Hydraulic investigation of the impact of retrofitting floating treatment wetlands in retention ponds

Sher Khan, Muhammad Shoaib, Mudasser Muneer Khan,
Bruce W. Melville and Asaad Y. Shamseldin

ABSTRACT

This paper describes the laboratory experimental investigations undertaken to analyse the influence of floating treatment wetlands (FTWs) on the hydraulic performance of a stormwater retention pond. Two experimental series were conducted, each focussed on investigating the influence of placing an FTW in a pond with firstly the inflow entering the retention pond from an inlet positioned 0.25 m offset from the longitudinal axis of the pond, and secondly the inlet positioned at the longitudinal axis of the pond. For both series of experiments, tests were undertaken at 1 l/s and 1.5 l/s, and with and without an artificial FTW installed. This study is the first to investigate the hydraulic impact of FTWs and their root systems on the performance of stormwater retention ponds. The results presented in this study suggest that FTWs are a viable method to minimise hydraulic inefficiencies, thereby increasing retention time and optimising hydraulic performance of stormwater retention ponds. The results highlight the importance of plant root characteristics. The optimal arrangement of root length is $L_R/D_P = 0.5$, where L_R = root length and D_P = pond depth. The results also indicate that the spatial variability of vegetation has a significant impact on the hydraulic performance of the pond.

Key words | floating treatment wetland, hydraulics, root density, short-circuiting, stormwater, stormwater ponds

Sher Khan
Bruce W. Melville
Asaad Y. Shamseldin
Department of Civil and Environmental Engineering,
University of Auckland,
Auckland,
New Zealand

Muhammad Shoaib (corresponding author)
Department of Agricultural Engineering,
Bahauddin Zakariya University,
Multan,
Pakistan
E-mail: *msho127@aucklanduni.ac.nz*

Mudasser Muneer Khan
Department of Civil Engineering,
Bahauddin Zakariya University,
Multan,
Pakistan

INTRODUCTION

Urbanisation carries with it the associated challenge of stormwater management. It is imperative that strategies and technologies are implemented in urban areas to improve the quality of stormwater discharges to protect the integrity of receiving environments, and to avoid the adverse impacts associated with sediment deposition and the accumulation of other pollutants. Floating treatment wetlands (FTWs) can be an effective way to mitigate these impacts.

FTWs are a novel and innovative variant of conventional surface-flow wetlands with sediment-rooted plants, which have been applied for water quality treatment with applications in stormwater (Kerr-Upal *et al.* 2000), wastewater (Knowles *et al.* 2010) and acid mine drainage (Sheoran & Sheoran 2006).

In contrast to surface-flow wetlands, FTWs grow on a mat floating on the surface of a water body while their roots are submerged in the water. A typical FTW arrangement is shown in Figure 1. While there are a number of complex chemical and biological processes occurring in an FTW, the main pathway of pollutant removal and immobilisation is the capture of fine particulates and their adsorbed pollutants in the roots of the floating mat (Headley & Tanner 2006).

Because they float on the surface of the water, the plants comprising FTWs are not affected by the water depth and the turbidity of water unlike those in conventional wetlands, which are effective for approximately 0.5 m depth of inundation (Wu *et al.* (2015). Hence, longer retention times can be achieved in FTWs over the same surface area due to the greater depths of the pond, which can enhance the settling process.

Although many researchers have investigated the effectiveness of FTWs in improving water quality (Keizer-Vlek *et al.* 2014; Wang *et al.* 2014; Borne *et al.* 2015; Ladislas *et al.* 2015; Lynch *et al.* 2015; Zhang *et al.* 2015), the hydraulic impacts that FTWs have on the pond system in which they are retrofitted have received very limited attention. Hydraulic performance is a wider concept that covers various

