Performance comparison of a field-scale Floating Treatment Wetland for phosphorus, heavy metals and TSS removal from stormwater runoff

Etude comparative d'une Ile Flottante Végétalisée pour le traitement des eaux de ruissellements chargées en phosphore, métaux lourds et MES

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RÉSUMÉ

Deux bassins de rétention des eaux pluviales géométriquement identiques, dont l'un contenait une ile flottante végétalisée (IFV), ont été suivis en parallèle sur une période d'un an afin d'évaluer le traitement apporté par une IFV. La performance du bassin de rétention conventionnel (BC) pour les matières en suspension (MES) et le cuivre total s'est révélée inférieure aux données présentes dans la littérature pour ce type d'ouvrage, tandis qu'aucune différence de traitement n'a été détectée pour les autres paramètres. La comparaison des débits d'entrée par rapport à la taille du bassin suggère que le BC était sous-dimensionné par rapport volume de ruissèlement de la plupart des évènements pluvieux échantillonnés. Le bassin parallèle équivalent avec IFV était plus performant, avec une concentration d'effluent inferieure de 16 à 41 % pour le phosphore total, les MES, le cuivre dissous et total, et le zinc total et un enlèvement massique statistiquement supérieur de 17, 30, 15, 18 et 20 % respectivement. Aucune amélioration n'a été statistiquement détectée pour le zinc dissous et l'orthophosphate, probablement du fait de leurs faibles concentrations en entrée. Les résultats de la présente étude suggèrent que l'installation d'une IFV sur un bassin de rétention conventionnel peut augmenter sa performance et fournit une solution pratique pour l'amélioration des bassins peu performants afin d'atteindre l'objectif de traitement de polluants clés présents dans les eaux de ruissellement.

ABSTRACT

A field trial study with side-by-side monitoring of two equivalent parallel stormwater treatment ponds, one of which contained a Floating Treatment Wetland (FTW), has been carried out to assess the benefit of retrofitting a conventional retention pond with a FTW. The conventional retention pond (CP) monitored over an annual period showed a relatively low level of performance for total suspended solids (TSS) and total copper to that reported for stormwater treatment ponds in the literature, while performance for all the other parameters was similar to that expected. Comparison of measured event flows relative to pond volume suggests the CP was undersized compared to the runoff volume of most of the sampled storm events. The equivalent parallel pond with a FTW showed significantly improved efficiency, with 16 to 41 % cleaner effluent for total phosphorus, TSS, dissolved and total copper, and total zinc, and increased mass removal efficiencies by 17, 30, 15, 18 and 20 % respectively. No statistical overall improvement was achieved for dissolved zinc and soluble reactive phosphorus probably due to their low inlet concentrations. The results suggest that inclusion of a FTW in a conventional retention pond can increase its performance and provide a practical solution for low efficiency ponds to reach treatment expectation of key stormwater pollutants.

KEYWORDS

Floating treatment wetland, Metals, Phosphorus, Stormwater runoff, TSS.

1 INTRODUCTION

Retention ponds are widely used to minimise the impact of nonpoint source pollution from stormwater runoff on the environment. Although relatively effective at removing coarse particulates and associated contaminants, they generally provide limited removal of dissolved contaminants (Van Buren, Watt, & Marsalek, 1996). A novel approach to improve the water quality performance of a stormwater retention basin is to retrofit it with a Floating Treatment Wetland (FTW). A FTW is composed of a floating mat planted with emergent aquatic plants that extend their roots into the water column. Previous studies have identified the pollutant removal capability of FTWs (De Stefani, Tocchetto, Salvato, & Borin, 2011; Hubbard, 2010; Stewart, Mulholland, Cunningham, Kania, & Osterlund, 2008; Tanner & Headley, 2011; Van De Moortel, Meers, De Pauw, & Tack, 2010). These studies mainly reported the nutrient removal efficiency, while a few mesocosm experiments addressed heavy metals' treatment. There is relatively little empirical evidence regarding the performance of these systems treating urban stormwater runoff at a field scale.

