Citation:
Nuruzzaman, M. and Anwar, A.H.M.F. and Sarukkalige, R. 2022. Assessing the impact of inlet-outlet configurations on the hydraulics and treatment efficiency of floating treatment wetland retrofitted stormwater pond. In: International Conference on Water and Environmental Engineering (iCWEE-2022), 27-30 Nov 2022, Sydney, Australia.

Assessing the impact of inlet-outlet configurations on the hydraulics and treatment efficiency of floating treatment wetland retrofitted stormwater pond

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Abstract

Floating treatment wetland (FTW) is becoming increasingly popular for stormwater treatment. The flow field of an FTW retrofitted stormwater pond and treatment efficiency will depend on the design configurations. In this study, we investigated the impact of inlet-outlet configuration on the flow field of pond, hydraulic performance and treatment efficiency by FTW. Hydraulic tracer experiments were conducted in a 0.3 m^3 tank for 13 cases with different inlet-outlet configurations and keeping the FTW (10% coverage) fixed at the center of the tank to estimate hydraulic performance of the cases. Simulations were performed for the same cases in ANSYS Fluent to determine treatment efficiency. It was revealed that inlets positioned away from the FTW along the transverse direction had lower hydraulic performance due to flow short-circuiting but generally higher treatment efficiency (up to 53%) compared to other cases. This was the result of high residence time of pollutant mass within FTW. When the inlets were positioned in line with the FTW, the high-velocity stream was intercepted by the FTW, but it reduced residence time within FTW and thus treatment efficiency even though the fraction of pollutant mass entry (85.5 – 100%) was increased in these cases. It signifies the importance of promoting the contact period between the inflow and FTW for a better treatment effect. Outlet positions also influenced hydraulic performance, flow field and treatment efficiency but to a lesser extent. Further research is required to understand the relationship between hydraulic performance and treatment efficiency of FTW retrofitted stormwater pond. The outcome of this study will help engineers and designers manipulate inlet-outlet configurations for efficient treatment by FTW.

Keywords: constructed floating wetland, design configuration, hydraulics, CFD.