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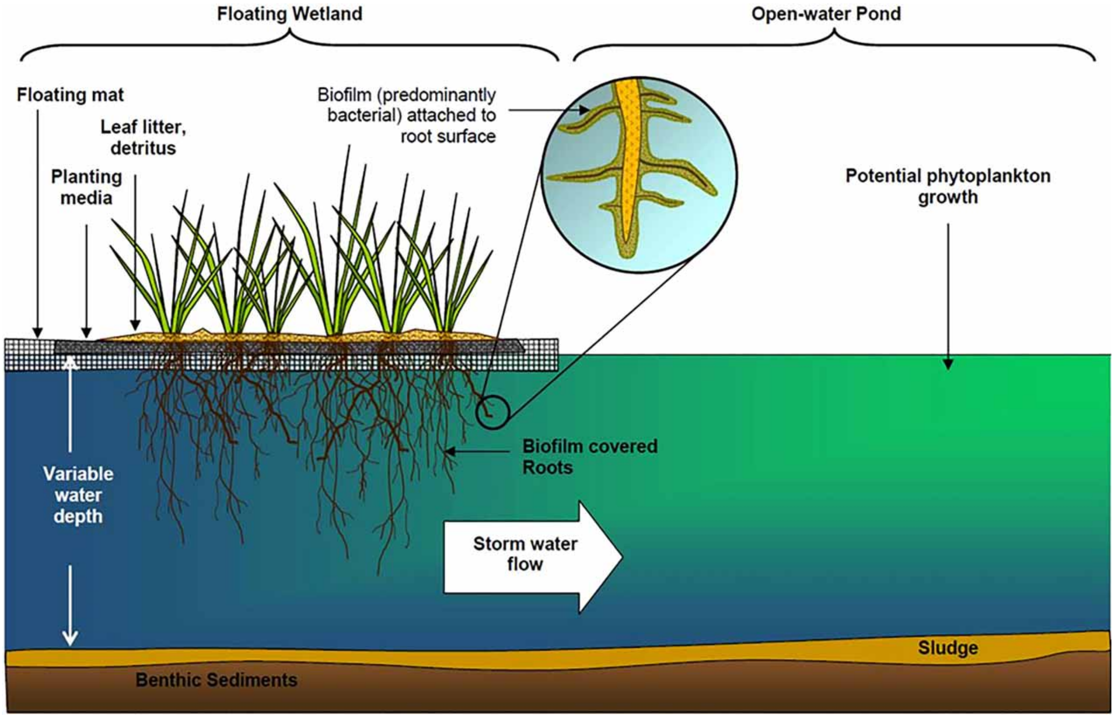

Figure 1 | Schematic functioning of FTWs (Headley *et al.* 2006).

aspects of the flow conditions (e.g. short-circuiting, effective volume and residence time distribution (RTD)) (Persson 2000). Khan *et al.* (2013) were the first to investigate the hydraulic performance of FTWs retrofitted in stormwater retention ponds. They investigated the hydraulic performance of FTWs for different placing arrangements, sizes and orientation of floating vegetated mats.

The aim of this study was to investigate the impact of the root characteristics of an FTW on the hydraulic performance of stormwater retention ponds, which is important because hydraulic performance heavily influences pollutant removal efficiency and sedimentation in ponds.

The study is based on measurements using a laboratory replica of a field retention pond in New Zealand (Figure 2).

METHODOLOGY

The model pond represents a field stormwater retention pond in New Zealand with a simple rectilinear shape. It's a scale model of Alpurt B2 stormwater retention pond situated in North of Auckland. The prototype pond has top dimensions of 41 m × 15 m (length L_p × width W_p) and depth D_p of 2.3 m. The inlet and outlet pipe diameters are 450 mm and 1,050 mm respectively. The field pond was designed for a peak inflow rate of 500 l/sec. However, during the operation of the field pond, it was observed that the inflow rate was approximately 300 l/sec (ARC 2008).

The model pond shown in Figure 3(a) is a 1/10th scale model. It has top dimensions of 4.1 m × 1.5 m (length L_m × width W_m) and depth D_m of 0.23 m with sloping sides (2H:1 V).

The inlet and outlet diameters are 45 mm and 105 mm respectively and are positioned on opposite ends of the pond. Both the inlet and outlet are aligned horizontally.

To calculate model flow rates and residence times, the scaling relationship between model and prototype was derived using the Froude number (*Fr*) scaling criterion as follows, where the subscripts '*m*' and '*p*' represent model and prototype respectively.

For the *Fr* similarity criterion:

$$Fr_m = Fr_p$$

Hence,

$$\frac{Fr_m}{Fr_p} = \frac{V_m}{V_p}\frac{\sqrt{gL_p}}{\sqrt{gL_m}} = 1$$

$$\frac{V_m}{V_p} = \frac{\sqrt{L_m}}{\sqrt{L_p}}$$

Figure 2 | View of the Alpurt B2 field pond.

i.e.

$$V_r = \sqrt{L_r},$$

where $\frac{V_m}{V_p}$ is velocity scale ratio, V_r, between model and prototype.

Also, $Q_r = L_r^{\frac{5}{2}}$, where Q_r is flow rate scale factor according to Fr similitude. Hence, $Q_m = 1$ l/s represents $Q_p = 316$ l/s, which in turn is representative of field inflow values.

During testing, the pond was filled at Q = 1 l/s until a steady state was achieved. Volume and residence time were estimated using flow depth.

The model FTW has dimensions of length $L_{fm} = 0.77$ m, width $W_{fm} = 1.14$ m and thickness $T_{fm} = 0.03$ m with the length of the roots varying from 5 to 15 cm, which represents common plant species in the real system (Tanner & Headley 2011) (Figure 3(b)). The roots were tightly sealed in the floating mat to avoid any losses of dye due to absorption during the experiments. During testing, it was ensured that at least 90% of dye was recovered, as shown in Table 1.

