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# Components of floating emergent macrophyte treatment wetlands influencing removal of stormwater pollutants

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ABSTRACT

Floating treatment wetlands planted with emergent macrophytes (FTWs) provide an innovative option for treating urban stormwaters. Emergent plants grow on a mat floating on the water surface, rather than rooted in the bottom sediments. They are therefore able to tolerate the wide fluctuations in water depths that are typical of stormwater ponds. To better understand the treatment capabilities of FTWs, a series of replicated ($n = 3$) mesocosm experiments ($12 \times 0.7\,m^3$ tanks using $0.36\,m^2$ floating mats) were conducted over seven day periods to examine the influence of constituent components of FTWs (floating mat, soil media, and four different emergent macrophyte species) for removal of copper, zinc, phosphorus and fine suspended solids (FSS) from synthetic stormwater. The presence of a planted floating mat significantly ($P < 0.05$) improved removal of copper (>6-fold), fine suspended particles (~3-fold reduction in turbidity) and dissolved reactive P (in the presence of FSS) compared to the control. Living plants provided a large submerged root surface-area ($4.6–9.3\,m^2$ of primary roots $m^{-2}$ mat) for biofilm development and played a key role in the removal of Cu, P and FSS. Uptake of Cu and P into plant tissues during the trials could only account for a small fraction of the additional removal found in the planted FTWs, and non-planted floating mats with artificial roots providing similar surface area generally did not provide equivalent benefits. These responses suggest that release of bioactive compounds from the plant roots, or changes in physico-chemical conditions in the water column and/or soils in the planted FTWs indirectly enhanced removal processes by modifying metal speciation (e.g. stimulating complexation or flocculation of dissolved fractions) and/or the sorption characteristics of biofilms. The removal of dissolved zinc was enhanced by the inclusion of a floating mat containing organic soil media, with reduced removal when vegetated with all except one of the test species. The results indicate that planted FTWs are capable of achieving dissolved Cu and Zn mass removal rates in the order of $5.6–7.7\,mg\,m^{-2}\,d^{-1}$ and $25–104\,mg\,m^{-2}\,d^{-1}$, respectively, which compare favourably to removal rates reported for conventional surface flow constructed wetlands treating urban stormwaters. Although not directly measured in the present study, the removal of particulate-bound metals is also likely to be high given that the FTWs removed approximately 34–42% of the turbidity associated with very fine suspended particulates within three days. This study illustrates the promise of FTWs for stormwater treatment, and supports the need for larger-scale, longer-term studies to evaluate their sustainable treatment performance.



## 1. Introduction

Urban watersheds are characteristically highly impervious, generating large flow peaks during storm events that mobilise a "cocktail" of particulate and dissolved pollutants. Conventional urban stormwater treatment devices, such as catch-pits and sedimentation ponds, can effectively remove coarse particulates from these flows, but are limited in their ability to remove dissolved, colloidal and fine suspended metal and nutrient fractions. These fine fractions have higher metal adsorption capacity than coarser particulates, and along with dissolved forms tend to be the most bioavailable and toxic to aquatic life (Luoma, 1983; Griffiths and Timperley, 2005). Appropriately sized constructed wetlands have been shown to be effective at removing a wide range of priority metals from stormwaters and wastewaters (Dunbabin and Bowmer, 1992; Carleton et al., 2001; Reddy and DeLaune, 2008; Kadlec and Wallace, 2009), and are generally considered to be more effective at removing dissolved and fine particulate contam-

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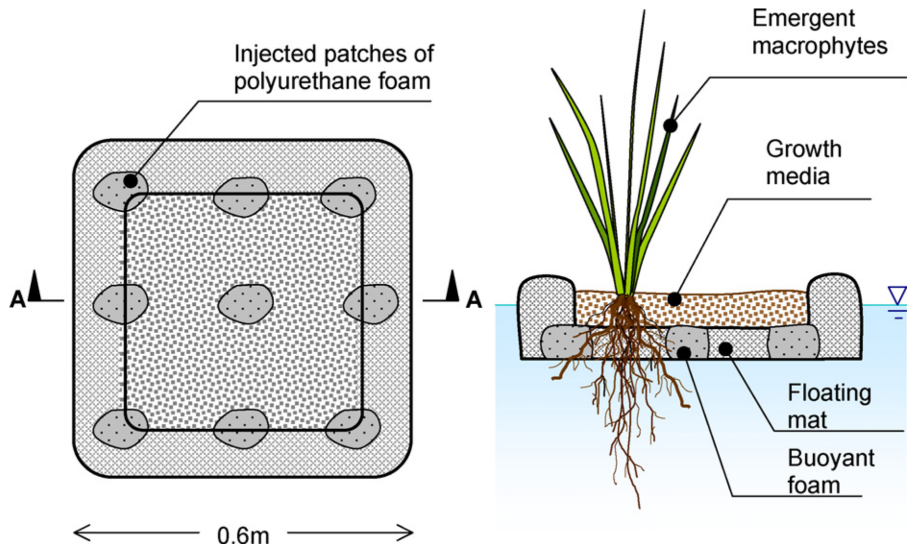


**Fig. 1.** Plan-view (right) and cross-section (left) of an experimental floating treatment wetland. Only a single plant is shown for clarity.

inant fractions than ponds (Wong et al., 2000; Bavor et al., 2001; Pontier et al., 2001). However, the rooted vegetation used in conventional wetland systems can only tolerate relatively shallow water depths (commonly <0.5 m over long periods) and short periods of total submergence, so depths (and residence times per unit area) of wetlands are generally less than for stormwater retention ponds.

Floating emergent macrophyte treatment wetlands (FTWs) are a novel treatment concept that employ rooted, emergent macrophytes growing in a floating mat on the surface of the water rather than rooted in the sediments (Fonder and Headley, 2010; Headley and Tanner, in press). The plant roots hanging beneath the floating mat provide an extensive surface area for attached biofilm growth and entrapment of fine suspended particulates (Fig. 1). Because the plants are not rooted in soils in the base of the wetland, they are forced to acquire their nutrition directly from the water column, which may enhance rates of nutrient and element uptake into biomass. Their buoyancy enables them to tolerate wide fluctuations in water depth. This provides potential to enhance treatment performance by increasing the water depth retained during flow events to extend the detention time of stormwaters in the wetland. It also presents opportunities to retro-fit FTWs into existing retention pond systems to improve performance and enhance their aesthetic and wildlife values. Despite these potential advantages, there have been only limited investigations conducted to date into the performance and functioning of FTWs for stormwater treatment.

This paper summarises a series of mesocosm experiments designed to better understand the capabilities of FTWs to remove common stormwater contaminants and elucidate the contribution made by their basic structural components; floating mat, soil media, and plants. Performance for the floating mat alone, the floating mat with soil media, and for the floating mat with soil media and either live plants or artificial roots is compared against a control. Our focus for this study was on pollutants which do not have significant gaseous removal mechanisms: fine inorganic particulates; the metals Cu and Zn; and the nutrient phosphorus. The specific objectives of the experiments were to:

1. quantify the rates of contaminant removal achievable using floating treatment wetlands;
2. identify which components of the FTW most influence contaminant removal performance; and compare the growth characteristics, pollutant assimilation rates and relative treatment performance of four different wetland plant species.

## 2. Methods

### 2.1. Mesocosms and experimental treatments

A series of batch mesocosm experiments were conducted during March and April of 2007 (Southern Hemisphere early autumn) at the Ruakura Research Centre in Hamilton, in the North Island of New Zealand (37°44′S, 175°19′E). Experiments were carried out in twelve polyethylene tanks (1 m × 1 m surface opening, tapering to 1 m depth; volume 0.717 $m^3$ at 0.75 m operational water depth), under a clear horticultural plastic shelter that excluded rainfall. The tanks were connected to a large 10 $m^3$ polyethylene mixing tank from which synthetic stormwater solutions were dispensed at the start of each batch.

To determine the influence of the different components of the floating wetlands, water quality responses were compared in triplicate for eight different randomly assigned treatments, including a control (Table 1). The control tanks were shaded by a rigid black polythene cover, the same size as the floating mats, suspended 100 mm above the water surface. This avoided proliferation of planktonic and attached algae in the control tanks, which would have complicated comparisons between treatments.

The floating wetland treatments comprised 0.36 $m^2$ square mats of intertwined polyester fibre (∼95% porosity) injected with patches of polystyrene foam to provide buoyancy (BioHaven™,

**Table 1**
Summary of experimental treatments.

| Treatment | Code |
|---|---|
| Control (no floating mat, but equivalent shading) | C |
| Floating mat only | M |
| Mat + soil media | MS |
| Mat + soil + artificial roots | AR |
| Mat + soil + *Carex virgata* | CV |
| Mat + soil + *Cyperus ustulatus* | CU |
| Mat + soil + *Juncus edgariae* | JE |
| Mat + soil + *Schoenoplectus tabernaemontani* | ST |

Floating Islands International, Shepherd, MT, USA) (Fig. 1). The buoyant mats were 150 mm thick on the edges with a 100 mm deep depression in the top to hold the growth media (1 part sand, 2 parts sphagnum peat, and 1 part compost, pH-neutralised with ground limestone). To ensure all floating mats sat level at the same depth in the tanks (half submerged), they were supported on two 10 mm thick fibreglass rods criss-crossed from corner to corner of the tanks. Four different emergent macrophyte species were individually tested; *Carex virgata* Sol. ex Boott, *Cyperus ustulatus* A. Rich., *Juncus edgaria*e LAS Johnson & KL Wilson, and *Schoenoplectus tabernaemontani* (CC Gmel.) Palla. Seed-raised plants (with potting media removed) were planted into soil media-filled floating mats at a rate of 15–17 plants per mat, and allowed to establish for 10 months in a large holding tank with approximately monthly addition of synthetic stormwater constituents. The non-vegetated mat treatments were also pre-conditioned in the same holding tank.