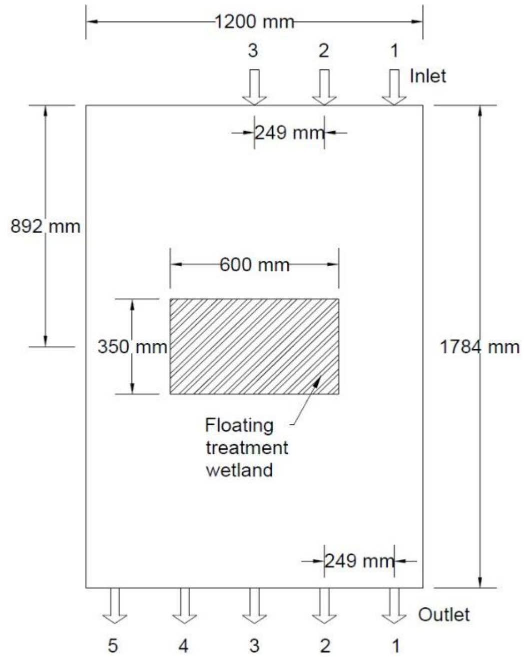
1. INTRODUCTION

Floating treatment wetland (FTW) is a recent innovation for water quality improvement. The use of FTW for stormwater treatment is gaining much attention due to its effectiveness and convenience of retrofitting in existing ponds (Schwammberger et al., 2019). An FTW consists of a floating bed planted with water-tolerant plant species. There has been a spike in research on FTW recently, most of them focusing on plant performance. While plant is the most essential component of FTW, its treatment efficiency also depends on the fraction of inflow entering into FTW and residence time within FTW to a great extent. Inflow and residence time within FTW is governed by the pond hydraulics, which are influenced by the design configuration of the pond and FTW. Design configurations are often overlooked and may lead to poor treatment efficiency (Lucke et al., 2019; Nuruzzaman et al., 2021). One of the crucial design features of a stormwater pond regulating the flow path is the position of inlet and outlet. Inlet-outlet configurations have been demonstrated to create preferential flow paths in constructed wetland (CW) and free surface wetland (FWS) (Sabokrouhiyeh et al.,2017; Su et al., 2009). The creation of the preferential flow path may undermine the efficacy of FTW by inflow short-circuiting, i.e., the inflow bypassing the FTW and not receiving enough treatment before exiting the pond. Conversely, flow short-circuiting can enhance residence time within FTW and may have some beneficial effect in some cases, which has not been investigated for FTW retrofitted stormwater pond yet. As such, it is essential to assess the impact of inlet-outlet configurations of stormwater pond on the creation of preferential flow paths and treatment efficiency by FTW. This study aimed to investigate the effect of inlet-outlet configurations on the short-circuiting phenomenon (measured by hydraulic performance indices), flow field of FTW retrofitted stormwater pond and treatment efficiency by FTW through lab experiments and computation fluid dynamics (CFD) simulation in ANSYS Fluent.

2. MATERIALS AND METHODS

2.1. Hydraulic tracer experiments

Hydraulic tracer experiments were conducted with 10% FTW coverage in a 0.3 m^3 (300 L) tank having a 2:1 (H:V) side slope by varying the positions of inlet and outlet. *Carex fascicularis* plant was used in the FTW. A total of 13 cases were investigated by fixing the FTW at the center of the tank. Inlet and outlet diameters were 0.03 m and 0.044 m. The flow rate was fixed at 0.236 L/s with a nominal hydraulic residence time (HRT) of 1271 seconds (21.2 min). Sodium chloride (NaCl) solution (40 g/L) was used as the tracer (250 mL injected) and the increase in outlet electrical conductivity (EC) was measured every 1 sec. The amount of NaCl in percentage by weight (*x*) exiting the pond over time was calculated from the EC measurements by the developed equation for this study, $x = 18176 * EC$. Residence time distribution (RTD) curves were plotted for each case by plotting the tracer exit over time.



Case ID	Operating condition	
	Inlet	Outlet
IO-1	1	1
IO-2	1	2
IO-3	1	3
IO-4	1	4
IO-5	1	5
IO-6	2	1
IO-7	2	2
IO-8	2	3
IO-9	2	4
IO-10	2	5
IO-11	3	1
IO-12	3	2
IO-13	3	3

Figure 1: Experimental tank and operating conditions

2.2. Simulation in ANSYS Fluent and treatment efficiency calculation

Once RTD curves were generated from the experiment, simulations were performed in ANSYS Fluent by the Reynolds Averaged Navier-Stokes (RANS) equation (ANSYS Inc., 2015). The transition shear stress transport (SST) model was utilized for the turbulence closure in the RANS equation. The exact geometry of the tank and inlet-outlet configurations were created and meshed using hexahedral and tetrahedral methods. There were a total of 1.5 million cells in the domain, which achieved mesh independency. The FTW was represented as a porous media. The drag due to the porous media was modeled using equation 1 (Yamasaki et al., 2022).

$$f_i = -\left(\underbrace{\frac{\mu}{K_{perm}} u_i}_{viscous\ drag} + \underbrace{\frac{1}{2} C_2 \rho |u_i| u_i}_{inertial\ drag} \right) \tag{1}$$

where K_{perm} is the permeability of the porous media, μ is the dynamic viscosity of water, u_i is the instantaneous velocity, ρ is the density of water and C_2 is the inertial drag coefficient.

