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Floating Vegetated Islands for Stormwater Treatment

Removal of Copper, Zinc and Fine Particulates

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Floating Vegetated Islands for Stormwater Treatment: Removal of Copper, Zinc and Fine Particulate

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₁ Executive Summary

The removal of Copper (Cu) and Zinc (Zn) from urban stormwater has been identified as a priority by the Auckland Regional Council in order to mitigate damages to aquatic ecosystems in receiving waters. Although effective at removing coarse suspended solids, conventional stormwater treatment ponds have a limited ability to remove dissolved metals or the fine suspended particulate fraction with which a significant porportion of Cu and Zn is typically associated. Constructed wetlands are generally more effective than conventional ponds at removing these dissolved and particulate metal fractions, but they typically require relatively large surface areas in order to maintain the required water depths (<0.5 m) that are necessary to ensure a healthy stand of emergent wetland plants. Floating treatment wetlands (FTWs), consisting of rooted emergent wetland plants growing on a mat floating on the water surface of a pond, have the potential to combine the strengths of both conventional ponds and wetlands into one system, whilst overcoming some of the limitations of each.

This study consisted of two parts. Part 1 aimed to identify suitable native NZ plant species for use in FTWs. Part 2 was an experimental study investigating the capabilities of FTWs to remove Cu, Zn and fine suspended particulates from urban stormwater, and to elucidate the role played by key structural elements of the FTWs.

The initial plant trial compared the growth response of six native wetland plant species chosen for their potential suitability (*Carex dipsacia, Carex virgata, Cyperus ustulatus, Eleocharis acuta, Juncus edgariae* and *Schoenoplectus tabernaemontani*) growing on small (0.36 m²) floating mats (six replicates of each) for 230 days. All plants grew well on the floating mats. Of the six species, *Carex virgata* (sedge) had the greatest amount of above and below-mat biomass at the end of the plant trial trial, while *Juncus edgariae* (rush) had the longest roots. *Eleocharis acuta* (spike rush) achieved very high shoot densities but had minimal root development beneath the mats – a feature expected to be important for stormwater treatment. *Carex virgata, Cyperus ustulatus, Juncus edgariae* and *Schoenoplectus tabernaemontani* (club-rush) were selected as suitable species for subsequent water quality improvement trials.

For the water quality improvement trials a series of batch loaded mesocosm experiments were conducted using twelve 1 m³ tanks to compare the effect of the various structural elements (floating mat, soil media, plant species) on removal of Cu, Zn and fine suspended particulates. The mats were comprised of a 100 mm thick non-woven polyester matrix injected in patches with foam to provide buoyancy. Eight different treatments were compared. These were:

- Control (C), consisting of open water with an equivalent area of shade to that of the floating mats provided over the water surface.

- Mat (M), consisting of a floating mat without soil or plants.

- Mat with soil media (MS), but no plants.

- Mat as above, but with artificial roots (AR) created using polyester threads hanging beneath the mat.

- Mat planted with *Carex virgata* (CV) growing in soil media.

- Mat planted with *Cyperus ustulatus* (CU) growing in soil media.

- Mat planted with *Juncus edgariae* (JE) growing in soil media.

- Mat planted with *Schoenoplectus tabernaemontani* (ST) growing in soil media.

Each treatment was run through two batches in triplicate. The mesocosms were loaded with an artifical stormwater made using tap water and nutrient salts to have a similar concentration of Cu, Zn and other nutrients to the more heavily contaminated stormwater within the Auckland region. Kaolin (white China clay) was added to simulate the fine residual suspended particulate fraction of stormwater for one of the two batches for each treatment. Batches were run for seven to 14 days and sampled after 0, 1, 3, 7 and (where applicable) 14 days.

All of the treatments with floating mats achieved a greater reduction of Cu, Zn and turbidity than the control mesocosms without a floating mat. The removal of Cu, Zn and turbidity over time generally followed a first-order (exponential decay) pattern with the most rapid reductions occuring during the first day of each batch followed by a gradual decrease in removal.

The planted FTWs were more effective at removing Cu and turbidity than the unplanted treatments. The role of the plants in Zn removal was less clear. The mats with artificial roots generally removed less Cu and turbidity than the mats containing living plants indicating that the role of the plants is more than simply providing a physical substrate for biofilm growth or sorption. It was estimated that the uptake of Cu and Zn into plant biomass was insignificant during the experiments, accounting for less than 1 per cent of the observed removal rates. Hence, it is hypothesised that either organic ligands released by the plant roots or physico-chemical conditions created within the root-zone under the planted mats may have enhanced the removal of Cu and turbidity.