The artificial root system treatments were fabricated by attaching bundles of a branched polyester yarn (Plumes knitting yarn, Sullivans International Pty., Ltd., Auckland, NZ) to the underside of floating mats. The yarn, which resembled roots, had numerous 20 mm long lateral threads along its length of similar diameter and length to the roots observed growing beneath the planted mats. Based on measurements of the root length and density of the planted floating mats before the treatment trials in January, 2007, seven hundred 0.45 m lengths of the thread (total length of 875 m "root" $m^{-2}$ of floating mat, not counting laterals) were attached to the base of floating mats to provide a similar density and surface area to that of the planted floating mats.

Each treatment was monitored four times over two 7-day batches. Artificial stormwater was prepared in a holding tank and gently mixed using a small submersible pump for 24 h prior to filling of the mesocosm tanks. The synthetic stormwater was adjusted to have an initial concentration of key pollutants as shown in Table 2. This was similar to the mean of the 90th percentile concentrations reported from a two year monitoring program of urban stormwater from eight different catchments in Auckland, New Zealand (ARC, 2004). A commercially available hydroponic fertiliser mix (Manutec Pty., Ltd., Cavan SA, Australia) was also added in small quantities to provide a background mix of other nutrients and trace elements (N, K, Ca, Mg, Fe, Mn, $SO_4$, B and Mo). Dissolved inorganic N levels measured in the tanks at the start of each batch were relatively high at 7–8 g $m^{-3}$ (>95% as nitrate), so unlikely to be limiting to plant growth relative to other nutrient levels. Water levels in each tank were topped up to their standard level in the morning before each sampling to make up for evaporation and transpiration losses. Between each batch the mesocosm tanks were emptied and carefully cleaned out to remove any sediment or biofilm that had accumulated on the base and walls of the tanks.

**Table 2**
Target concentrations of key pollutants in the artificial stormwater, based on rounded means of ninety percentile values reported for urban stormwater in Auckland City, New Zealand (Griffiths and Timperley, 2005) compared to measured concentrations achieved in the experimental trials.

| | Dissolved Cu | Dissolved Zn | Total dissolved P |
|---|---|---|---|
| Target concentration ($mg\,m^{-3}$) | 16 | 485 | 100 |
| Mineral salt added | $CuSO_4{\cdot}5H_2O$ | $ZnSO_4{\cdot}7H_2O$ | $KH_2PO_4$ |
| Range of initial concentrations measured in experimental trials ($mg\,m^{-3}$) | 10.0–16.7 | 442–517 | 96–136[a] |

[a] DRP.

During the second batch of each of the treatments, ultrafine (97% <2 μm, 60% <0.4 μm) halloysite clay (New Zealand China Clays Ltd., Matauri Bay, NZ) was added to the stormwater solution at a rate of approximately 160 g per mesocosm (≈200 g $m^{-3}$) in order to simulate the fine suspended particulate load that typically remains in urban stormwater following primary sedimentation. The clay was added to the artificial stormwater solution holding tank and gently mixed using a small submersible pump for 24 h prior to filling of the mesocosm tanks. There was noticeable deposition of the clay in the mixing tank at the end of this procedure, meaning that only the very finest particulate fractions of the clay remained in suspension and were transferred to the experimental tanks.

### 2.2. Water sampling and analysis

All water sampling equipment was acid-rinsed followed by flushing in distilled water prior to sampling of each tank. At the start of each batch a sample of the artificial stormwater was collected during the filling of the mesocosms and used to represent the water quality at day 0 for all mesocosms. Depth-averaged water samples were collected from the mesocosms on days 1, 3 and 7 of each batch using a 70 cm length of 50 mm diameter PVC pipe submersed vertically down through the upper 50 cm of the water column. The sampling pipe was capped with a rubber bung then drawn up towards the surface so that the lower end could be capped before withdrawal. Two 100 ml subsamples, one filtered on site (0.45 μm Advantec™ cellulose acetate disposable syringe filters; Advantec MFS Inc., Dublin CA, USA) and one left unfiltered were transported on ice to the laboratory and analysed for dissolved and total Cu and Zn, and dissolved reactive (DRP) and total phosphate (TP). Total Cu and Zn samples were subjected to nitric acid digestion prior to analysis by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) in accordance with APHA method 3125 (APHA, 1998). DRP (after filtration) and TP (after persulphate digestion) were analysed by automated flow injection analysis (QuikChem™ 8000 FIA+, Lachat Instruments, Loveland, CO, USA).

Calibrated portable field meters were used to measure turbidity (Hach 2100M turbidimeter, 0–1000 NTU range, Hach™ Co., Loveland, CO, USA), temperature, pH and dissolved oxygen (TPS™ WP81 and WP82Y, TPS Pty., Springwood, QLD, Australia) from 200 mm below the water surface (top) and 200 mm above the bottom of the tanks. Diurnal fluctuations in water temperatures at mid-depth in the tanks were measured during batches at 15 min intervals using StowAway Tidbit™ Temperature Loggers (Model TB132; Onset Computer Corporation, Bourne, MA, USA).

To facilitate direct comparison of the results between different treatments and batches with slight variations in the starting concentration of some parameters, the concentration data was normalised by dividing by the initial concentration ($C_{in}$). Analysis of variance (ANOVA; Genstat version 10; VSN International Ltd., UK) was performed separately on the water quality data for batches with and without fine suspended sediment added, and for each sampling time, using split plot analysis with mesocosm tank as the main plot. From the separate analyses for each sampling time, the means for each treatment were compared using Tukey's test (Hsu, 1996).

### 2.3. Plant sampling and analysis

All biomass values are reported after drying to constant weight (typically at least 48 h) in a fan-circulated oven at 80 °C. The above and below-mat biomass was determined for each of the planted mats ($n$ = 3 for each species) before the treatment trials in mid-summer (January 2007) after 230 days growth. Above-mat biomass was estimated by determining the shoot density per mat and the dry weight per shoot (cut off at the mat surface) based on a subsample of between 40 and 300 shoots, depending on the growth habit of each species. Below-mat biomass was estimated by harvesting all of the root material protruding below the mat surface within a quadrat of 0.01 $m^2$ positioned near the centre of the mat.

The biomass of each of the planted mats ($n = 3$ for each species) was again determined after the treatment trials in May 2007 (365 days growth). On this occasion all of the above and below-mat biomass protruding from the mat surface was harvested. The mean growth rate of plant biomass ($g\,m^{-2}\,d^{-1}$) for the period January to May 2007 was calculated for the four selected species by subtracting the plant biomass ($g\,m^{-2}$) for the 3 test replicates measured in January from that measured in May and then dividing by the number of days for the period of measurement (approximately 135 days). This calculation was made for above-mat and below-mat biomass and then summed to give the total biomass growth rate. Representative dried tissue subsamples of above- and below-mat plant biomass taken before and after the treatment trial were then ground and analysed for macro- and micro-nutrients, including Zn and Cu. Nitrogen was measured by Dumas combustion, and all other elements by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) after nitric acid/hydrogen peroxide digestion.

The shoot base, rhizome and root biomass that had grown within the polyester mat or the associated soil media was difficult to access and so was not included in the biomass measurements or the nutrient and metal analyses. The harvested root material was not specifically cleansed or rinsed of attached biofilm. However, when the FTWs were removed from the tanks at the end of the trials and allowed to drain on a rack, detachment of some loosely held biofilm, and associated flocs and FSS was observed. The biomass and plant uptake measurements reported thus include well attached biofilms, and represent only the potentially harvestable portions of the plants protruding from the mat and soil media.

Before and after the treatment trials, the maximum and 'majority' (visual approximation ∼90 percentile) shoot heights and root lengths were also determined from the upper or lower surface of the mats, respectively, using a graduated ruler. Shoot density was estimated for each mat either by counting the number of shoots on the entire mat, within a 0.01 $m^2$ quadrat or within individual clumps, depending on the species' growth habit and relative density of shoots. At the final harvest, the primary root density was estimated by counting the number of individual roots that were protruding from the mat surface within a 0.01 $m^2$ quadrat. An estimation of the total primary root length and surface area (excluding fine lateral roots) was also made by measuring the length, diameter and biomass of six typical roots from each mat to give the root length and surface area per gram of dry root. These values were then multiplied by the total dry weight of root biomass to give the total root length and surface area per mat.