The inertial drag was neglected due to high sensitivity and poor model validation outcome (Sonnenwald et al., 2016). K_{perm} was found to be 2×10^{-6} m^2 by trial and error, achieving a good agreement between experimented and modeled RTDs. The tracer was injected as discrete phase mass (DPM) with a total of 52,224 particles. The DPM particles were tracked within the porous media with their individual particle IDs and thus, the fraction of particles coming in contact with the porous media was calculated. Assuming that mass removal was only occurring within FTW, percent mass removal was estimated using equation 2:

$$R\ (\%) = f\left(1 - e^{-k_r\left(\frac{V_r}{Q_r}\right)}\right) \times 100 \qquad (2)$$

where f is the fraction of tracer mass coming in contact with the floating wetland, k_r is the removal rate within FTW, V_r is the volume of the root zone (m^3), Q_r is the flow rate to the root zone (m^3/sec), the residence time within FTW, $t_r = V_r/Q_r$.

The removal rate k_r was varied between 0.000393 and 0.015736 s^{-1} (Yamasaki et al., 2022) to achieve a non-dimensional removal rate, $k_r t_{HRT}$ between 0.5 and 20, which is the typical range for stormwater pond (Headley and Tanner, 2012; Xavier et al., 2018).

3. RESULTS AND DISCUSSION

Hydraulic performance indices, including initial arrival time (S_i), short-circuiting index (S_c) for various fractions of tracer mass exit, hydraulic efficiency index (λ), volumetric efficiency (e), moment index (M_I), and Morril index (M_o) were calculated following the derivation of RTDs from tracer experiments (Farjood et al., 2015; Khan et al.,2013; Wahl et al.,2010). The stark difference in t_{mean} (from 10.68 min to 17.25 min) and normalized t_{50} (from 0.57 to 0.86) among different cases (Table 1) represents how inlet-outlet configuration alters the hydraulic performance of an FTW retrofitted stormwater pond. Cases 1 – 5, where the inlets are all on the far side of the tank, are characterized by a high level of flow short-circuiting ($S_c > 0.8$). Initial arrival times for all cases were poor ($S_i < 0.05$) and hydraulic efficiency (λ) was remarkably fast ($\lambda < 0.1$) except for cases 10 – 12. Lower values of λ indicate the quick occurrence of the peak of the RTD curve, which deviates from the plug flow condition. Moment index (M_I) was less sensitive to changes in inlet-outlet configuration, which is probably due to the fact that M_I is taken at $t_{HRT}=1$ and is unaffected by the RTD tail (Wahl et al., 2010). Volumetric efficiency (e) varied between 0.50 and 0.81. But for the most part, it was less than 0.75, indicating the presence of dead zones in the tank (Persson and Wittgren, 2003). This might be due to the low aspect ratio (length/width = 1.486) of the tank. It was found that ponds having a low aspect ratio generally have poor volumetric efficiency (Thackston et al., 1987). Morril index (M_o) illustrates the mixing effect for inlet-outlet variation. A low value of M_o indicates a high level of mixing and vice-versa. The values of M_o were low for cases 11 – 13 (10.13 – 13.95), followed by cases 6 – 10 (15.55 – 41.01) and cases 1 – 5 (28.2 – 164.67). One of the reasons was due to the fact that the high-velocity stream from the inlet is intercepted and completely dispersed by the FTW for cases 11 – 13 (Figure 2). Cases 6 – 10 were only deflecting the high-velocity stream, being less effective in mixing. On the other hand, FTW had little effect on the mixing phenomenon for cases 1 – 5 and it was mostly influenced by the elongation of the high-velocity flow path due to the location of outlet as observed in velocity contours.