A total of eight arrangements were investigated, with each arrangement being run with Q = 1 l/s (details are given in Table 1). The FTW was positioned centrally across the width of the pond in all cases and at a distance of 0.5 m (5 m in field pond) away from the inlet end of the pond (Figure 3(a)). This position of the FTW gives optimal hydraulic performance (Khan *et al.* 2013).

The root characteristics; that is, root length, densities and spatial variability, were investigated for the optimised location of the FTW in the pond. Three root lengths were tested to optimise the design of the FTW in terms of root length to pond depth, i.e. $L_R/D_P = 0.25$, 0.5 and 0.71, where L_R = root length and D_P = pond depth (Cases 8–10, details are given in Table 2). For the optimised root length, three root densities (720, 360 and 180 root sets/m^2) and two arrangements of spatial variability for root density of 360 root sets/m^2 were tested as detailed in Table 2.

Similar to earlier work (Jones & Jung 1990; Shilton 2001), the present study used Rhodamine W T as an inert tracer to avoid any chemical reactions with water and to facilitate recovery of the maximum mass at the pond outlet (Holland *et al.* 2004). A 10 ml amount of 1 g/l solution of Rhodamine W T was injected into the inlet pipe as a pulse (within 1 second) at a distance of 720 mm upstream of the inlet end of the pond to allow complete mixing of the dye solution with the inflow (location of dye injection is shown in Figure 3(a)). The dye concentrations were measured at the outlet at a rate of 100 samples per second using a Seapoint Rhodamine fluorometer. Further details on fluorometer measurements are given in Khan *et al.* (2011).

From tracer experiments, RTD curves were derived, which are graphical representations of the tracer concentrations measured at the outlet against the time after the dye injection (pulse) at the inlet. These curves represent the

Figure 3 | (a) Physical model of stormwater retention pond with FTW installed. (b) Side view of FTW model and synthetic root system.

tracer distribution and its movement through the pond and indicate the time that every water particle resides in the pond. A typical RTD curve is shown in Figure 4, where $t_f =$ time at which the first parcel of the tracer reaches the outlet, and t_{p1} and $t_{p2} =$ times at which the first and second tracer concentration peaks reach the outlet. The first peak of the RTD curve represents the time that the tracer in the core of the flow needs to pass from inlet to outlet. The second and subsequent peaks represent the time that the tracer takes to reach the outlet after recirculation.

The hydraulic performance is normally measured in terms of quantities derived from the RTD curves, termed 'hydraulic parameters' herein. Similar to previous studies, the hydraulic parameters used in this study are short-circuiting, effective volume ratio, hydraulic efficiency and moment index.

The short-circuiting factor (S) is the ratio of t_{16} to t_n, where t_{16} is the time when the 16th percentile of the tracer added at the inlet has passed the outlet and t_n is the nominal residence time calculated as pond volume divided

Table 1 | Hydraulic parameters

	x/L$_m$	Cases	Q (l/s)	t$_{mean}$ (min)	t$_{16}$ (min)	t$_{50}$ (min)	t$_{p1}$ (min)	t$_n$ (min)	E	S$_C$	λ	M$_I$	Dye recovery (%)
Side-inlet		1 No FTW	1.0	9.76	1.27	7.91	0.62	12.12	0.81	0.90	0.05	0.61	97
	0.125	2 FTW	1.0	12.31	5.98	10.26	6.71	11.94	1.00	0.50	0.56	0.79	95
		Improvement in performance (%)							24%	−44%	1,000%	30%	
		1 No FTW	1.5	6.64	0.76	5.30	0.49	8.37	0.79	0.91	0.06	0.59	96
	0.125	2 FTW	1.5	8.27	3.12	6.32	3.26	8.26	1.00	0.62	0.40	0.72	93
		Improvement in performance (%)							26%	−32%	570%	22%	
Centre-inlet		3 No FTW	1.0	11.77	3.94	9.36	2.17	12.12	0.97	0.67	0.18	0.71	94
	0.125	4 FTW	1.0	11.37	5.83	9.97	5.94	11.94	0.98	0.52	0.48	0.77	92
		Improvement in performance (%)							0%	−24%	178%	10%	
		3 No FTW	1.5	8.11	2.76	6.71	2.15	8.37	0.97	0.67	0.26	0.72	95
	0.125	4 FTW	1.5	8.62	5.27	7.82	5.86	8.26	1.00	0.36	0.71	0.85	94
		Improvement in performance (%)							3%	−46%	173%	18%	
	0.25	5	1.0	11.88	6.87	10.61	8.36	11.94	1.00	0.42	0.70	0.82	92
	0.5	6	1.0	11.69	4.88	9.81	5.25	11.94	0.98	0.59	0.44	0.74	91
	0.75	7	1.0	12.12	4.82	9.97	5.20	11.94	1.0	0.60	0.44	0.75	95