This paper summarizes the findings of a field study with side-by-side monitoring of two geometrically similar retention ponds, one of which contained a FTW with fully developed vegetation. The main objective was to quantify the pollutant removal improvement in a stormwater retention basin retrofitted with a FTW compared to a conventional unvegetated retention pond. During 17 storm events, inflow and outflow event mean concentrations (EMCs) were quantified and used to assess the overall pollutant removal efficiency of each system. This paper focuses on total suspended solids (TSS), dissolved and particulate copper (Cu) and zinc (Zn) and total and soluble reactive phosphorus (P) removal performance.

2 METHODS

2.1 Experimental site

The experimental site is a stormwater retention pond located on a highway interchange at Silverdale about 35 km north of Auckland, New Zealand. The catchment is approximately 1.7 ha, which is 75% impervious. To allow a side by side performance comparison, the retention pond was divided into two parallel straight-walled sections (~100 m^2 each), fed by a common forebay. Each partitioned section had a permanent water depth of 0.75 m with infiltration losses expected to be negligible due to a thick clay base. Inlets and outlets, and overall partition geometry had the same dimensions (Figure 1). Centrally-located V-notch weirs at the inlets and outlets show inflows and outflows presenting similar hydrographs with equivalent water volumes for both ponds.

An approximately 50 m^2 (5.2 x 9.75 m^2) FTW was installed on 8 December 2010 (summer in the Southern Hemisphere) in one partition ("FTW pond", abbreviated as "FTWP"), while the other partition ("control pond", abbreviated as "CP") served as a control. The FTW comprised a rectangular 200 mm thick mat of tangled polyester fibre injected with patches of buoyant polyurethane foam (Biohaven™ Floating Islands, Waterclean Technologies, Kaiwaka, New Zealand) planted with *Carex virgata* (~17 plants/m^2).

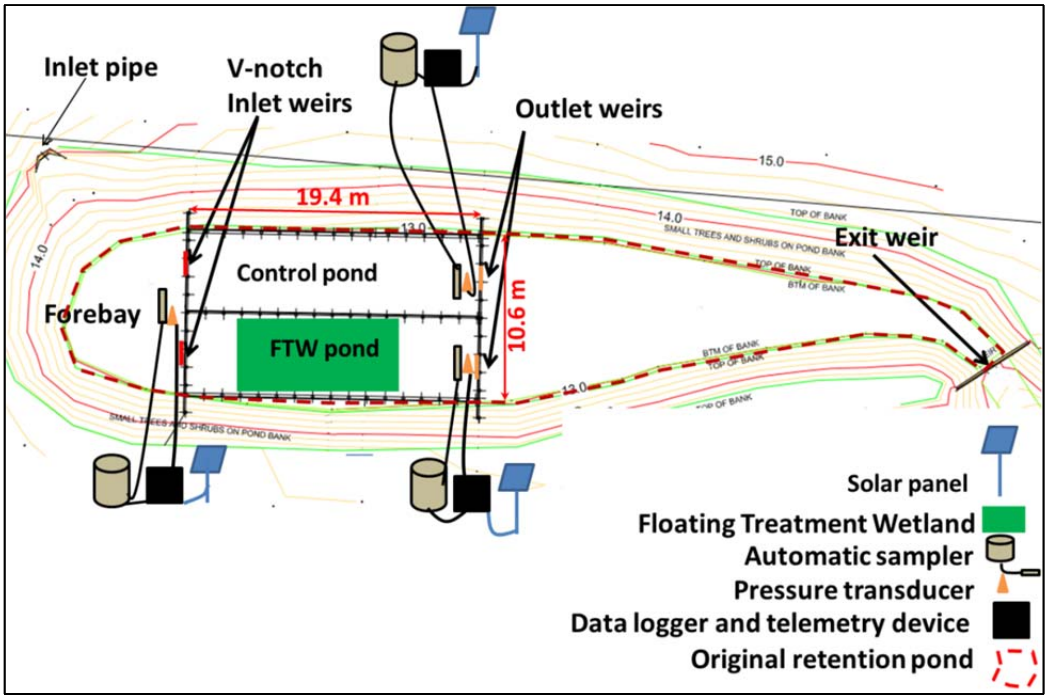

Figure 1.Pond partitioning and instrumentation location (Borne, Fassman, & Tanner, 2013)