Velocity contours passing through the center of the inlet cross-section at a flow depth of 0.203 m were derived from ANSYS Fluent. The velocity contours visually illustrated how the flow field is altered due to changes in inlet-outlet configuration (Figure 2). It is noticeable that the high-velocity streams marked by red color is completely bypassing the FTW for cases 1 – 5 due to the positioning of inlet (on the far side of the longitudinal centroidal axis of the tank) and FTW (at the center). In these cases, velocity within FTW is also very low, achieving high residence time. It is also noticeable that the flow is recirculating after hitting the wall on the outlet side of the tank when the outlet no. 2 – 5 are operated. When the inlet moves between the far side and centroidal of the longitudinal axis (cases 6 – 10), the high-velocity stream is partially intercepted and then deflected by the FTW. Flow recirculation is also occurring in these cases but with less strength (velocity) due to partial interception and deflection of the high-velocity stream. It is important to note that the velocity strength is represented by colors and not the number of arrows. For cases 11 – 13, the high-velocity stream is completely diffused by the FTW, but in doing so, the residence time within FTW is also reduced compared to any other cases. Flow recirculation is mainly in the tank's first half before FTW.

Table 1: Hydraulic performance indices

Case ID	t_{mean} (min)	t_{50}	S_i	$S_{c(5)}$	$S_{c(10)}$	$S_{c(16)}$	$S_{c(25)}$	M_{75-25}	M_{90-10}	e	λ	M_I	M_o
1	10.68	0.57	0.01	0.99	0.98	0.98	0.92	1.37	2.53	0.50	0.01	0.48	164.67
2	14.73	0.80	0.01	0.98	0.97	0.86	0.72	1.41	2.85	0.69	0.02	0.62	90.41
3	15.23	0.81	0.01	0.97	0.92	0.83	0.69	1.34	2.68	0.71	0.02	0.65	42.31
4	14.46	0.74	0.02	0.97	0.91	0.85	0.72	1.25	2.45	0.67	0.03	0.62	28.20
5	14.73	0.78	0.02	0.96	0.91	0.83	0.70	1.31	2.74	0.68	0.03	0.63	41.01
6	15.01	0.77	0.02	0.95	0.90	0.80	0.67	1.21	2.48	0.70	0.03	0.64	40.22
7	16.38	0.81	0.02	0.95	0.86	0.78	0.65	1.26	2.57	0.73	0.02	0.66	19.86
8	15.83	0.79	0.03	0.94	0.84	0.77	0.65	1.22	2.54	0.72	0.04	0.66	16.95
9	15.17	0.80	0.03	0.94	0.85	0.77	0.65	1.30	2.90	0.70	0.04	0.66	20.03
10	16.16	0.82	0.05	0.93	0.83	0.75	0.62	1.19	2.42	0.75	0.06	0.67	15.55
11	17.25	0.86	0.05	0.83	0.76	0.68	0.55	1.09	2.18	0.81	0.38	0.71	10.13
12	13.63	0.69	0.03	0.90	0.83	0.76	0.66	0.97	1.97	0.65	0.22	0.63	12.70
13	15.73	0.80	0.03	0.88	0.82	0.74	0.62	1.16	2.34	0.74	0.11	0.67	13.95