by inlet flow rate (Persson 2000). A value of S greater than 0.4 is considered good, indicating an efficient pond, while a value of S less than 0.3 indicates short-circuiting (S_c) (Thackston *et al.* 1987). The short-circuiting S_c is calculated as (1-S). The maximum value for this parameter (S) is unity which would indicate no short-circuiting in the pond. The effective volume ratio (e) is the ratio of mean residence time (t_{mean}) to the nominal residence time (t_n) (Persson 2000). The maximum value of e = 1 indicates completely mixed flow or plug flow; however, it does not provide information on the mixing process which is better described by the hydraulic efficiency parameter. Further, this parameter is highly susceptible to influence from the tail effects of the RTD curve and cannot detect variations among RTDs having a common centroid. t_{mean} (average time that a tracer particle spends in the pond) can be calculated using:

$$t_{mean} = \frac{\int_0^\infty tCdt}{\int_0^\infty Cdt}$$

where C = tracer concentration measured at the outlet, at time t. Hydraulic efficiency (λ) is defined as the ratio of t_{p1} to t_n where t_{p1} is the time when the first higher peak of the RTD curve occurs. A value of hydraulic efficiency above 0.5 is considered satisfactory (Persson *et al.* 1999). The λ factor is made up of two equally weighted components, the effective volume ratio, e, and the degree of

Table 2 | Hydraulic parameters

Root length, L$_R$	L$_R$/D$_P$	Case	Q (l/s)	t$_{mean}$ (min)	t$_{16}$ (min)	t$_{50}$ (min)	t$_{p1}$ (min)	t$_n$ (min)	e	S$_C$	λ	M$_I$	Dye recovery (%)
	0	3 No FTW	1.0	11.77	3.94	9.36	2.17	12.12	0.97	0.67	0.18	0.71	97
5 cm	0.25	8 FTW	1.0	11.28	4.63	9.24	4.5	11.94	0.94	0.61	0.38	0.72	95
10 cm	0.50	9 FTW	1.0	11.88	6.87	10.61	8.36	11.94	1.00	0.42	0.70	0.82	98
15 cm	0.71	10 FTW	1.0	12.48	6.42	11	7	11.94	0.96	0.46	0.59	0.81	98

Root length, L$_R$	Roots/m^2	Case	Q (l/s)	t$_{mean}$ (min)	t$_{16}$ (min)	t$_{50}$ (min)	t$_{p1}$ (min)	t$_n$ (min)	e	S$_C$	λ	M$_I$	Dye recovery (%)
10 cm	360 Uniformly distributed	11 FTW	1.0	11.85	6.70	10.90	7.40	11.94	0.99	0.44	0.62	0.82	95
10 cm	360 A^a	12 FTW	1.0	12.35	8.20	11.92	8.70	11.94	1.00	0.31	0.73	0.89	90
10 cm	180	13 FTW	1.0	11.70	5	10	3.7	12	0.97	0.58	0.31	0.72	97
15 cm	360 Uniformly distributed	14 FTW	1.0	11.19	6.32	10.93	5.21	11.94	0.94	0.47	0.44	0.81	92

[a] In Case 12 roots are distributed such that the distance between root sets in transverse direction is half of that in longitudinal direction.

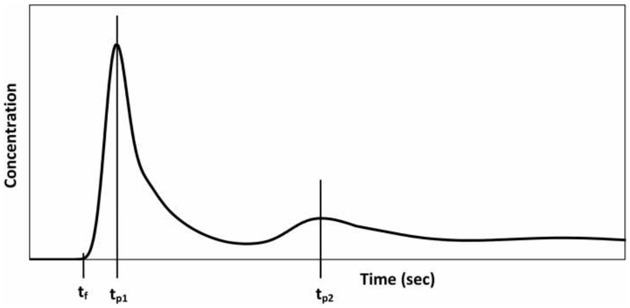

Figure 4 | A typical RTD curve.

mixing (1 – 1/N) as follows:

$$\lambda = e\left(1-\frac{1}{N}\right) = \frac{t_p}{t_n}$$

where N = number of stirred tanks. The higher the value of N, the more plug-flow-like the flow is. It is calculated as:

$$N = \frac{t_n^2}{\sigma^2}$$

where σ^2 is the variance of the RTD. This parameter provides a balance in accessing the hydraulic performance of ponds and wetlands against the uniformity of flow and effective volume ratio and accounts for the mixing characteristics in the pond. Further details are given in (Persson *et al.* 1999).