2.2 Hydrologic monitoring

Three pressure transducers (PT) (INW AquiStar® PT12, 3 m range, accuracy:+/- 0.1% full scale output (FSO)), were installed to measure the water level. One PT was located in the forebay, just upstream of the inlet weirs, and one upstream of each outlet weir (Figure 1). PT measurements coupled with the standard equation for a fully contracted sharp-crested 90º V-notch weir (Bos, 1989) were used to calculate inflows at two minute intervals. Due to small leaks in the outlet walls of both ponds causing some of the flow to not exit via the outlet weirs, outflows were determined as the difference between the inflows and the variation in water storage over two minute intervals. Hydrologic routing was used to calculate outflows with the following equation:

$$(1)\ Qout(t2) = Qin(t2) - A * \frac{h(t2)-h(t1)}{t2-t1}$$

where :

- A: pond area (no change of the surface area depending on pond depth as pond walls are vertical)
- h(t): water level in the pond at time t
- Qin: inflow
- Qout: outflow

2.3 Storm events sampling and analysis

Three ISCO 3700 automatic samplers were installed in the forebay and upstream of each outlet weir to collect storm event samples (Figure 1). Within 24 h of each storm event, the samples were transported to the University of Auckland laboratory to make flow-weighted composite samples which were sent immediately for analysis to an external laboratory (Watercare Ltd., Auckland, New Zealand, an International Accreditation New Zealand laboratory). Composite samples were made with 8 to 96 aliquots (average of 33 for the inlet and 15 for the outlets) representing at least 63% of the runoff hydrograph with an overall average for all storm events of 88%. The analysis of each composite sample gave the event mean concentrations (EMCs) for each sampling station. Samples to be analysed for dissolved copper (DCu) and zinc (DZn) were filtered according to method 3030 B (APHA, 2005)-modified to acidify to 10 mL HNO_3 /L of sample to match standard/control samples acid concentration used during subsequent analysis. Samples for total copper (TCu) and total zinc (TZn) were digested according to method 3030 E (APHA, 2005) – modified to allow automated digestion process using a Hotblock® rather than hotplate and with a nitric/hydrochloric acid digest (4:1 ratio). Both metals were quantified by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) in accordance with EPA method 200.8 (USEPA, 1994) modified to use reaction cell to minimize interferences. Particulate copper (PCu) and zinc (PZn) were calculated as the total metal concentration minus dissolved metal concentration. Samples for soluble reactive phosphorus (SRP-P) analysis were filtered according to method 4500-P B (APHA, 2005). SRP-P and total phosphorus (TP) were quantified by automated ascorbic acid reduction method according to method 4500-P F (APHA, 2005).Total suspended solids (TSS) were analysed according to method 2540 D (APHA, 2005) .

For individual storm events, pollutant mass removal efficiency (MRE) was calculated as:

$$(2)\ MRE\ (\%) = \frac{(V_{in} * EMC_{in}) - (V_{out} * EMC_{out})}{(V_{in} * EMC_{in})} * 100$$

where V_{in} and V_{out} are volume of runoff in and out, respectively and EMC_{in} and EMC_{out} are event mean concentrations of inlet and outlet samples, respectively. When EMCs were below the method detection limit (MDL), the MRE was calculated using the MDL value.

The water quality data were statistically analysed to compare paired influent and effluent concentrations, paired FTWP effluent and CP effluent concentrations and paired FTWP and CP MREs. The difference between each set of paired data was tested for normality using the Shapiro-Wilk test. If data were normally distributed, a paired Student's t-test was performed. Otherwise, a Wilcoxon signed rank test was used. All tests were achieved using the software SPSS statistics 19 (IBM).

3 RESULTS AND DISCUSSION

Auckland is located in a sub-tropical climate zone, with warm humid summers and mild rainy winters. Over the monitoring period, recorded air temperatures at a weather station 15 km away ranged from 2.7 to 20.75ºC (mean of 11.7ºC) in winter and from 12.85 to 24.6ºC (mean of 18.1ºC) in summer (National Institute of Water and Atmospheric Research, 2012). The annual precipitation over the sampling period was 1257 mm (recorded 3.5 km from the site (Auckland Council, 2012)) which is similar to the long-term average of 1240 mm for the Auckland region (National Institute of Water and Atmospheric Research, 2012).