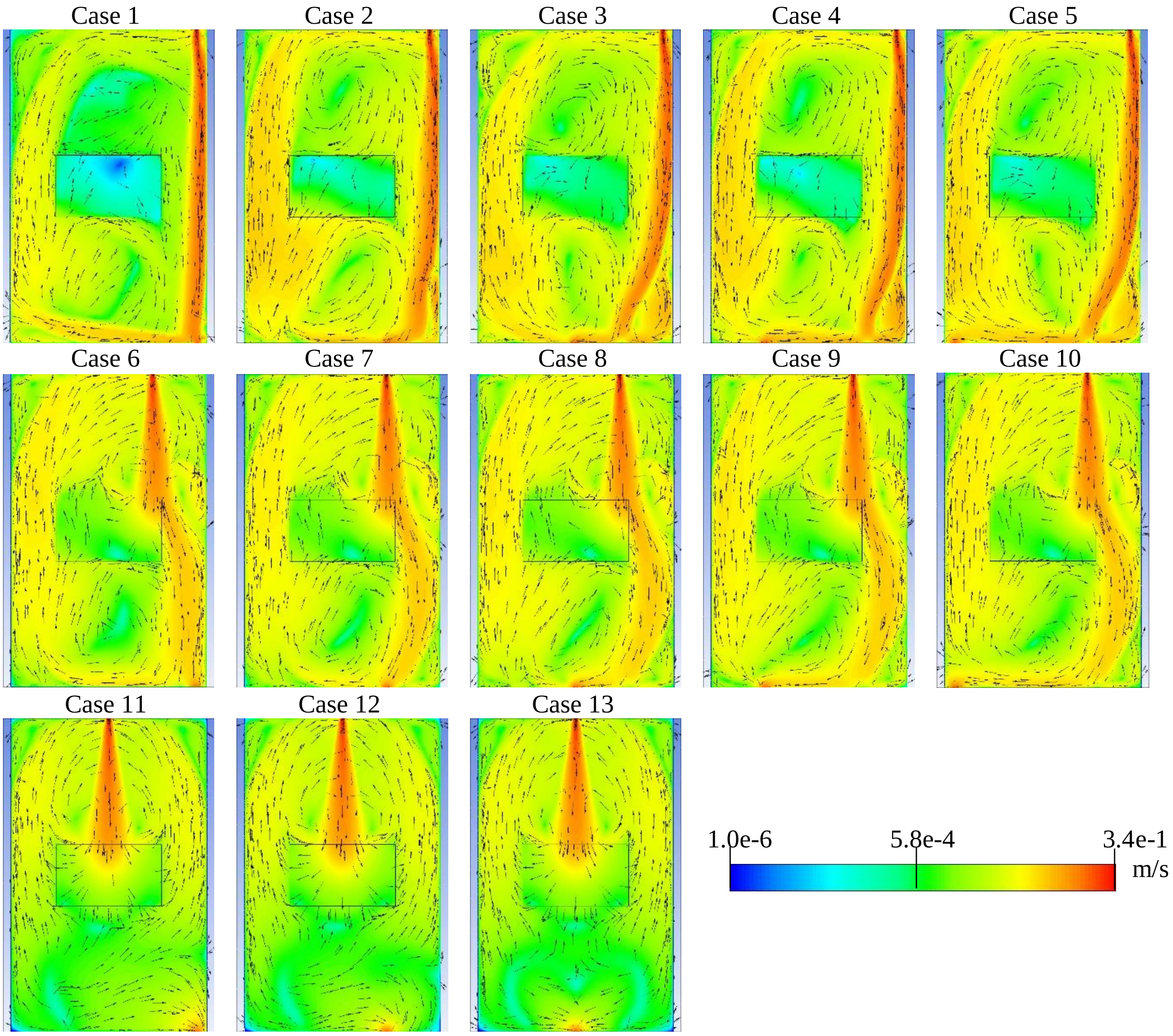


Figure 2: Velocity contours from ANSYS Fluent. The contour plane passes through the center of the inlet at y = 0.203 m. Top to bottom of the contour is the streamwise direction.

The treatment efficiency for variable values of the non-dimensional removal rate $k_r t_{HRT}$ was calculated for the studied cases, which tells a different story than described by the hydraulic performance indices. From a hydraulic performance point of view, cases 1 – 5 were among the group of worst performing cases. Nevertheless, cases 2 – 5 achieved the highest treatment efficiency compared to other cases. This discrepancy between hydraulic performance and treatment efficiency can be explained by the residence time within FTW for these cases (Table 2). The residence time within FTW for cases 2 – 5 varied between 229 and 542 s compared to 31 – 45 s for other cases for the nominal HRT of 1271 s of the tank. The high residence time within FTW achieved higher treatment efficiency for these cases (Case 2 – 5). However, for case 1, residence time was 732 s, which should have even higher treatment efficiency. It could not achieve higher treatment efficiency because pollutant mass entry to the FTW was only 22.3% compared to 45.1 – 53.0% for cases 2 – 5. As such, all supplied mass to the FTW was removed for krtHRT > 7, but due to lack of enough mass supply, it was unable to achieve any further removal. The same thing is happening for cases 2 – 4 at $k_r t_{HRT} > 10$. On the other hand, it can be observed that for cases 6 – 13, there is a continuous substantial increase of removal with the increase of $k_r t_{HRT}$. Nevertheless, due to low residence time within FTW for these cases, mass removal was mostly lower than in cases 2 – 5.