Overall, the results indicate that FTWs are capable of achieving dissolved Cu mass removal rates in the order of 3.8 – 6.4 mg m^{-2} d^{-1} and Zn mass removal rates of 25 – 88 mg m^{-2} d^{-1} (based on mat surface area), which compare favourably to removal rates reported for conventional surface flow and subsurface flow constructed wetlands at similar loading rates. Although not directly measured in the present study, the removal of particulate metals is also likely to be high given that the FTWs removed approximately one third of the very fine suspended particulate load within the first three days of the batch experiments.

The findings of this study provide strong support for trialling FTWs at full- or pilot-scale in the field in order to test the long-term capabilities of FTWs treating stormwater under the more highly variable conditions of the field. It is therefore recommended that a FTW be established in a stormwater pond in the Auckland region that recieves significant loads of metals and fine particulates (ie a catchment with commerical and/or industrial land uses). An important aspect of this work will be to provide a comparison of the performance of a conventional pond against that of a FTW system. It is proposed that this is either done by:

- splitting an existing pond into two parallel ponds using an impermeable barrier and establishing a vegetated floating mat on one side to provide a direct side-by-side comparison of treatment performance (preferred option);

- constructing a pond and FTW side-by-side within a newly developed or proposed stormwater treatment system; or

- conducting a "before-and-after" trial by obtaining a performance record for an existing pond (possibly one that has previously been monitored), retro-fitting a FTW onto the pond and then monitoring for several events to identify any change in performance (potentially easiest option to set up, but may be difficult to obtain conclusive results).

If proven, potential applications of the technology include the retro-fitting of existing stormwater ponds with FTWs in order to improve the removal of metals and fine suspended particulates and the creation of purpose-built FTW systems designed to optimise metal removal in problematic catchments.

2 Introduction

Within the Auckland region, copper and zinc have been identified as significant contaminants of concern in urban stormwater, particularly from catchments dominated by commercial and industrial land uses, due to the risk posed to aquatic ecosystems in receiving waters (Griffiths and Timperley, 2005). Consequently, the Auckland Regional Council (ARC) has recently released a proposed "Auckland Regional Plan: Air, Land and Water" which include provisions specifically aimed at promoting practices that minimize the quantities of contaminants discharged from industrial and trade sites (Pennington, 2006).

Studies have demonstrated that as stormwater moves away from the contaminant source, the proportion of copper and zinc in the dissolved phase decreases as these metals become increasingly adsorbed to suspended particles (Griffiths and Timperley, 2005). Furthermore, as the stormwater travels further from the source, the concentration of particulate copper and zinc associated with the smaller particle size fraction tends to increase. The fine and colloidal particle size fractions (<63 μm) remain in suspension even at very low-flow velocities, and are therefore difficult to remove through conventional settling processes.

To date, sedimentation ponds and constructed wetlands have been the most commonly applied treatment technologies aimed at removing suspended solids and metals from stormwater. They offer the benefits of relatively passive, low-maintenance, and simple operation coupled with opportunities to enhance habitat and aesthetic values within the urban landscape. However, a number of limitations have become apparent in the application of ponds and wetlands for the removal of metals from stormwater. Although ponds can be effective at removing substantial amounts of coarse particulates, they are much less effective at removing the fine and colloidal sediment fractions. For example, ARC (2004) assessed the effectiveness of ponds of various sizes at reducing copper and zinc loadings from Auckland stormwater and concluded that, although ponds can reduce the rate of contaminant accumulation in receiving estuaries, the level of treatment currently attainable will not be adequate to prevent adverse effects in the long-term. The report went on to state that in highly urbanized catchments, where opportunities to retro-fit traditional treatment technologies (such as ponds) are limited, more innovative treatment options will need to be considered. Whilst constructed wetlands tend to be more effective at removing fine particulates, metals and other contaminants, the sediment-rooted vegetation used in conventional wetland systems can only tolerate relatively shallow water depths (< 0.5m) and are susceptible to chronic die-back if they experience excessive water depths for extended periods of time. Consequently, conventional sediment-rooted wetland systems either need to occupy relatively large areas in order to buffer against extremes in water level fluctuation, or be preceded by a high-flow bypass system which means that only a fraction of the flow receives treatment during large storm events.

