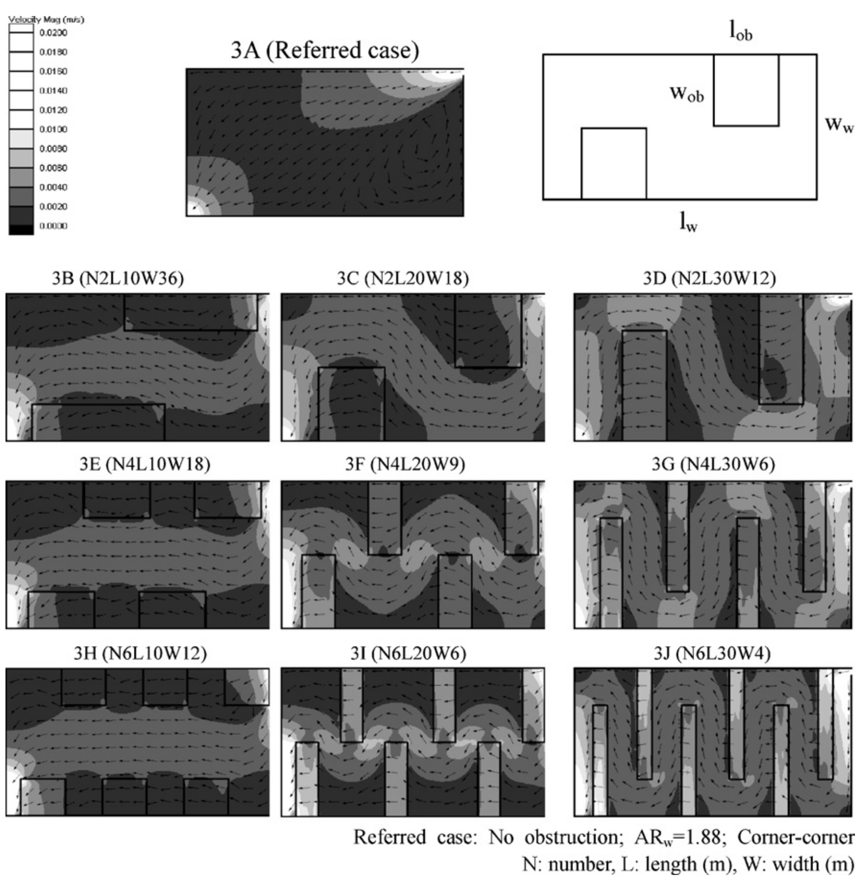

Fig. 7. Flow condition with the velocity magnitude and direction for different cases of various obstruction designations.

Table 3
Simulated results for different obstruction designations.

Case	n_{ob}	w_{ob} (m)	l_{ob} (m)	Ω (m^3)	t_n (h)	t_m (h)	e_v	$e_v \times \Omega$ (m^3)	N	λ	Note
3A	0	–	–	2100.0	14.60	9.57	0.66	1386.0	98.11	0.65	Satisfactory; referred case
3B	2	10	36	1670.8	11.60	10.92	0.94	1570.6	119.35	0.93	Good
3C	2	20	18	1670.8	11.60	11.14	0.96	1604.0	79.74	0.95	Good
3D	2	30	12	1670.8	11.60	11.07	0.95	1587.3	66.77	0.94	Good
3E	4	10	18	1670.8	11.60	9.29	0.80	1336.6	100.66	0.79	Good
3F	4	20	9	1670.8	11.60	11.06	0.95	1587.3	106.57	0.94	Good
3G	4	30	6	1670.8	11.60	10.98	0.95	1587.3	79.38	0.94	Good
3H	6	10	12	1670.8	11.60	8.27	0.71	1186.3	86.57	0.71	Satisfactory
3I	6	20	6	1670.8	11.60	10.67	0.92	1537.1	134.95	0.91	Good
3J	6	30	4	1670.8	11.60	10.76	0.93	1553.8	88.04	0.92	Good

AR_w = 1.88; inlet and outlet configuration = corner–corner.

Although the effective volume ratio and the λ increased slightly after installing the obstruction, the real effective volume actually decreases after deducting the obstruction volume from it. In other words, improper obstruction designation may lead to the decrease of wetland effective volume.