Seventeen storm events were sampled over a period of 1 year (May 2011-June 2012) for both ponds. Inlet and outlet EMC statistics are presented in Table 1.

Table 1- Summary EMC statistics across 17 storm events

		SRP-P	TP	TSS	DCu	PCu	TCu	DZn	PZn	TZn
		µg/L	µg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
Inlet	Median EMC	10	90	30	4.9	3.6	9.2	7.6	27.5	35.0
	25th-75th percentile	5-80.5	63-136	23.5-53.5	4-7	1.8-5.2	7.3-10.5	5.8-11.5	19.3-40.6	26-55.8
CP	Outlet median EMC	15	66	25	4.4	3.1	7.6	6.3	17.0	23.0
	25th-75th percentile	5-27.5	52-100	22.4-32.6	3.7-5.4	2.1-3.9	6.9-8.3	4.4-8.4	12.1-24.3	18.5-30.5
FTWP	Outlet median EMC	11	45	15	3.8	1.8	5.8	6.2	10.0	15.0
	25th-75th percentile	7-34.5	35.5-78.5	8.5-17.2	3.2-4.5	0.9-2.6	5-6.5	4.9-7.9	5.5-15.1	12-22.8
Statistical tests results (p value where relevant)*										
CP outlet vs. Inlet EMCs		0.048	0.006	0.024	0.027	-	0.008	-	0.0002	<0.0001
FTWP outlet vs. Inlet EMCs		-	<0.0001	<0.0001	0.0001	0.0001	<0.0001	0.049	<0.0001	<0.0001
CP outlet vs FTWP outlet EMCs		-	<0.0001	<0.0001	0.008	<0.0001	<0.0001	-	<0.0001	<0.0001

* p value specified only if < 0.05 otherwise " - " indicates that no significant statistical difference was found

Outlet EMCs of both ponds were statistically lower than inlet EMCs except for PCu and DZn for the CP and SRP for the FTWP (Table 1). FTWP outlet EMCs of all the parameters, except SRP and DZn, were statistically lower from 16 to 41 % than CP (median of the % difference between paired outlet EMCs). No statistical improvement was noticed for SRP and DZn probably because their inlet EMCs were already low. Indeed the median EMCs were below or equal to the Australian and New Zealand Environment Conservation Council (ANZECC & ARMCANZ, 2000) trigger values. These guidelines recommend a fresh water DZn concentration lower than 8 µg/L for the protection of 95% of the species for soft water (the most restrictive hardness for freshwater) and 10 µg/L SRP to ensure a low risk of adverse biological effects. TP, TSS, DCu, PCu, TCu, PZn and TZn MREs of the FTWP were significantly higher than the CP MREs (Table 2) by 17, 30, 15, 28, 18, 25 and 20 % respectively (median of the differences between paired MREs). These results are promising and imply that inclusion of a FTW into a conventional retention pond can significantly improve its performance for most of the monitored analytes.

Table 2- Summary MRE statistics across 17 storm events

		SRP-P	TP	TSS	DCu	PCu	TCu	DZn	PZn	TZn
CP	Median MRE (%)	16	24	12	10	19	15	22	40	41
	25th,75th percentile	-7,49	1,46	-4,54	-5,26	-16,50	0,29	4,46	4,62	14,56
FTWP	Median MRE (%)	4	42	58	25	50	36	21	65	57
	25th,75th percentile	-9,42	24,63	34,75	14,42	35,70	20,46	6,50	40,81	38,72
Statistical tests results (p value where relevant)*										
CP MREs vs FTWP MREs		-	<0.0001	<0.0001	0.0006	<0.0001	0.0003	-	<0.0001	<0.0001

* p value specified only if < 0.05 otherwise " - " indicates that no significant statistical difference was found

In order to appreciate the potential improvement brought by the FTW in a more general context, the performance of CP and FTWP was compared to reported efficiencies for typical retention ponds and wetlands. Three references were selected for comparison (Watershed Management Institute Inc.(1997), Center for Watershed Protection (2007) and Geosyntec Consultants Inc and Wright Water Engineers Inc (2012)) which summarize the general performance of various stormwater best management practices, primarily sourced from data generated across the USA. The CP median MREs for TP, TSS and TCu in the present study were below the reported or expected efficiencies for retention ponds (Table 3), while TZn median MRE was in the lower range.