The review conducted by Headley and Tanner (2006) concluded that Floating Treatment Wetlands (FTWs) show promise as a means of promoting removal of

metals and fine particulates whilst overcoming the above-mentioned limitations by combining the beneficial elements of ponds and wetlands within the one system. Floating Treatment Wetlands are an innovative variant on the constructed wetland concept that incorporates emergent wetland plants (normally sediment-bound) grown in a hydroponic floating mat on the surface of a water body (Figure 1, Figure 2). Such a system enables the incorporation of treatment wetland elements into a deeper pond-like system that can accommodate the large and rapid fluctuations in water depth common in stormwater systems.

Figure 1
Schematic longitudinal cross-section through a typical Floating Treatment Wetland system. Note that the water depth can vary appreciably in such a system without affecting plant growth. (Courtesy: Headley and Tanner, 2006).
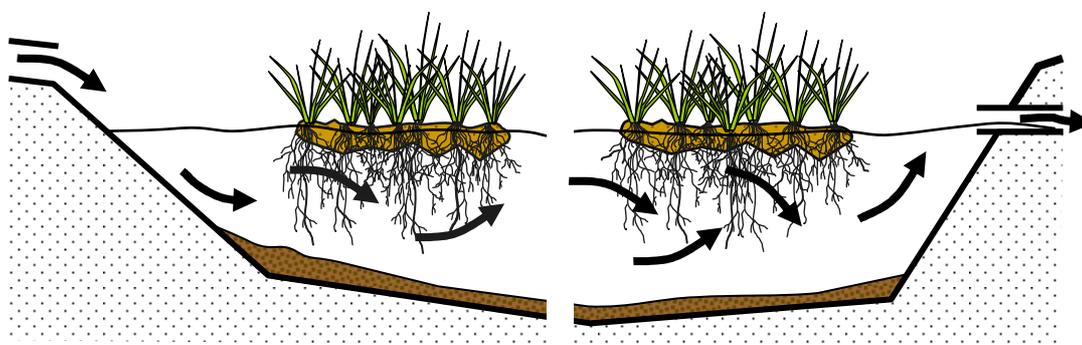
Floating wetland ecosystems occur naturally in various locations around the world, such as the Danube Delta, Germany, New Zealand, The Netherlands, England, the lower reaches of the Sud in Africa, the Central Amazon, the Gulf Coast of the USA, and Tasmania in Australia. These natural ecosystems may have provided the inspiration for some of the first purpose-engineered FTWs that emerged almost two decades ago, such as the Canadian trials beginning in 1989 for the treatment of acid mine drainage reported by Kalin and Smith (1992). Since that time, the uptake of the concept has been somewhat limited, but has included applications of various forms of FTWs for the improvement of acid mine drainage (Smith and Kalin, 2000), airport run-off (Revitt et al. 1997), piggery effluent (Hubbard et al. 2004), poultry processing wastewater (Todd et al. 2003), river water[1], water supply reservoirs (Garbutt, 2004), sewage (Ash and Troung, 2003; Todd et al. 2003) and combined sewer overflows (Van Acker et al. 2005). To the authors' knowledge, there have been no studies specifically on the treatment of urban stormwater using FTWs. Furthermore, there have been minimal conclusive investigations of the key treatment processes involved with FTW systems. Thus, there is currently a knowledge gap concerning some of the fundamental treatment processes and key design parameters in such systems, particularly with regard to metal removal.

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[1] www.waterrestore.com/india/projects/floating_islands.htm

Figure 2

Cross-section of a typical floating treatment wetland showing main structural elements in comparison with an open-water pond (Source: Headley and Tanner, 2006).