### 2.4. Calculation of pollutant removal and plant uptake rates

Mass removals of Cu, Zn and P were determined for the first 3 and complete 7 days of each batch as the initial concentration ($g\,m^{-3}$) multiplied by the mesocosm water volume ($m^3$), minus the concentration multiplied by the water volume on the day of sampling. These were converted to areal mass removal rates ($g\,m^{-2}\,d^{-1}$) by dividing by the area of the floating mat ($m^2$) and the time since start of the batch (d). Thus, the removal rates are per floating mat area, not per area of water surface. For brevity, only the mass removals over the first 3 days are reported here as this period is close to the annual average return period of runoff generating storms in Auckland, New Zealand. This is, however, at the lower end of nominal residence times reported for 26 stormwater treatment wetlands in the USA (Carleton et al., 2001).


**Fig. 2.** Representative examples of aerial and submersed plant biomass in the vegetated floating mats after one years' culture in synthetic stormwater; (A) *Schoenoplectus tabernaemontani*; (B) *Juncus edgariae*; (C) *Carex virgate*; (D) *Cyperus ustilatus*. The dimensions of the square floating mats are 60 × 60 cm, with a depth of 15 cm.

Plant nutrient and metal accumulation was estimated for each species by multiplying the measured above and below-mat plant biomass ($g\,m^{-2}$) before and after the treatment trials by their corresponding tissue concentrations ($mg\,g^{-1}$). Plant uptake rates during the treatment trial period ($mg\,m^{-2}\,d^{-1}$) were calculated as the difference between their accumulated areal mass before and after the treatment trials, divided by the number of days between samplings.

## 3. Results

### 3.1. Plant growth, nutrition and pollutant uptake

A range of growth characteristics of the four test plant species measured at the end of the batch experiments are summarised in Table 3. The four plant species used in the experiments all showed robust growth on the floating mats, with extensive development of roots through and beneath the floating mats (Fig. 2).

**Table 3**
Mean plant biomass characteristics (± one standard deviation) of the four species at the end of the treatment trials in May 2007, after ~365 days growth on the floating mats ($n = 3$ for each species).

| | Above-mat | | | | | Below-mat | | | | | | Combined | Biomass ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plant species | Biomass dry weight ($g\,m^{-2}$) | Biomass growth rate# ($g\,m^{-2}\,d^{-1}$) | Majority shoot height (cm) | Max. shoot height (cm) | Shoot density ($m^{-2}$) | Biomass dry weight ($g\,m^{-2}$) | Biomass growth rate# ($g\,m^{-2}\,d^{-1}$) | Majority root depth (cm) | Max. depth (cm) | Total root length* ($km\,m^{-2}$) | Total root surface area* ($m^2\,m^{-2}$) | Above- and below-mat biomass growth rate ($g\,m^{-2}\,d^{-1}$) | Above-mat: below-mat |
| CU | 1528 ± 199 | 8.1 ± 1.4 | 65 ± 5 | 106 ± 8 | 7767 ± 862 | 329 ± 37 | 0.7 ± 1.0 | 35 ± 6 | 68 ± 7 | 1.0 ± 0.27 | 4.6 ± 0.7 | 8.8 ± 2.0 | 4.6 |
| CV | 2350 ± 84 | 10.3 ± 1.7 | 81 ± 8 | 149 ± 5 | 3647 ± 560 | 533 ± 66 | 1.1 ± 0.7 | 28 ± 6 | 57 ± 6 | 1.7 ± 0.48 | 7.8 ± 2.5 | 11.4 ± 1.9 | 4.4 |
| JE | 1113 ± 174 | 5.0 ± 0.1 | 82 ± 8 | 130 ± 13 | 2914 ± 502 | 299 ± 38 | 0.05 ± 0.50 | 48 ± 17 | 87 ± 12 | 3.0 ± 0.12 | 9.3 ± 1.8 | 5.0 ± 0.4 | 3.7 |
| ST | 834 ± 128 | 2.2 ± 0.7 | 76 ± 4 | 122 ± 9 | 1446 ± 123 | 184 ± 33 | 0.8 ± 0.48 | 24 ± 2 | 62 ± 6 | 3.2 ± 0.57 | 7.7 ± 0.65 | 3.0 ± 1.1 | 4.5 |

# Average growth rate for period January to May 2007.
* Does not include lateral roots or fine root hairs.

**Table 4**
Mean plant tissue macro and micro-nutrient concentrations recorded in the above and below-mat biomass of the four test species at the beginning and end of the experimental trials.

| Species | Nitrogen (%) | Phosphorus (%) | Potassium (%) | Sulphur (%) | Calcium (%) | Magnesium (%) | Sodium (%) | Iron ($\mu g\,g^{-1}$) | Manganese ($\mu g\,g^{-1}$) | Zinc ($\mu g\,g^{-1}$) | Copper ($\mu g\,g^{-1}$) | Boron ($\mu g\,g^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Start of trial (±January) | | | | | | | | | | | | |
| *Above-mat biomass* | | | | | | | | | | | | |
| CU | 1.1 | 0.32 | 1.8 | 0.28 | 0.49 | 0.19 | 0.60 | 59 | 140 | 26 | 6 | 12 |
| CV | 1.0 | 0.40 | 1.7 | 0.13 | 0.29 | 0.19 | 0.02 | 98 | 180 | 24 | 7 | 11 |
| JE | 1.1 | 0.22 | 1.5 | 0.20 | 0.32 | 0.10 | 0.05 | 42 | 110 | 44 | 5 | 10 |
| ST | 1.2 | 0.24 | 2.1 | 0.41 | 0.40 | 0.17 | 0.88 | 37 | 420 | 29 | 5 | 12 |
| *Below-mat biomass* | | | | | | | | | | | | |
| CU | 0.8 | 0.13 | 0.8 | 0.20 | 0.51 | 0.32 | 0.68 | 417 | 110 | 670 | 35 | 54 |
| CV | 0.6 | 0.12 | 1.1 | 0.10 | 0.16 | 0.27 | 0.50 | 130 | 68 | 270 | 10 | 11 |
| JE | 0.7 | 0.18 | 1.2 | 0.12 | 0.28 | 0.13 | 0.34 | 612 | 90 | 220 | 17 | 39 |
| ST | 1.0 | 0.14 | 0.9 | 0.82 | 0.24 | 0.42 | 1.06 | 193 | 150 | 860 | 17 | 41 |
| End of trial (±May) | | | | | | | | | | | | |
| *Above-mat biomass* | | | | | | | | | | | | |
| CU | 1.3 | 0.17 | 2.3 | 0.14 | 0.29 | 0.10 | 0.44 | 40 | 44 | 32 | 7 | 8 |
| CV | 1.1 | 0.17 | 2.0 | 0.15 | 0.33 | 0.17 | 0.05 | 49 | 180 | 64 | 8 | 8 |
| JE | 1.2 | 0.17 | 1.7 | 0.18 | 0.24 | 0.09 | 0.08 | 30 | 92 | 110 | 7 | 8 |
| ST | 1.4 | 0.16 | 2.3 | 0.50 | 0.6 | 0.15 | 0.67 | 36 | 110 | 70 | 7 | 7 |
| *Below-mat biomass* | | | | | | | | | | | | |
| CU | 0.9 | 0.09 | 0.7 | 0.16 | 0.62 | 0.22 | 0.60 | 763 | 170 | 1700 | 47 | 14 |
| CV | 0.8 | 0.06 | 1.6 | 0.11 | 0.17 | 0.18 | 0.35 | 262 | 83 | 510 | 21 | 9 |
| JE | 0.9 | 0.10 | 0.9 | 0.15 | 0.38 | 0.09 | 0.48 | 329 | 130 | 990 | 34 | 13 |
| ST | 0.9 | 0.10 | 1.0 | 0.57 | 0.36 | 0.28 | 0.90 | 230 | 170 | 1000 | 33 | 13 |

**Table 5**
Estimated mean plant uptake rates of Cu, Zn and P ±standard deviations) for the four test species, and their percentage of overall removal rates measured over the 7 day batch periods in the absence of FSS additions.

| Plant species | Copper uptake | | | | Zinc uptake | | | | Phosphorus uptake | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Above-mat ($mg\,m^{-2}\,d^{-1}$) | Below-mat ($mg\,m^{-2}\,d^{-1}$) | Total ($mg\,m^{-2}\,d^{-1}$) | Percentof FTW removal rate (%) | Above-mat ($mg\,m^{-2}\,d^{-1}$) | Below-mat ($mg\,m^{-2}\,d^{-1}$) | Total ($mg\,m^{-2}\,d^{-1}$) | Percent of FTW removal rate (%) | Above-mat ($mg\,m^{-2}\,d^{-1}$) | Below-mat ($mg\,m^{-2}\,d^{-1}$) | Total ($mg\,m^{-2}\,d^{-1}$) | Percent of FTW removal rate (%) |
| CU | 0.061 ± 0.011 | 0.054 ± 0.029 | 0.114 ± 0.031 | 3.0% | 0.282 ± 0.048 | 3.027 ± 0.685 | 3.309 ± 0.687 | 6.3% | 8.64 ± 2.58 | −0.13 ± 0.98 | 8.51 ± 2.76 | >100% |
| CV | 0.089 ± 0.016 | 0.054 ± 0.014 | 0.143 ± 0.021 | 3.9% | 0.934 ± 0.065 | 1.228 ± 0.371 | 2.162 ± 0.377 | 10.1% | 1.54 ± 8.61 | −1.04 ± 1.27 | 0.50 ± 8.70 | 4% |
| JE | 0.041 ± 0.011 | 0.038 ± 0.015 | 0.079 ± 0.019 | 2.5% | 0.760 ± 0.151 | 1.703 ± 0.316 | 2.463 ± 0.350 | 8.5% | 6.87 ± 3.49 | −1.67 ± 1.31 | 5.20 ± 3.73 | >100% |
| ST | 0.024 ± 0.008 | 0.036 ± 0.009 | 0.059 ± 0.012 | 1.8% | 0.320 ± 0.072 | 0.881 ± 0.319 | 1.201 ± 0.327 | 5.9% | 0.30 ± 2.73 | 0.57 ± 0.41 | 0.87 ± 2.77 | na* |

* P released in these treatments.