3.4. Multivariate regression equation

Flow uniformity is highly dependent on the obstruction number and the ratio of obstruction width to wetland width. Generally obstruction is helpful in increasing the λ. However, too many short obstructions would have negative impacts on the λ. For practical purpose, we stated a multi-linear regression equation of λ as follows:

$$\lambda = 0.63 - 0.02n_{ob} + 0.64\frac{w_{ob}}{w_w} \quad (R^2 = 0.85) \tag{5}$$

Eq. (5) indicates a clear and strong relationship between n_{ob}, w_{ob}/w_w, and λ. A comparison between the predicted and simulated λ is demonstrated in Fig. 8, with the predicted λ obtained from Eq. (5). Rather than using tracer test with the numerical model, the λ can be calculated simply by the regression equation. From Eq. (5), higher w_{ob}/w_w contributes to higher λ whereas higher n_{ob} reduces the λ. Compared to n_{ob}, w_{ob}/w_w has a more significant influence on the λ. Besides, the increase w_{ob}/w_w is an effective way to increase the λ.

As the flow velocity in the preferential zone is so high that the hydraulic retention time becomes short, the removal ratio will also decrease. In addition, the existence of the preferential zone may increase the mix gradient which will also reduce the removal ratio of pollutant (Dal Cin and Persson, 2000; Stern et al., 2001).

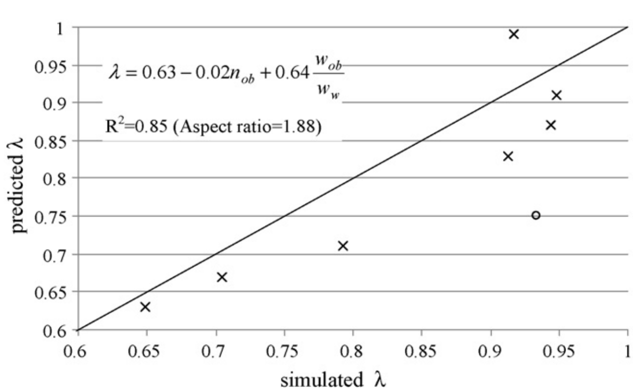

Fig. 8. Comparison of simulated and predicted hydraulic efficiency (λ). Rather than using tracer testing with the numerical model, the hydraulic efficiency can be calculated simply by the regression equation. Compared to n_{ob}, w_{ob}/w_w has a more significant influence on the hydraulic efficiency. The outlier comes from case 3B. The obstructions of case 3B cause meandering preference flow and uniform flow.

Dierberg et al. (2005) pointed out that 46% of the fluid elements went through the preferential zone which only accounted for 8% pollutant of the wetland. Non-uniform flow will also cause the occurrence of preferential zone in the wetland. In conclusion, when designing a FWS CW we should aim to improve flow uniformity, minimize the preferential zone and increase the effective wetland volume.

4. Conclusions

The TABS-2 model has been used to simulate the flow condition in wetlands in conjunction to a numerical tracer test. The position and distribution of the outlet RTD curve is taken into consideration when calculating the λ. The λ was used as an index of flow uniformity and to determine the optimal design of FWS CWs. In this study, three factors including aspect ratio of wetland, configuration of inlet and outlet, obstruction designation were investigated and their influence on the hydraulic efficiency was discussed.

Based on the simulation results of the different FWS CWs, it was found that the AR_w should be preferably greater than 5. If the field condition does not allow significant geometry change, the AR_w has to be at least 1.88 to maintain the uniform flow. In addition, the best configuration of inlet and outlet is uniform–midpoint, and the second option is midpoint–midpoint. Obstruction in the wetland is required to increase the λ when it does not meet the demand of the project. We also developed a regression equation to estimate the λ of obstruction: $\lambda = 0.63 - 0.02n_{ob} + 0.64(w_{ob}/w_w)$, R^2 = 0.85. This equation implies that the use of slender obstructions could be an efficient way to improve the λ.

Hydraulic retention time, the period during which the fluid can be treated, is the key factor in estimating the effectiveness of water purification in a FWS CW. By conducting a numerical experiment of the tracer test, the mean retention time can be measured easily. Compared to the nominal retention time, the mean retention time is closer to the real retention time of the fluid. In other words, the efficiency of water purification calculated based on the mean retention time is more likely to reveal the real condition of the wetland.

The outcome of this study in designing an optimal FWS CW can serve as a reference for designers. These procedures have been also implemented in improving the FWS CWs of Guandu Nature Park in Taipei, Taiwan.

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