Moment index (M_I) is derived from the first moment of the normalized RTD curve (M_f), i.e. $M_I = 1 - M_f$ and M_f is calculated at $t' = \frac{t}{t_n} = 1$ as:

$$M_f = \int_0^1 (1 - t'_c) C' dt'$$

where t'_c = the normalized distance on the time-axis from the origin to the centroid of the area under the normalized RTD curve between $t' = 0$ and $t' = 1$, as shown in Figure 5 (Wahl *et al.* 2010) and $C' = \frac{C}{C_o}$ = normalized concentration, where C_o is the amount of dye added to the pond divided by the pond volume. The method assumes that residence times of a completely efficient basin meet or exceed the nominal residence time and considers hydraulic efficiency relative to the fraction of tracer exiting prematurely before $t' = \frac{t}{t_n} = 1$.

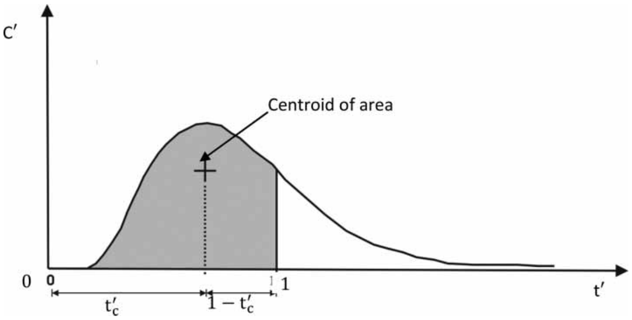

Figure 5 | Normalized tracer RTD curve.

An advantage of using M_I is that it is independent of the effects of the long tail of the RTD curve. The maximum value of $M_I = 1$ indicates plug flow.

RESULTS AND DISCUSSION

Normalized RTD curves resulting from the tracer studies of Cases 1 to 4 are shown in Figures 6 and 7. The actual concentration (C) is normalized using the concentration (C_o). The first peak of the RTD curve represents the time that the tracer in the core of the inlet jet needs to pass from inlet to outlet. The second and subsequent peaks represent the time that the tracer takes to reach the outlet after completing additional circuits of circulation cells in the pond.

Analysis of these curves gives the concentrations of the dye leaving the pond, the occurrence of the tracer peak concentration at the outlet and the time at which it occurs, directly indicating the residence times for each case. The hydraulic parameters calculated from these RTD curves are related back to the hydraulic performance of the pond as presented in Tables 1 and 2. The RTD curves presented in Figures 6 and 7 were obtained from the average data of three replicate tracer experiments for each case. A correlation analysis was also performed on each set of data. Intercorrelation between tracer tests for each set-up was above 0.97, confirming the similarity of tests. Correlations were statistically significant at 0.01 significance level.

The normalized RTD curves for Case 1 and Case 2 are given in Figure 6 for Q = 1 l/s and 1.5 l/s, respectively. The results are similar for both flow rates except for a delayed peak for the lower flow rate for Case 2.

For Case 1, the dye arrived at the outlet very quickly, i.e. $t_f = 19$ and 16 seconds for Q = 1 l/s and 1.5 l/s, respectively. The rapid appearance of the tracer at the outlet indicates the existence of preferential flow paths. The RTD curves feature two peaks for both flow rates; namely, a very high, narrow initial peak and a second much smaller peak. This indicates that a large percentage of the dye travelled directly to the outlet as a single slug while a small fraction of the dye dispersed or re-circulated, subsequently leaving the system at a slower rate. This resulted in a long tail for both flow rates suggesting the existence of dead zones in the pond.

The first peaks for Case 1 (without FTW) occurred at t_{p1} = 37 seconds and 29 seconds for flow rates of 1 l/s and 1.5 l/s, respectively, demonstrating poor performance in terms of