**Table 6**
Summary statistics for pH, electrical conductivity and temperature during the treatment trial batches. Statistics are based on individual measurements from all treatments.

| Parameter | pH | EC ($\mu S\,cm^{-1}$) | Water temperature (°C) |
|---|---|---|---|
| Mean | 7.2 | 253 | 17.5 |
| Standard deviation | 0.3 | 5.5 | 0.75 |
| Maximum | 7.7 | 265 | 22.7 |
| Minimum | 6.5 | 226 | 11.9 |

Average above-mat dry weight biomass of 834–2350 g $m^2$ and root biomass of 184–533 g $m^2$ (both highest for *Carex virgata*) and average species above:below-mat biomass ratios between 3.7 and 4.5 were recorded at the end of the trial after one years' growth. The 90 percentile depth of roots for the four test species averaged between 24 and 48 cm below the mat, with maximum root depths of up to 87 cm recorded for *Juncus edgariae*. However, this species showed minimal increase in below-mat biomass (0.05 $g\,m^{-2}\,d^{-1}$) during the course of the experiments.

The harvestable above and below mat plant biomass growth rates over the experimental period ranged from 3.0 to 11.4 $g\,DW\,m^{-2}\,d^{-1}$ (Table 3). Tissue nutrient/metal concentrations recorded at the beginning and end of the experimental trials are shown in Table 4. Overall, the tissue nutrient/metal levels were relatively similar between all test species. Tissue concentrations of P, S, Mg, Mn and B concentrations showed general declines during the course of the experimental trials, while Zn and Cu concentrations increased.

Mean plant uptake rates of 0.059–0.114 $mg\,Cu\,m^{-2}\,d^{-1}$, 1.2–3.3 $mg\,Zn\,m^{-2}\,d^{-1}$, and 0.5–8.5 $mg\,P\,m^{-2}\,d^{-1}$ were recorded for the test species (Table 5). This corresponded to <4% of the overall Cu removal rates, ≤10% of the Zn removal rates, and between 4% and more than 100% of the DRP removal rates recorded over the 7-day experimental batches (see Section 3.3). Plant Cu uptake was relatively equally divided between above and below-mat plant tissues, while the majority of plant Zn uptake was associated with below-mat roots and the majority of plant P uptake with above-mat shoots. There was considerable variability in P uptake between the four species, with *Cyperus ustilatus* and *Juncus edgariae* attaining much higher overall uptake rates (8.5 and 5.2 $mg\,m^{-2}\,d^{-1}$, respectively) than *Schoenoplectus tabernaemontani* (0.87 $mg\,m^{-2}\,d^{-1}$) and *Carex virgata* (0.5 $mg\,m^{-2}\,d^{-1}$).

### 3.2. Physico-chemical responses

Conductivity, pH, temperature and dissolved oxygen measured near the top and bottom of the tanks between late morning and early afternoon were very similar with no indication of thermal stratification. Conductivity and pH varied little between batches and treatments, or over the course of each batch (Table 6). Water temperatures varied diurnally by 3–5 °C and from day to day in response to ambient weather conditions. Water temperatures, measured at the time of sampling, were a few degrees higher ($P < 0.05$) at 3- and 7-day samplings for one batch including C, M, MS and CV treatments without fine sediment addition, but otherwise overall temperature ranges were not significantly different between batches and treatments (Table 6).

Dissolved oxygen levels generally remained above 75% saturation in the non-planted C, M, MS and AR treatments (Fig. 3). In some batches the non-planted treatments with added growth media (MS and AR) showed significantly lower oxygen saturation ($P < 0.05$) than those without any growth media. Dissolved oxygen showed greatest depression in the planted FTW treatments. Lowest oxygen levels ($P < 0.05$; ∼30–40% saturation after 7 days) occurred in the two higher mean biomass treatments (CU and CV), and interme-

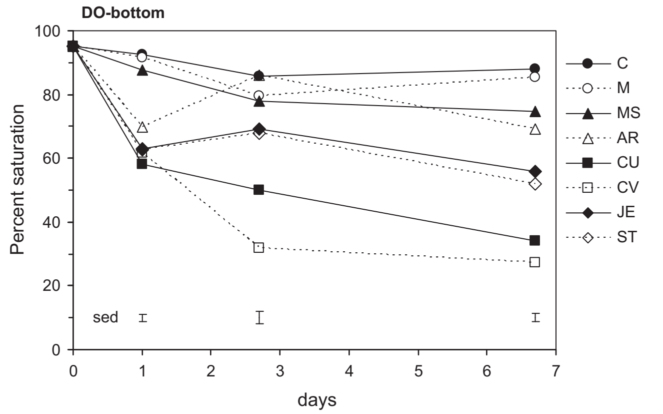


**Fig. 3.** Mean percent saturation of dissolved oxygen (DO) in the water 20 cm from the bottom of the mesocosm tanks throughout the batches. The error bars show the standard error of the difference for each sampling time.

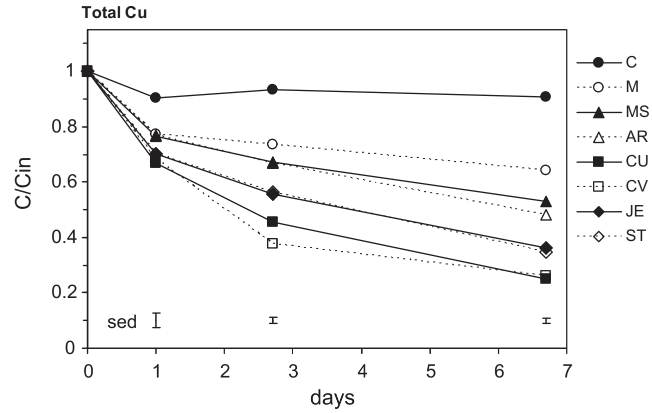


**Fig. 4.** Changes in mean total copper concentration ($C/C_{in}$) for the treatments without fine suspended sediment addition. Initial concentrations ($C_{in}$) ranged from 10 to 17 mg m$^{-3}$. The error bars show the standard error of the difference for each sampling time.

diate levels ($P < 0.05$; 50–60% saturation after 7 days) in the two treatments with lower mean biomass (JE and ST).

### 3.3. Pollutant responses

#### 3.3.1. Metals

There were very small differences between dissolved and total metal concentrations during the course of the experiments, even with addition of the fine sediment, so for brevity only the total metal concentrations from batches without FSS addition are presented. Full results including dissolved and total metal concentrations and results of ANOVA for experiments with and without FSS addition are summarised in Appendices A and B.

The initial concentrations of total Cu in the treatments without FSS addition ranged from 10 to 17 mg m$^{-3}$, of which more than 90% was soluble. The planted floating wetlands achieved the greatest reduction in total Cu concentrations ($P < 0.05$; 65–75% after seven days; Fig. 4), followed by the synthetic root treatment ($P < 0.05$; 50% after seven days). The MS and M treatments achieved an intermediate degree of total Cu removal (43% and 30% reductions after 7 days, respectively). There was little change in the total Cu concentrations in the control treatments over the 7-day batch. After 3 and 7 days there were significant differences ($P < 0.05$) between the FTWs planted with different species. At mass loadings of 11.1 mg m$^{-2}$ d$^{-1}$, total Cu removal rates in the planted treatments translated to between 5.6 and 7.7 mg m$^{-2}$ d$^{-1}$ over the first 3 days, compared to 0.8 mg m$^{-2}$ d$^{-1}$ in the control (Table 7). In the planted treatments there was a strong linear correlation between mass areal removal rates (over the initial 3 days) and the above-mat ($r^2 = 0.98$) or total plant biomass ($r^2 = 0.97$).