Floating Treatment Wetland

Open-water pond

Floating mat

Leaf litter, detritus

Planting media

Biofilm (predominantly bacterial) attached to root surface

Potential phytoplankton growth

Biofilm covered roots

Variable water depth

Storm water flow

Accumulated sludge

Benthic sediments
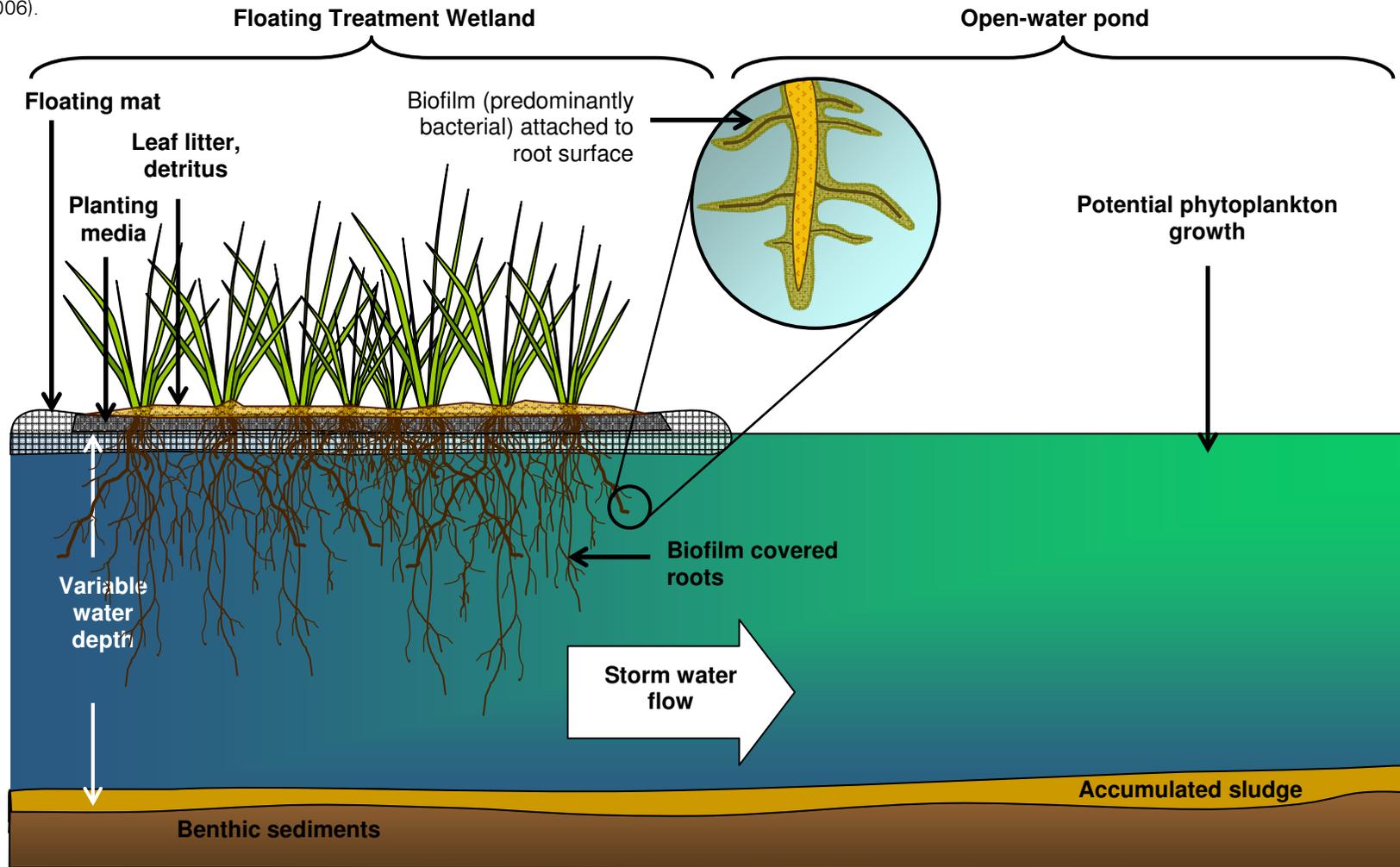
Headley and Tanner (2006) provided a conceptual overview of the key processes likely to promote removal of fine suspended particulates, copper and zinc in FTWs receiving stormwater. They surmised that the dense hanging root mat that forms beneath the FTW provides a large surface area for the development of biofilms which intercept and entrap fine suspended particulates and associated metals in the stormwater as it flows under the floating mat. The biofilms and organic exudates associated with the plant roots also have the potential to act as flocculants of colloidal metals or as ligands complexing dissolved metals resulting in the formation of larger aggregates more susceptible to sedimentation or entrapment in the root mat. Over time, the accumulating material within the root mat will become heavier and eventually slough off and fall to the bottom of the pond. Here, metals associated with the sloughed material may be permanently buried within the sediments or converted into tightly bound metal sulphides if anaerobic conditions are present (Headley and Tanner, 2006). Floating treatment wetlands are also likely to experience higher rates of uptake and cycling of metals, nutrients and other contaminants within plant biomass than in conventional sediment-rooted wetlands, as the plants are forced to meet their nutrient requirements from the water column rather than the soil.