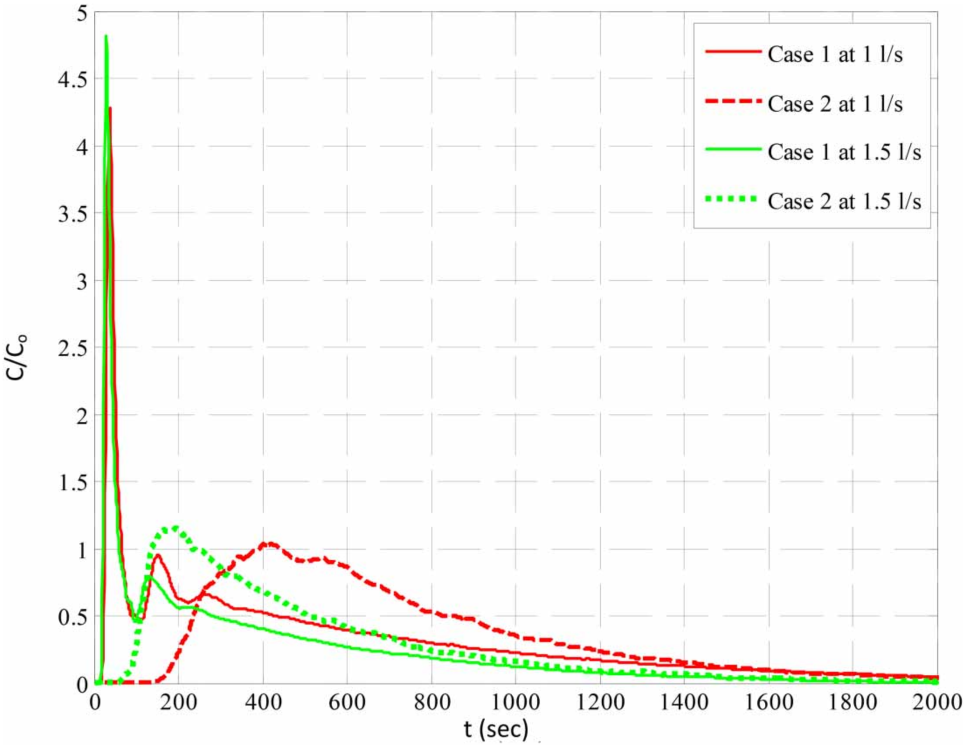

Figure 6 | Tracer response curves with and without an FTW for the side-inlet tests at a flow rate of 1 l/s and 1.5 l/s.

short-circuiting, effective volume and hydraulic efficiency. The hydraulic efficiency and effective volume were 5–6% and 79–81%, respectively, with short-circuiting of 90–91% for the range of flow rates tested. This indicates that short-circuiting was significant within the pond and the design capacity of the pond was reduced, rendering it inefficient.

In contrast to Case 1, Case 2 (with FTW) showed a vastly different tracer response (Figure 6). The t_f values were higher and the peaks were lower compared to those for Case 1 at both flow rates. Also, the peaks occurred later, indicating reduced or no re-circulation. These factors indicate reduced short-circuiting and increased effective volume and hydraulic efficiency. The hydraulic efficiency increased by 1,000% and 570% for 1 l/s and 1.5 l/s, respectively, with 100% reduction in stagnant volume. Similarly, the moment index improved by 30% and 22% and short-circuiting was reduced by 44% and 32% at $Q = 1$ l/s and 1.5 l/s, respectively.

The centre-inlet tests (Cases 3 and 4) also showed significant improvement in hydraulic performance for the tests conducted with an FTW, refer Figure 7. Compared to Case 3 (without FTW), the hydraulic efficiency of Case 4 (with FTW) was improved by 173–178% with a decrease in short-circuiting between 24 and 46% for the range of flow rates tested. Similarly the moment index was also improved significantly between 10 and 18%.

The performance parameters are summarized in Table 1. The presence of an FTW in the pond significantly reduces the prevalence of short-circuiting. The FTW induces uniform distribution of the inlet flow, which reduces the fraction of stagnant pond volume, increasing the retention time of the system. Overall, the hydraulic performance of the retention pond was significantly improved with an FTW installed.

The results also show that the pond hydraulic performance reduces at the higher flow rate for the side-inlet tests. This is attributed to high velocities at the inlet. For the side-inlet, the increased flow rate may have caused the flow circulation to be stretched towards the walls, causing an increased dead volume in the centre of the pond (Table 1, Figure 6).

Once it was found that the presence of the FTW in a retention pond increase its hydraulic performance, further testing was carried out to optimise the location of the FTW in the pond as shown in Figure A.1 in Appendix A (available online).

Comparison of Cases 3–7 in terms of hydraulic parameters shows the importance of FTW location in the pond. The values for λ, S_c, M_I and e are given in Table 1, which show that the optimum position for the FTW is $x/L_m = 0.25$, where x = distance of the model FTW from the inlet end of the model pond.