The initial concentrations of Zn in the artificial stormwater ranged between 440 and 490 mg m$^{-3}$ with 95% in dissolved forms. Zinc removal varied substantially for different planted and non-planted treatments (Fig. 5), with less than 40% concentration reductions achieved by any treatments after 7 days. All of the treatments that included floating mats removed more total Zn than the controls, which showed negligible removal. Intermediate removal occurred for the M, JE and ST treatments (not significantly different from each other at $P < 0.05$ after 7 days). The MS, AR and CU treatments achieved the greatest reduction of total Zn (not significantly different from each other at $P < 0.05$ after 7 days). Addition of the peat-based growth media (e.g. MS and AR) significantly increased removal above that of the mat alone (M). This greater removal also occurred for mats containing growth media planted with CU, but not for mats planted with JE or ST or CV. Except for the control (11 mg m$^{-2}$ d$^{-1}$), mass removal rates of Zn were, however, relatively high overall for treatments containing mats, ranging from 25 to 104 mg m$^{-2}$ d$^{-1}$ over the first 3 days (Table 7) at Total Zn mass loadings of 343–353 mg m$^{-2}$ d$^{-1}$.

#### 3.3.2. Phosphorus

The initial concentrations of TP ranged from 96 to 136 mg m$^{-3}$ of which 85–90% was in dissolved reactive forms. There were notable differences with respect to DRP and TP removal in the presence and absence of fine suspended sediment addition (Fig. 6). Without FSS addition, DRP and TP levels were relatively unchanged in the control or when a floating mat without soil (M) was added. However, DRP and TP levels rose significantly ($P < 0.05$) in the non-planted treatments with soil added to the mat (MS ~ 20% DRP and 40% TP increases after 7 days), and rose even further ($P < 0.05$) when artificial roots were added (AR ~ 60% DRP and 80% TP increases after 7

**Table 7**
Mean areal mass removal rates ± standard deviations for total copper and total zinc (without FSS addition), DRP (with and without FSS addition), and fine particulate (turbidity) percentage reductions (with FSS addition) for the treatments over the first 3 days of the batches.

| Treatment | Cu removal rate (mg m$^{-2}$ d$^{-1}$) | Zn removal rate (mg m$^{-2}$ d$^{-1}$) | DRP removal – FSS) (mg m$^{-2}$ d$^{-1}$) | DRP removal + FSS) (mg m$^{-2}$ d$^{-1}$) | Fine particulate (turbidity) (% reduction) |
|---|---|---|---|---|---|
| C | 0.8 ± 0.07 | 11.4 ± 3.66 | 13.3 ± 3.23 | −2.9 ± 0.72 | 16.6 ± 0.17 |
| M | 3.3 ± 0.13 | 41.3 ± 8.65 | 5.4 ± 2.14 | −7.2 ± 0.72 | 20.6 ± 0.40 |
| MS | 4.0 ± 0.11 | 100.5 ± 3.34 | 0.0 ± 7.15 | −16.4 ± 4.12 | 21.0 ± 0.62 |
| AR | 4.3 ± 0.39 | 83.3 ± 10.79 | −24.7 ± 1.54 | −2.7 ± 0.43 | 26.8 ± 0.42 |
| CU | 7.0 ± 0.16 | 104.3 ± 5.99 | 1.8 ± 5.89 | 26.5 ± 7.02 | 42.2 ± 1.76 |
| CV | 7.7 ± 0.48 | 24.7 ± 8.16 | 26.9 ± 5.61 | 2.7 ± 4.18 | 33.7 ± 0.40 |
| JE | 5.7 ± 0.67 | 47.8 ± 19.09 | −3.34 ± 1.18 | 15.2 ± 0.43 | 36.8 ± 0.69 |
| ST | 5.6 ± 0.23 | 37.0 ± 5.40 | −0.77 ± 4.08 | 15.7 ± 4.73 | 35.6 ± 1.84 |

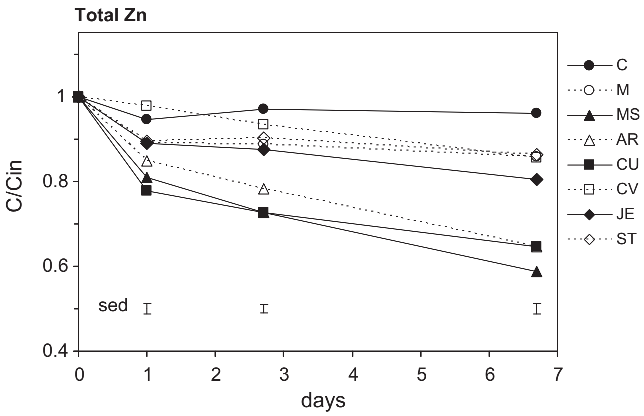


**Fig. 5.** Changes in mean total zinc concentration ($C/C_{in}$) for the treatments without fine suspended sediment addition. Initial concentrations ($C_{in}$) ranged from 440 to 490 mg m$^{-3}$. The error bars show the standard error of the difference for each sampling time.

days, respectively). In the presence of both soil and plants DRP and TP levels stayed either relatively stable (ST and JE) or were reduced significantly (CU and CV; ~20–50% reduction after 7 days).

With FSS addition, both DRP and TP levels in the MS treatment rose during the 7-day batches, but not in the presence of the artificial roots (AR; 12% DRP and 15% TP reduction). Again both DRP and TP removals were negligible in the C and M treatments, but in the planted treatment ranged from 30% to 60% DRP and 28% to 58% TP removal after 7 days. Mean areal mass removals of DRP measured over the first 3 days in treatments with FSS addition ranged from −3 to 27 mg m$^{-2}$ d$^{-1}$ for the planted treatments (Table 7), at DRP mass loadings of 179–231 mg m$^{-2}$. Curiously, CU, which showed the greatest removal of all the planted treatments in the absence of FSS, recorded the lowest removal in the presence of FSS.

### 3.3.3. *Turbidity*

The initial turbidity in the treatments with FSS addition was consistently 10.2 NTU, and the initial Total Suspended Solids (TSS) concentration was 7.7–10 g m$^{-3}$. However, the majority of FSS in suspension was finer than the 0.45 μm pore size of the filter paper used for the TSS analyses. The turbidity resulting from this very fine particulate fraction was most effectively reduced (Fig. 7 and Table 7) by the planted floating wetlands ($P < 0.05$; 34–42% and 57–67% reduction after 3 and 7 days, respectively), followed by the floating mats with synthetic roots (27% and 36% reduction after 3 and 7 days, respectively). The turbidity reductions in the M and MS treatments (21% and 30% reduction after 3 and 7 days, respectively) were only slightly better than the controls (17% and 23% reduction after 3 and 7 days, respectively). Some later batches were allowed to continue on for a second week. The turbidity in the CV treatment declined to less than 1 NTU after 14 d, while it