When hydraulic performance indices and removal efficiencies were plotted (not shown here due to space limitation), a second-order polynomial relationship seemed to exist between Morril index (M_O) and treatment efficiency. For other indices, no relationship was observed. Further research and data are required to establish or disprove any link between the hydraulic performance of ponds and treatment efficiency by FTWs.

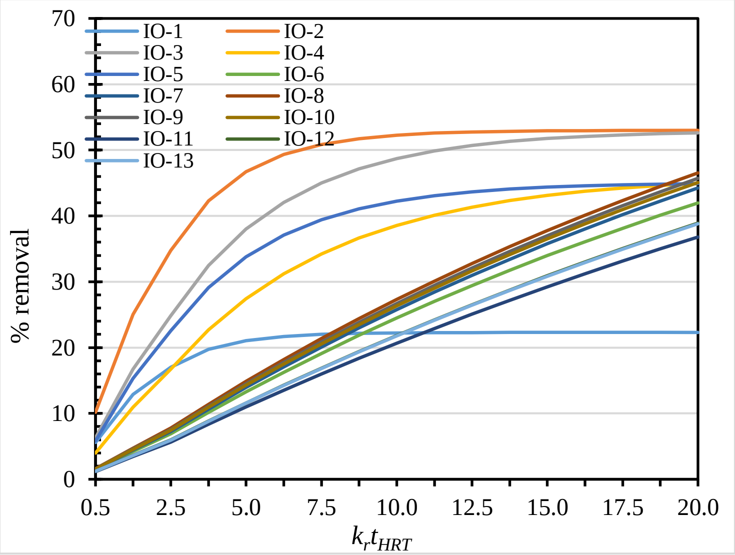


Figure 3: Pollutant mass removal for variable removal rate

Table 2: Fraction of pollutant mass entry to the FTW and residence time within FTW for t_{HRT} = 1271 s

Case ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
f	0.22	0.53	0.53	0.46	0.45	0.86	0.91	0.92	0.93	0.91	0.94	1.00	1.00
t_r (s)	732	542	322	229	352	43	42	45	43	43	32	31	31

Our study has demonstrated how inlet-outlet configurations influence hydraulic performance, flow field of pond and treatment efficiency by FTW. It is also to be noted that the treatment efficiency results of this study mainly correspond to dissolved pollutants and not sediment and sediment-bound pollutants.

4. CONCLUSIONS

We investigated the influence of inlet-outlet configurations on the flow field of FTW retrofitted stormwater pond, its hydraulic performance and ultimately, treatment efficiency by FTW. The results demonstrated that flow field is strongly altered by the inlet-outlet configuration. Especially, the creation and diffusions of high-velocity streams are governed by inlet-outlet configurations. No evidence was found that better hydraulic performance leads to higher treatment efficiency by FTW and further research is required on this issue. The best performance (53% for $k_r t_{HRT}$ =20) was found when inlet was positioned on the far side of the longitudinal axis of the pond and the outlet was located between the far side and center of the longitudinal axis of the pond. When the inlet and outlet were positioned in a way that the high-velocity stream was intercepted by the FTW, pollutant removal efficiency declined. This happened due to poor residence time within FTW despite a high fraction of pollutant mass entry to the FTW. It reveals that just mass entry to the FTW is not enough for effective treatment, rather the design of pond and FTW requires to promote higher residence time within FTW along with the high mass entry.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Australian Government Research Training Program (RTP) scholarship for supporting this research awarded to the first author of this paper at Curtin University, Australia.

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