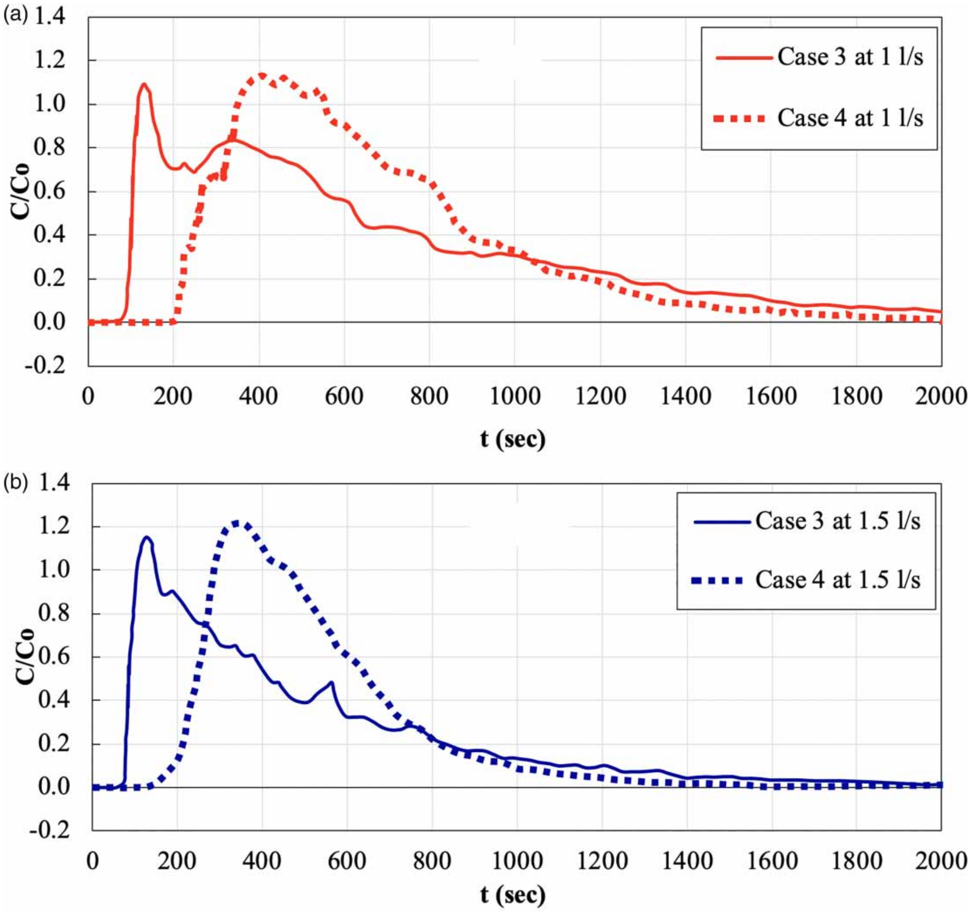

Figure 7 | Tracer response curves with and without an FTW for the centre-inlet tests at a flow rate of (a) 1 l/s, (b) 1.5 l/s.

Further investigations of root characteristics were carried out for FTW at $x/L_m = 0.25$. The results for Cases 8–10 are shown in Figure A.2 in Appendix A, which highlights the importance of plant root characteristics in terms of root length. The optimal arrangement of root length is $L_R/D_P = 0.5$; that is, the roots extend to half of the depth of the pond. For the optimal root length ($L_R/D_P = 0.5$), the effect of root density and spatial variability was investigated. It was found that reducing the root density from 720 roots/m^2 (Case 9) to 360 roots/m^2 (Case 11), where plant roots are uniformly distributed, did not significantly affect the pond hydraulic performance. However, when the roots (density = 360 roots/m^2) were distributed such that the distance between root sets in the transverse direction was half of that in the longitudinal direction (Case 12), the hydraulic efficiency was improved by 18% and the short circuiting was reduced by 30%, compared to Case 11 where the roots were uniformly distributed. This case of optimal root densities and spatial variability (Case 12, Table 2) is 400% more hydraulically efficient compared to the case with no FTW installed (Case 3, Table 2). Reducing the root density below 360 roots/m^2 gives less improvement in the hydraulic performance compared to Case 3 with no FTW (Figure A.3 in Appendix A, Case 13 in Table 2). The results indicate that the spatial variability of vegetation does have a significant effect on the hydraulic performance of the pond, this finding being consistent with previous research (Jenkins & Greenway 2005; Keefe *et al.* 2010).

CONCLUSIONS

Laboratory experiments were conducted using a physical model of a field stormwater retention pond. Measurements revealed that installing an FTW in a stormwater retention pond significantly improves the pond hydraulic performance. The presence of an FTW disrupts short-circuiting pathways within the pond, reduces the stagnant volume of the pond and significantly improves hydraulic efficiency. Such increases in efficiency are characterised by a delay in the time to peak of the RTD curves and uniform distribution of inflow in the pond.

The optimum position for the FTW is at a location 25% of the longitudinal length of the pond for centred inlet cases.

The optimal arrangement of root length is for the roots to extend to half of the depth of the pond. It was also found that the optimal root density is 360 roots/m^2 where each root contains 65 sub roots and their spatial distribution is such that the distance between the roots in the longitudinal direction is half of that in the transverse direction.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at https://dx.doi.org/10.2166/wst.2019.397.

REFERENCES

ARC 2008 *Performance of A Sediment Retention Pond Receiving Chemical Treatment Auckland Regional Council Technical Publication No. 021*.