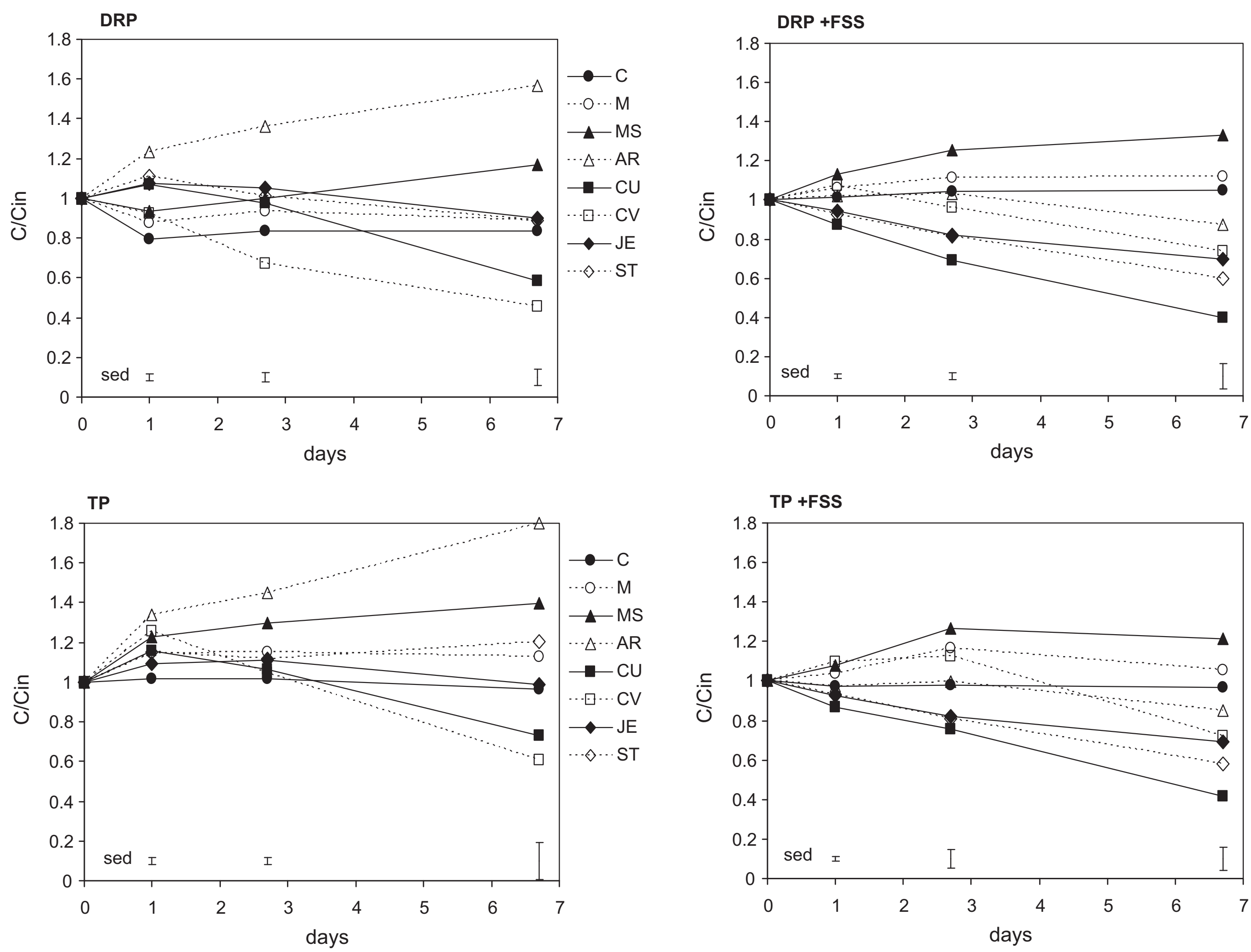


**Fig. 6.** Changes in mean TP and DRP concentration ($C/C_{in}$) for treatments with and without fine suspended sediment (FSS) addition. Initial concentrations ($C_{in}$) ranged from 88 to 116 mg DRP m$^{-3}$ and 96 to 136 mg TP m$^{-3}$. The error bars show the standard error of the difference for each sampling.

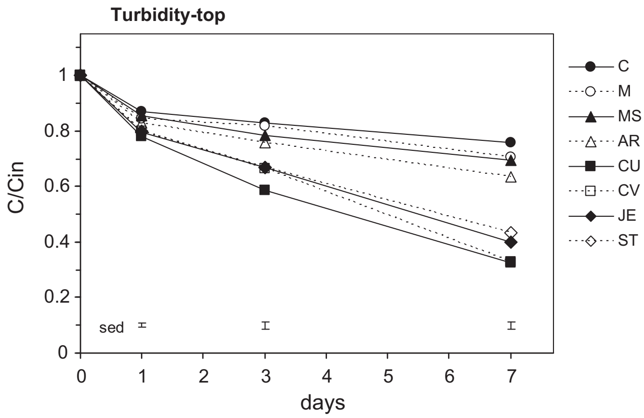


**Fig. 7.** Changes in mean turbidity ($C/C_{in}$) measured 20 cm below the water surface of the tanks for the treatments with fine sediment added ($n = 3$). Mean initial concentrations ($C_{in}$) were consistently 10.2 NTU. The error bars show the standard error of the difference for each sampling time.

was still at $6.9 \pm 0.123$ NTU in the controls, and $6.23 \pm 0.09$ and $5.82 \pm 0.166$ NTU in the M and MS treatments, respectively (data not shown).

## 4. Discussion

### 4.1. Plant growth, nutrition and pollutant uptake

The four wetland plant species selected for the experiments all showed good growth rooted in the fibrous floating mats supplied with artificial stormwater. These indigenous species were chosen because they are capable of forming a dense perennial sward of moderate stature (~1–1.5 m above-mat height). This enables them to compete successfully with weeds and resist grazing and trampling damage by wildlife, but minimises the risk of the FTWs being flipped over by the wind. Apart from *Schoenoplectus tabernaemontani*, these species also retain live green shoots year-round without significant winter senescence under the mild temperate conditions of New Zealand. This generally improves aesthetics and makes them easier to manage in urban green-space applications.

The mean biomass and tissue nutrient levels recorded for *Schoenoplectus tabernaemontani* at the end of the present study (one years' growth) were at the lower end of the range found in gravel-bed constructed wetlands supplied with nutrient-rich agricultural wastewaters (Tanner, 2001). However, they were well within the normal range found for this species in natural stands (Tanner, 2001). To the best of our knowledge, no comparative quantitative growth or nutritional data is available for any of the other test species.

The range of tissue nutrient concentrations found for the FTW grown plants in the present study were broadly similar to nutrient levels recorded for 8 emergent macrophyte species grown in gravel-bed wetland mesocosms supplied with agricultural wastewaters by Tanner (1996), except that P and Mn concentrations were relatively lower, and Zn in below-mat tissues was relatively higher in the present study. Cu and Zn tissue concentrations in the present study were at the lower end of the range reported for 5 emergent aquatic species growing in contaminated urban streams in southeast Queensland, Australia (Cardwell et al., 2002), and substantially lower than reported for 12 wetland species in metal-contaminated sites in China associated with metal mines, processing and industrial sites (Deng et al., 2004). This likely reflects the relatively lower metal levels in the artificial urban stormwater used in the present study, and lack of plant access to sediment stores in the FTWs.

Tissue elemental concentrations were relatively similar between the test species, but differences in growth rates over the experimental period resulted in a broad range of plant uptake rates. Additional plant uptake is also likely to have occurred into plant bases, rhizomes and roots contained within the fibrous matrix of the floating mats, which were not able to be sampled in this study. For mature *Schoenoplectus tabernaemontani* stands growing in subsurface-flow wetlands treating nutrient-rich wastewaters, Tanner (2001) found all of the rhizome biomass and 45–65% of below-ground root biomass in the upper 100 mm of the gravel media. All together this constituted ~20–30% of total plant biomass. Even allowing for such additional unsampled biomass, plant uptake in the present study could not be considered to be a dominant removal mechanism (except possibly for DRP removal in the CU treatment in the absence of FSS). For example, adding an additional 30% metal uptake to that recorded above and below the floating mat, our results suggest that at most 5% of the Cu and 13% of the Zn removal rates recorded in the mesocosm experiments could be attributed to plant uptake. This relatively minor role of plant assimilation in wetland metal removal is consistent with other studies of surface-flow systems receiving metal contaminated inflows (Dubinski et al., 1986; Sinicrope et al., 1992; Murray-Gulde et al., 2005).

### 4.2. Influence of FTW components on physico-chemical conditions

Water temperatures, pH (~ neutral) and conductivity in the mesocosms were minimally affected by the presence or absence of various components of the FTWs. However, daytime dissolved oxygen saturation in the water column varied markedly between treatments. Oxygen saturation was slightly reduced in the unplanted mesocosms with floating mats containing soil media (MS and AR), but became markedly reduced over the 7-day batch periods in treatments with planted floating mats. The reduced oxygen concentrations found beneath planted FTWs, but not those with artificial roots (AR), indicates a higher respiration rate from live and dead plant roots and/or attached biofilms. This higher respiration may have been fuelled by release of plant root exudates and secretions (Lynch and Whipps, 1990; Neori et al., 2000), leachates from aerial plant tissues, or decomposing plant and microbial biomass (Davis and van der Valk, 1978; Sala and Jurgens, 2004; Vahatalo and Wetzel, 2008). Of the 30–70% of net photosynthetically fixed carbon estimated to be translocated to below-ground plant tissues, 40–90% (~50–300 g $m^{-2}$) is estimated to be respired by roots or released into the rhizosphere (Lynch and Whipps, 1990).

Such reduction in root-zone dissolved oxygen levels in the presence of the plants is perhaps surprising given the well-known capability of wetland plants to transport atmospheric oxygen internally though aerenchymous tissues, and to release oxygen into their rhizospheres (Armstrong, 1979; Reddy et al., 1989). It is, however, consistent with experimental and modelling studies that show that the rate of oxygen release from wetland plant roots depends on the relative strength of the external oxygen demand (Armstrong et al., 1990; Sorrell and Armstrong, 1994; Sorrell, 1999). Free-oxygen was still present in the water column beneath the planted FTWs and the external oxygen demand would therefore have been relatively low compared to that common in anaerobic wetland sediments. The results suggest that any oxygen released by the roots was more than outweighed by the additional respiratory oxygen demand associated with plant roots and associated biofilms.

Although our measurements taken around mid-day showed dissolved oxygen levels in the water column still remained above 30–60% saturation beneath the planted FTWs, it is likely that oxygen levels would have become further depressed overnight in the absence of photosynthetic oxygen production. Anoxic and anaerobic microzones are likely to have occurred within the floating mats, soil media, and biofilms, with the potential to influence pollutant transformations (e.g. microbial denitrification), and retention of phosphorus and metals (Reddy and DeLaune, 2008).

### *4.3. Pollutant removal*

#### *4.3.1. Potential fate of pollutants*

None of the stormwater pollutants investigated in this study (fine inorganic SS, Zn, Cu and P) are likely to have significant volatilisation or gaseous transformation losses under the conditions of the experiments (Reddy and DeLaune, 2008). Depth-integrated sampling of the water column in the experimental tanks, and analysis for both dissolved and total concentrations (including suspended particulate fractions) means that any reductions measured in the water must have been retained in the tanks, either within or on the surfaces of the floating mats, soil media, plants, artificial roots or on the base or sides of the tanks.