Table 3-Retention ponds removal efficiencies reported in the literature

	SRP-P	TP	TSS	DCu	PCu	TCu	DZn	PZn	TZn
Watershed Management Institute Inc. (1997)									
Expected removal efficiency range (%)	-	30-80	50-90	-	-	20-80	-	-	30-90
Center for Watershed Protection (2007)									
Removal efficiency range (25th-75th percentile) (%)	-	39-76	60-88	-	-	45-74	-	-	40-72
Median removal efficiency (%)	-	52	80	-	-	57	-	-	64

- No data

MRE is highly influenced by the inlet EMC, where a higher MRE results from a higher inlet EMC. The present study site exhibited fairly low inlet median EMCs (Table 1) compared to the retention ponds reported in the literature (Table 4), except for TCu. This could explain the lower MREs of some of the parameters.

Table 4-Retention ponds and wetland basins EMCs reported in the literature (Geosyntec Consultants Inc & Wright Water Engineers Inc, 2012)

		SRP-P	TP	TSS	DCu	PCu	TCu	DZn	PZn	TZn
		µg/L	µg/L	mg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
Retention ponds										
Inlet	median EMC	104	295	70.8	6.6	-	9.6	22.6	-	53.6
	25th-75th percentile	85.7-108	270-314	20.7-180	5.98-7.0	-	8-10	18-26	-	49-59
Outlet	median EMC	40.4	128	13.5	4.2	-	5.0	9.6	-	21.2
	25th-75th percentile	30.8-45	116-140	5.72-33.0	4.0-4.57	-	4.43-5	5.29-10.9	-	20-23
Wetland basins										
Inlet	median EMC	42.7	127	20.3	5.99*	-	5.6	35.1	-	70.2
	25th-75th percentile	36.6-48.5	114-138	9.4-54.4	3.9-7.68	-	4.33-6.34	30.1-45	-	31.6-87.3
Outlet	median EMC	19.3	82.8	9.06	5.75*	-	3.6	22.3	-	29.8
	25th-75th percentile	12-21	71-91	2.36-19.5	4.56-7.3	-	3.0-4.0	10.1-26.8	-	12-33.3

- No data, *based on only 2 studies including 15 inlet and outlet EMCs

In terms of outlet EMCs, only TSS and TCu were distinctly higher at the study site while the other parameters were lower or relatively close (for DCu and TZn) to the reported outlet median EMCs for retention ponds (Table 4). The CP thus seems to have provided low level of treatment for TSS and TCu compared to general literature expectations, but didn't show any specific differences for the other parameters.

Design guidelines in Auckland (Auckland Regional Council, 2003) recommend a permanent pool for storage of 1/3 of the 2 year average recurrence interval (ARI) storm to enable the capture of most storm events and allow settling of particles. The original retention pond, in which the CP and FTWP were built, complied with these guidelines. The CP and FTWP extend over only part of the original pond (Figure 1) and thus only provide about half of this storage capacity. As a consequence only 4 storm events out of 17 sampled were entirely captured in the CP (those data below the flow ratio = 1 line, Figure 2). These storm events showed mainly high TSS MREs (>57% for ¾ of the storms, 12% for the 4th storm) and TCu MREs (>26% for all storms) compared to the overall performance of the pond (12% for TSS and 15 % for TCu). These storms exhibited lower outlet EMCs (median of 19 mg/L for TSS and 7 µg/L for TCu). The relatively poor performance of the CP thus appears to be attributable to its relatively low permanent pool volume compared to the runoff volume of most of the sampled storm events.