Borne, K. E., Fassman-Beck, E. A., Winston, R. J., Hunt, W. F. & Tanner, C. C. 2015 Implementation and maintenance of floating treatment wetlands for urban stormwater management. *Journal of Environmental Engineering* **141** (11), 04015030.

Headley, T. R. & Tanner, C. C. 2006 *Application of Floating Wetlands for Enhanced Stormwater Treatment: A Review, Prepared by NIWA for Auckland Regional Council*.

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. *Ecological Engineering* **23** (3), 189–203.

Jenkins, G. A. & Greenway, M. 2005 The hydraulic efficiency of fringing versus banded vegetation in constructed wetlands. *Ecological Engineering* **25** (1), 61–72.

Jones, D. R. & Jung, R. F. 1990 Analytical problems arising from the use of bromide and rhodamine WT as co-tracers in streams. *Water Research* **24** (1), 125–128.

Keefe, S. H., Daniels, J. S., Runkel, R. L., Wass, R. D., Stiles, E. A. & Barbe, L. B. 2010 Influence of hummocks and emergent vegetation on hydraulic performance in a surface flow wastewater treatment wetland. *Water Resources Research* **46** (11), W11518.

Keizer-Vlek, H. E., Verdonschot, P. F. M., Verdonschot, R. C. M. & Dekkers, D. 2014 The contribution of plant uptake to nutrient removal by floating treatment wetlands. *Ecological Engineering* **73**, 684–690.

Kerr-Upal, M., Seasons, M. & Mulamoottil, G. 2000 Retrofitting a stormwater management facility with a wetland component. *Journal of Environmental Science and Health – Part A Toxic/Hazardous Substances and Environmental Engineering* **35** (8), 1289–1307.

Khan, S., Melville, B. & Shamseldin, A. 2011 Retrofitting a stormwater retention pond using a deflector island. *Water Science & Technology* **63** (12), 2867–2872.

Khan, S., Melville, B. & Shamseldin, A. 2013 Design of storm-water retention ponds with floating treatment wetlands. *Journal of Environmental Engineering* **139** (11), 1343–1349.

Knowles, P. R., Griffin, P. & Davies, P. A. 2010 Complementary methods to investigate the development of clogging within a horizontal sub-surface flow tertiary treatment wetland. *Water Research* **44** (1), 320–330.

Ladislas, S., Gérente, C., Chazarenc, F., Brisson, J. & Andrès, Y. 2015 Floating treatment wetlands for heavy metal removal in highway stormwater ponds. *Ecological Engineering* **80**, 85–91.

Lynch, J., Fox, L. J., Owen, J. J. S. & Sample, D. J. 2015 Evaluation of commercial floating treatment wetland technologies for nutrient remediation of stormwater. *Ecological Engineering* **75**, 61–69.

Persson, J. 2000 The hydraulic performance of ponds of various layouts. *Urban Water* **2** (3), 243–250.

Persson, J., Somes, N. L. G. & Wong, T. H. F. 1999 Hydraulics efficiency of constructed wetlands and ponds. *Water Science & Technology* **40** (3), 291–300.

Sheoran, A. S. & Sheoran, V. 2006 Heavy metal removal mechanism of acid mine drainage in wetlands: a critical review. *Minerals Engineering* **19** (2), 105–116.

Shilton, A. 2001 *Studies Into the Hydraulics of Waste Stabilization Ponds*. PhD, Massey University.

Tanner, C. C. & Headley, T. R. 2011 Components of floating emergent macrophyte treatment wetlands influencing removal of stormwater pollutants. *Ecological Engineering* **37** (3), 474–486.

Thackston, E. L., Shields, F. D. & Schroeder, P. R. 1987 Residence time distributions of shallow basins. *Journal of Environmental Engineering* **116** (6), 1319–1332.

Wahl, M. D., Brown, L. C., Soboyejo, A. O., Martin, J. & Dong, B. 2010 Quantifying the hydraulic performance of treatment wetlands using the moment index. *Ecological Engineering* **36** (12), 1691–1699.

Wang, C. Y., Sample, D. J. & Bell, C. 2014 Vegetation effects on floating treatment wetland nutrient removal and harvesting strategies in urban stormwater ponds. *Science of the Total Environment* **499** (1), 384–393.

Wu, H., Zhang, J., Ngo, H. H., Gu, W., Hu, Z., Liang, S., Fan, J. & Liu, H. 2015 A review on the sustainability of constructed wetlands for wastewater treatment: design and operation. *Bioresource Technology* **175**, 594–601.

Zhang, L., Li, Z., Wu, J. & Cheng, S. 2015 The efficiencies of floating treatment wetland on water quality improvement for loach (*Misgurnus anguillicaudatus*) cultivation. *Fresenius Environmental Bulletin* **24** (4A), 1380–1385.

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