Although each of the experiments reported here were of relatively short duration (one week), the floating mats, and associated soils and plants (where present) had been established and pre-acclimatised in artificial stormwater containing similar levels of metals and nutrients. Therefore rates of uptake into plant and microbial biomass, adsorption to soils, material surfaces, biofilm extracellular polymeric substances (Freeman et al., 1995; Pal and Paul, 2008) and embedded organic matter (attached to plant roots, the polyester mat matrix, and artificial roots) are likely to have been reasonably representative of operational conditions in treatment systems subject to pulsed stormwater inflows.

The internal surface area of the experimental tanks presented a potentially significant area ($\sim$3.8 $m^2$) for biofilm development, which may have influenced pollutant removal. We attempted to minimise growth of both attached and suspended (planktonic) photosynthetic microbial communities by careful cleaning before and between the relatively short duration experimental batches. This was also assisted by the shade cast by the floating mats (or equivalent cover in the controls) and by minimal inoculum in the potable water supply used to prepare the artificial stormwater solution in the enclosed mixing tank, but the submerged portions of the floating mats, and the live and artificial roots would have introduced an inoculum of algae and other microbes. However, no significant proliferation of photosynthetic bacteria or algae was evident from visual observations, turbidity measurements, elevated day-time dissolved oxygen or pH levels in any treatments, suggesting proliferation of attached and suspended microbial communities was well controlled and unlikely to be a major sink for nutrient and metal loss.

Benthic sediments have generally been found to be the dominant sink for metal and P retention in ponds and wetlands (Reddy and DeLaune, 2008; Kadlec and Wallace, 2009). Our experimental tanks had no bottom sediments, and the only sediment-like material in the mesocosms was the peat, sand and compost-based growth media used in some of the treatments. This avoided potential complications (e.g. due to metal or nutrient release from the sediments), but also excluded potentially important biogeochemical interactions between the FTWs and benthic sediments. Shading of planktonic and benthic photosynthesis, promotion of suspended solid deposition, and reductions in water movement in the vicinity of FTWs may affect associated physico-chemical conditions in the water column and benthic sediments in field-scale applications. Benthic sediments may also affect processes beneath and within FTWs by exertion of benthic oxygen demand (promoting deoxygenation), and release of reactants (e.g. sulphides) and/or organic ligands (e.g. humic compounds). Thus the contaminant removal rates observed in our investigations represent specifically those processes directly influenced by the floating components of a FTW. In field-scale FTW applications the benthic sediments are also likely to play an important role in the long-term cycling and storage of conservative contaminants such as metals, P and inorganic FSS.

#### *4.3.2. Influence of FTW components on pollutant removal.*

*4.3.2.1. Metals.* The planted FTWs showed >6-fold better removal of Cu than the control. The addition of a floating mat alone or with soil media only provided a small increase in Cu removal compared to the control. Further addition of artificial roots (AR) provided no significant extra benefit, with Cu removals still substantially less than for the planted FTW treatments. These results, and the low proportion of recorded removal that could be attributed to plant uptake (see Section 4.1), suggest that the plants enhanced Cu removal by providing more than just additional surface area on their roots for growth of biofilms (as mimicked in the artificial root treatment). It is also conceivable that different and more prolific biofilms developed on the living plant roots compared to the artificial roots, due to the plants providing a direct source of organic substrates for growth of microbial biofilms (see Section 4.2). This may have enhanced the Cu sorption potential of the biofilms in the planted treatments. Release of plant and microbially derived dissolved organic materials may also have promoted complexation and flocculation of Cu (Neori et al., 2000; Mucha et al., 2005, 2008), increasing its sorption within biofilms, and/or its rate of settling to the base of the tanks.

The influence of plants on Zn removal was less clear. Greatest Zn removal was associated with treatments with soil media, especially MS, AR and CU. The metal retention capacities of peat and compost materials are well known (Brown et al., 2000), suggesting that the organic soil media may have been an important repository for retained Zn. Planting generally reduced retention, except for FTWs planted with *Cyperus ustilatus*. None of the measurements of physico-chemical conditions within the water columns of the tanks, or characteristics of plant biomass gives any indication as to why CU should have performed differently than the other test species in terms of Zn removal. Although not measured in the present study, it is possible that this species modified the soil pH, redox or other factors within the soil media differently than the other test species, influencing its Zn retention capacity.

*4.3.2.2. Phosphorus.* Phosphorus removal varied depending on whether FSS was present in the artificial stormwater. When P was supplied in combination with FSS, reduction of DRP and TP was significantly enhanced in planted FTW treatments. This suggests that a key P removal pathway was via sorption of DRP to the clay in the FSS before or after entrapment within the root-biofilm matrix. Treatments with artificial roots (which provided 27–88% of the "root" length measured in the planted treatments at the end of the trials) showed intermediate levels of DRP and TP removal between the planted treatments and the control, M and MS treatments in the presence of FSS. This suggests the surface area for biofilm attachment provided by both live and artificial roots contributed to the additional P removal. However, although there was not a clear monotonic relationship between P removal and total root lengths or estimated surface area in the planted treatments.

In the absence of FSS addition, DRP and TP concentrations generally increased, when unplanted soil media and, in particular, artificial roots were present. This suggests that P desorption or leaching was occurring from the soil media and polyester fibre used for the artificial roots (e.g. possibly from P-containing flame retardant or finishing additives or coatings) or from associated microbial communities. Plant uptake from the soil media in the planted treatments during the preceding year of acclimation may have reduced levels of sorbed P (and other nutrient ions) in the soil media or modified its physico-chemical conditions (e.g. elevated redox potential) causing an increase in P retention capacity during the batches (Wathugala et al., 1987; Reddy and DeLaune, 2008). Although, measured oxygen concentrations in the water column were significantly lower in the planted FTW treatments, oxygen status and redox potentials in the soil media contained within the FTWs (not measured in the present study) are likely to have been maintained at higher levels in the presence of plants (Reddy et al., 1989; Moore et al., 1994; Aldridge and Ganf, 2003; Bezbaruah and Zhang, 2004).

*4.3.2.3. Fine suspended solids.* Suspended solids mobilisation is highly variable in urban stormwaters, with concentrations commonly exceeding 200 $g\,m^{-3}$ during storm events (Griffiths and Timperley, 2005). The turbidity from these suspended particulates (measured as light scattering) varies depending on the concentration, size, shape and surface characteristics of the particles (Davies-Colley et al., 1993). The ultra-fine (60% <0.4 $\mu$m) inorganic halloysite particles used in the present study were physically representative of only the very slowly settlable fractions that occur in urban stormwaters. The addition of an unplanted floating mat, soil media or artificial roots made little difference to turbidity reductions beyond those achieved in the controls, but the addition of planted FTWs provided ~2-fold greater reduction in turbidity after 3 and 7 days. This indicates that the plants provided additional mechanisms that enhanced FSS removal, beyond the simple physical settling processes which would have prevailed in the unplanted treatments. The fact that the turbidity reduction in the planted treatments was markedly higher than in the treatment with artificial roots suggests that there was an effect specific to the living plants. Fine suspended sediments may have adhered to the root–biofilm network of the planted treatments. As postulated to explain the greater Cu removal in the presence of plants (Section 4.3.2), the supply of organic compounds from plants may have increased biofilm biomass or stimulated coagulation and flocculation of the FSS, causing the formation of larger and more readily settleable flocs in the treatments with living plants.

The proportion of metals and other contaminants adsorbed to suspended particulates commonly increases as stormwaters are transported away from their source (Griffiths and Timperley, 2005). The relative efficiency shown by planted FTWs in trapping these FSS fractions suggests that substantially higher rates of sediment-associated Cu, Zn and P removal are likely to be achieved from "real" stormwaters, than seen in the present study where association between metals and FSS was minimal (the majority of Cu and Zn were in the dissolved form). This is important as these FSS fractions typically possess the highest surface-area to mass ratios and the most elevated concentrations (by mass) of metals and other sorbed contaminants (ARC, 2004; Timperley et al., 2004), tend to be highly bioavailable to benthic aquatic and marine organisms in receiving environments (Luoma, 1983), and are relatively poorly removed in normal stormwater retention ponds (Wong et al., 2000; Bavor et al., 2001; Pontier et al., 2001).

### 4.4. Care in extrapolation to field-scale

Care must be taken in extrapolating these results to field-scale applications. On the positive side, the FTWs used in the trials had been acclimatised over an extended period and had well-established vegetation. However, the FTWs and trial tanks were still relatively small and therefore prone to edge effects, such as exposure of plant canopy to lateral as well as downward solar radiation, potentially resulting in elevated plant biomass (Tanner, 1996). The stormwaters used were artificial, lacking the dissolved organic constituents and wider range of contaminants found in real urban stormwaters. There was minimal binding of metals to the fine inorganic sediments added in our experiments. The mesocosms also did not include any bottom soil or sediments which are likely to significantly influence sequestration processes and play a key role in the long term dynamics and storage of metals and nutrients removed from the water column.

## 5. Conclusions

The results of the present study indicate that planted FTWs are capable of achieving dissolved Cu and Zn mass removal rates in the order of 5.6–7.7 $mg\,m^{-2}\,d^{-1}$ and 25–104 $mg\,m^{-2}\,d^{-1}$ at average loading rates of ~11 and 350 $mg\,m^{-2}\,d^{-1}$, respectively. These removal rates compare favourably with those reported for conventional surface flow constructed wetlands treating urban stormwaters (Kadlec and Wallace, 2009). Although not directly measured in the present study, the removal of particulate-bound metals is also likely to be high given that the FTWs removed approximately 34–42% of the very fine suspended particulate load within three days.