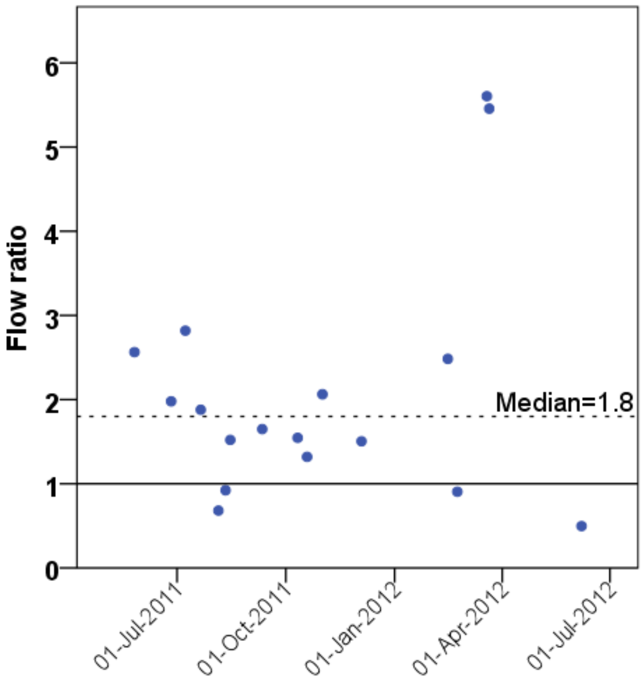

Figure 2-Flow ratio (ratio of inflow volume to permanent pool volume of CP) of the 17 storm events

FTWP median MREs for TP, TSS, TCu and TZn were all within the range of expected efficiencies reported for retention ponds (Table 2 and Table 3). Unlike the CP, the FTWP exhibited lower (for DCu and TZn) or relatively close (for TSS and TCu) outlet EMCs to the reported data for retention ponds (Table 1 and Table 4).

The FTWP can be classified as an intermediate system between a retention pond and a wetland basin. Wetland basins are often recognised as providing more treatment for fine particles, nutrient and dissolved metals than retention ponds (Bavor, Davies, & Sakadevan, 2001; Stumm & Morgan, 1981). Distinctly better performance for wetlands than retention ponds is not evidenced from the data presented in Table 4 especially for DCu, DZn and TZn, although lower outlet concentrations were reported for SRP, TP, TSS and TCu (Table 4). For these parameters, except TSS, the FTWP achieved lower or similar outlet EMCs to those reported for wetlands. This suggests that retrofitting a undersized retention pond providing a relatively modest water quality treatment (such as that found in the present study) with a FTW would improve its efficiency to expected retention pond and/or wetland basins performances.

An experimental study (Tanner & Headley, 2011) also found significantly improved removal of Cu, fine suspended solids and SRP for mesocosms with planted FTWs compared to controls without. FTWs planted with the same species used in the present study (*Carex virgata*) achieved reductions of ~ 67, 14, 26 and 28% of TCu, TZn, SRP and TP concentrations respectively during 7 day batches. Lower reductions for TCu and SRP were recorded in the present study with medians of 34 and 0% difference between inlet and outlet EMCs respectively. TZn and TP exhibited higher concentration reduction with a median of 57 and 40 % in the present study, respectively. It has to be noted that TZn and SRP initial concentrations in the mesocosm experiment were about 10 to 50 times higher than the median inlet concentrations of the present study. The volume of water to be treated compared to the size of the FTW differed with 2 m^3/m^2 of FTW in Tanner and Headley (2011) and from 0.8 to 8.8 m^3/m^2 of FTW (median of 2.7 m^3/m^2) in the present study. These elements and the fact that the FTWP was a dynamic system, in contrast with stagnant water in the mesocosm experiment, are factors which can explain the different performances.

4 CONCLUSION

The CP, monitored over an annual period, showed a relatively low level of performance for TSS and TCu than reported for stormwater treatment ponds in the literature, while performance for all the other parameters was similar to that expected. Comparison of measured event flows relative to pond volume suggests the CP was undersized compared to the runoff volume of most of the sampled storm events. An equivalent parallel pond with a FTW showed improved efficiency, with 16 to 41 % cleaner effluent than the conventional retention pond for TP, TSS, DCu, PCu, TCu, PZn and TZn and statistically improved MREs by 17, 30, 15, 28, 18, 25 and 20 % respectively. No statistical overall improvement was achieved for DZn and SRP probably due to their low inlet EMCs. The results suggest that retrofitting ponds with FTWs can provide enhanced treatment efficiencies for key stormwater pollutants.

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