The mesocosm approach employed for this study has allowed the relative importance of the constituent components of the FTWs to be assessed. Living plants, which provide an extensive submerged root surface-area (4.6–9.3 $m^2\,m^{-2}$ of floating mat) for biofilm development and reduce oxygen concentrations in the water column, were shown to play a key role in the removal of Cu, P and fine suspended sediments. Uptake of Cu and P into plant tissues could not account for more than a small fraction of the additional removal found in the planted FTWs. Except for P in the presence of FSS, artificial roots providing similar surface area generally did not provide equivalent benefits. These responses suggest that indirect effects of the plants such as release of bioactive compounds from the plant roots, or changes in physico-chemical conditions in the water column and/or soils may have enhanced sorption or sedimentation processes in the planted FTWs. The role of plants in Zn removal was less clear, with Zn removal primarily enhanced by presence of organic soils in the FTWs, but reduced in the presence of all but one of the plant species. Further investigations of the *Cyperus ustilatus* are warranted to confirm if it has special characteristics with regard to promotion of Zn removal in FTWs.

In general, the porous matrix of the floating mats on their own did not appear to provide significant enhancement of treatment in our relatively mature FTWs. However, short-term experimental studies reported by Stewart et al. (2008) show that the matrix can be an effective support surface for microbial biofilms, and with appropriate manipulation of physico-chemical conditions (e.g. ±aeration) and/or supply of organic substrates can promote a range of microbially mediated nutrient removal processes (e.g. nitrification, denitrification, and P adsorption).

The potential of FTWs demonstrated here and in other recent studies (Yang et al., 2008; Hubbard, 2010; Sukias et al., in press), supports the need for further pilot and field-scale testing and evaluation in a range of water treatment roles. Floating emergent macrophyte treatment wetlands provide a practical means of enhancing the treatment performance of open-water systems by integrating wetland components that provide extensive surface areas for active biofilm attachment. The fact that the plants are grown on a buoyant mat makes them particularly suitable for event-driven stormwater applications where water depths and flow rates can vary significantly over time. Adjustment of the relative size and cover of FTWs, the plant species grown on them and the soil media contained within them, offers significant potential to manipulate biochemical, physico-chemical and hydraulic conditions to optimise desired pollutant removal processes.

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## Appendix A.

Summary of mean normalised values ($C/C_{in}$) and standard errors of the difference for key water quality variables at 3 and 7 days in experiments without FSS addition. Treatments with different letters beneath them are significantly different from each other at $P < 0.05$.

| Water quality variables | Days | Treatments | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | C | M | MS | AR | CU | CV | JE | ST | sed |
| Dissolved Cu | 3 | 0.96f | 0.75e | 0.68d | 0.65d | 0.46b | 0.37a | 0.57c | 0.54c | 0.021 |
| | 7 | 0.93f | 0.68e | 0.53d | 0.44c | 0.24a | 0.27ab | 0.35b | 0.33b | 0.024 |
| Total Cu | 3 | 0.93e | 0.74d | 0.67d | 0.67d | 0.46b | 0.38a | 0.56c | 0.56c | 0.022 |
| | 7 | 0.91e | 0.64d | 0.53c | 0.48c | 0.25a | 0.26a | 0.36b | 0.35b | 0.018 |
| Dissolved Zn | 3 | 0.98c | 0.92bc | 0.74a | 0.77a | 0.73a | 0.95bc | 0.87b | 0.89b | 0.024 |
| | 7 | 0.99d | 0.88c | 0.60a | 0.63a | 0.63a | 0.88c | 0.78b | 0.85c | 0.020 |
| Total Zn | 3 | 0.97c | 0.89b | 0.73a | 0.78a | 0.73a | 0.93bc | 0.87b | 0.90bc | 0.020 |
| | 7 | 0.96c | 0.86b | 0.59a | 0.65a | 0.65a | 0.85b | 0.80b | 0.86b | 0.026 |
| DRP | 3 | 0.84b | 0.93bc | 1.00bc | 1.36d | 0.97bc | 0.67a | 1.05c | 1.01c | 0.047 |
| | 7 | 0.83bc | 0.89c | 1.17d | 1.56d | 0.59ab | 0.46a | 0.90cd | 0.89c | 0.079 |
| TP | 3 | 1.02a | 1.15b | 1.29d | 1.45e | 1.06ab | 1.04ab | 1.11ab | 1.11ab | 0.037 |
| | 7 | 0.96ab | 1.13ab | 1.39bc | 1.80c | 0.73ab | 0.61a | 0.99ab | 1.20abc | 0.191 |
| Dissolved oxygen – subsurface | 3 | 0.88d | 0.89d | 0.81cd | 0.91d | 0.55b | 0.40a | 0.74c | 0.73c | 0.038 |
| | 7 | 0.93d | 0.89d | 0.77c | 0.75c | 0.38a | 0.32a | 0.59b | 0.58b | 0.028 |
| Dissolved oxygen – bottom | 3 | 0.90d | 0.84cd | 0.82cd | 0.91d | 0.53b | 0.33a | 0.73c | 0.72c | 0.041 |
| | 7 | 0.93d | 0.90d | 0.79c | 0.73c | 0.36a | 0.29a | 0.59b | 0.55b | 0.026 |

## Appendix B.

Summary of mean normalised values $C/C_{in}$ and standard errors of the difference for key water quality variables at 3 and 7 days in experiments with FSS addition. Treatments with different letters beneath them are significantly different from each other at $P < 0.05$.

| Water quality variable | Days | Treatments | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | C | M | MS | AR | CU | CV | JE | ST | sed |
| Turbidity – subsurface | 3 | 0.83c | 0.82c | 0.78c | 0.76bc | 0.59a | 0.66a | 0.67ab | 0.67ab | 0.027 |
| | 7 | 0.76d | 0.71cd | 0.70cd | 0.64c | 0.33a | 0.33a | 0.40ab | 0.43b | 0.027 |
| Turbidity – bottom | 3 | 0.83d | 0.79d | 0.79d | 0.73c | 0.58a | 0.66b | 0.63b | 0.64b | 0.014 |
| | 7 | 0.76c | 0.70bc | 0.70bc | 0.60b | 0.33a | 0.34a | 0.40a | 0.42a | 0.030 |
| Dissolved Cu | 3 | 0.95d | 0.84c | 0.78c | 0.85cd | 0.61b | 0.49a | 0.78c | 0.78c | 0.032 |
| | 7 | 0.95d | 0.79c | 0.71c | 0.77c | 0.50b | 0.36a | 0.72c | 0.74c | 0.032 |
| Total Cu | 3 | 0.93e | 0.77cd | 0.76cd | 0.85de | 0.56b | 0.43a | 0.72c | 0.73c | 0.029 |
| | 7 | 0.93d | 0.74c | 0.66bc | 0.69bc | 0.43a | 0.33a | 0.59b | 0.63b | 0.029 |
| Dissolved Zn | 3 | 0.98c | 0.92bc | 0.74a | 0.77a | 0.73a | 0.95bc | 0.87b | 0.89b | 0.024 |
| | 7 | 0.99d | 0.88c | 0.60a | 0.63a | 0.63a | 0.88c | 0.78b | 0.85c | 0.020 |
| Total Zn | 3 | 0.97d | 0.93cd | 0.77a | 0.88bc | 0.85bq | 0.86b | 0.96d | 0.96d | 0.016 |
| | 7 | 1.01c | 0.95c | 0.71a | 0.81b | 0.81b | 0.86b | 0.94c | 0.96c | 0.023 |
| DRP | 3 | 1.04bc | 1.11c | 1.25d | 1.03bc | 0.69a | 0.96b | 0.82a | 0.82a | 0.039 |
| | 7 | 1.05cd | 1.12cd | 1.33d | 0.88bc | 0.40a | 0.74abc | 0.70abc | 0.60ab | 0.129 |
| TP | 3 | 0.98abcd | 1.17cd | 1.26d | 1.00abcd | 0.76a | 1.13bcd | 0.82abc | 0.81ab | 0.099 |
| | 7 | 0.97bcd | 1.05cd | 1.22d | 0.85bcd | 0.42a | 0.72abc | 0.69abc | 0.58ab | 0.119 |
| Dissolved oxygen – subsurface | 3 | 0.97e | 0.96e | 0.92de | 0.88d | 0.64a | 0.66ab | 0.73bc | 0.74c | 0.022 |
| | 7 | 0.92c | 0.89c | 0.84c | 0.89c | 0.61a | 0.53a | 0.72b | 0.72b | 0.027 |
| Dissolved oxygen – bottom | 3 | 0.97e | 0.95e | 0.91de | 0.87d | 0.63a | 0.65ab | 0.71bc | 0.74c | 0.022 |
| | 7 | 0.89c | 0.88c | 0.83c | 0.88c | 0.60a | 0.51a | 0.69b | 0.71b | 0.027 |

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