In order to better understand the capabilities of FTWs to remove fine suspended particulates, copper and zinc from urban stormwater and to elucidate the contribution made by key structural elements of the FTW system, a series of batch loaded mesocosm studies were conducted at the Ruakura Research Campus in Hamilton, New Zealand during 2006 and 2007. These experiments were preceeded by a trial evaluating the suitability for use in FTWs of six selected native New Zealand wetland plants. For these trials, commerically available floating polyester mats were used to provide the bouyant structure for creating the small FTWs. The objectives of the experiments were:

- to compare and assess the growth response of six native New Zealand sedges and rushes (*Carex dipsacea*, *Carex virgata*, *Cyperus ustulatus*, Eleocharis acuta, *Juncus edgariae*, and *Schoenoplectus tabernaemontani*) grown on small scale floating mats;

- to assess the relative importance of the various structural components of the FTWs (polyester floating mat, plants, soil media) for fine particulate, Cu and Zn removal; and

- to determine the rate of turbidity, Cu and Zn removal from stormwater by the FTW mesocosms planted with four selected plant species (*Carex virgata*, *Cyperus ustulatus*, *Juncus edgariae*, and *Schoenoplectus tabernaemontani*).

₃ Methodology

3.1 Plant species growth assessment

The growth response of six native New Zealand wetland plant species growing on floating mats was evaluated with a view to identifying their suitability for use in floating treatment wetlands. The rushes and sedges that were evaluated (Table 1) were selected on the basis of potential for vigorous root growth under waterlogged conditions (assumed to play a key role in treatment processes), perceived aesthetic appeal and suitable growth habit. The selected species were limited to those that typically grow to a height of less than one metre, so as to minimise the potential for smaller floating wetlands to become "top heavy" and over-turn in high winds. Ultimately, the development of an extensive root system beneath the mat was deemed to be the most important trait by which suitability for use in FTWs was assessed.

Table 1
Plant species and number planted for floating wetland plant trial in May 2006. Different numbers of each species were planted due to variation in seedling size. Six mats of each species were trialled.

Plant species	Plant ID	Number of individuals per mat
Carex dipsacia	CD	16
Carex virgata	CV	15
Cyperus ustulatus	CU	17
Eleocharis acuta	EA	16
Juncus edgariae	JE	17
Schoenoplectus tabernaemontani	ST	17

Seedlings of each species were planted to individual 0.6 m x 0.6 m squares of a commerically available self-buoyant floating polyester matrix (BioHaven™ floating islands produced by Floating Islands International, Shepherd, Montana, USA; Figure 3) in late May 2006 (Autumn). Six floating mats were planted per species. The plants were planted into an 8 cm depth of growth media consisting of sand, peat and compost in a 1:2:1 ratio, with a small amount of lime added to balance the pH. The planted floating mats were grown on a synthetic stormwater solution within a series of plastic-lined concrete troughs (4 m^2 with a water depth of 0.8 m) at the Ruakura Research Centre in Hamilton, New Zealand (37° 47' S, 175° 19' E). The synthetic stormwater was adjusted to have an initial concentration of key elements as shown in

Table 2, which are similar to the mean of the 90th percentile concentrations reported by Timperley and Reed (2004) from a two-year monitoring program of stormwater from eight different catchments in Auckland city. A commercially available hydroponic fertiliser (Hydroponic Nutirent, Manutec Pty Ltd, Cavan, South Australia, Australia) was also added in small quanitites to provide a background mix of other nutrients and trace elements (P, K, Ca, Mg, Fe, Mn, SO_4, B and Mo). The water level in the troughs was maintained at a depth of 0.7 – 0.8 m, and a new batch of nutrient salts added at approximately six-weekly intervals.

Figure 3

The 0.6m x 0.6m polyester floating mats produced by Floating Islands International that were used in the trials: (A) before planting; (B) after planting; (C) aerial diagram; (D) cross-sectional diagram through A-A.
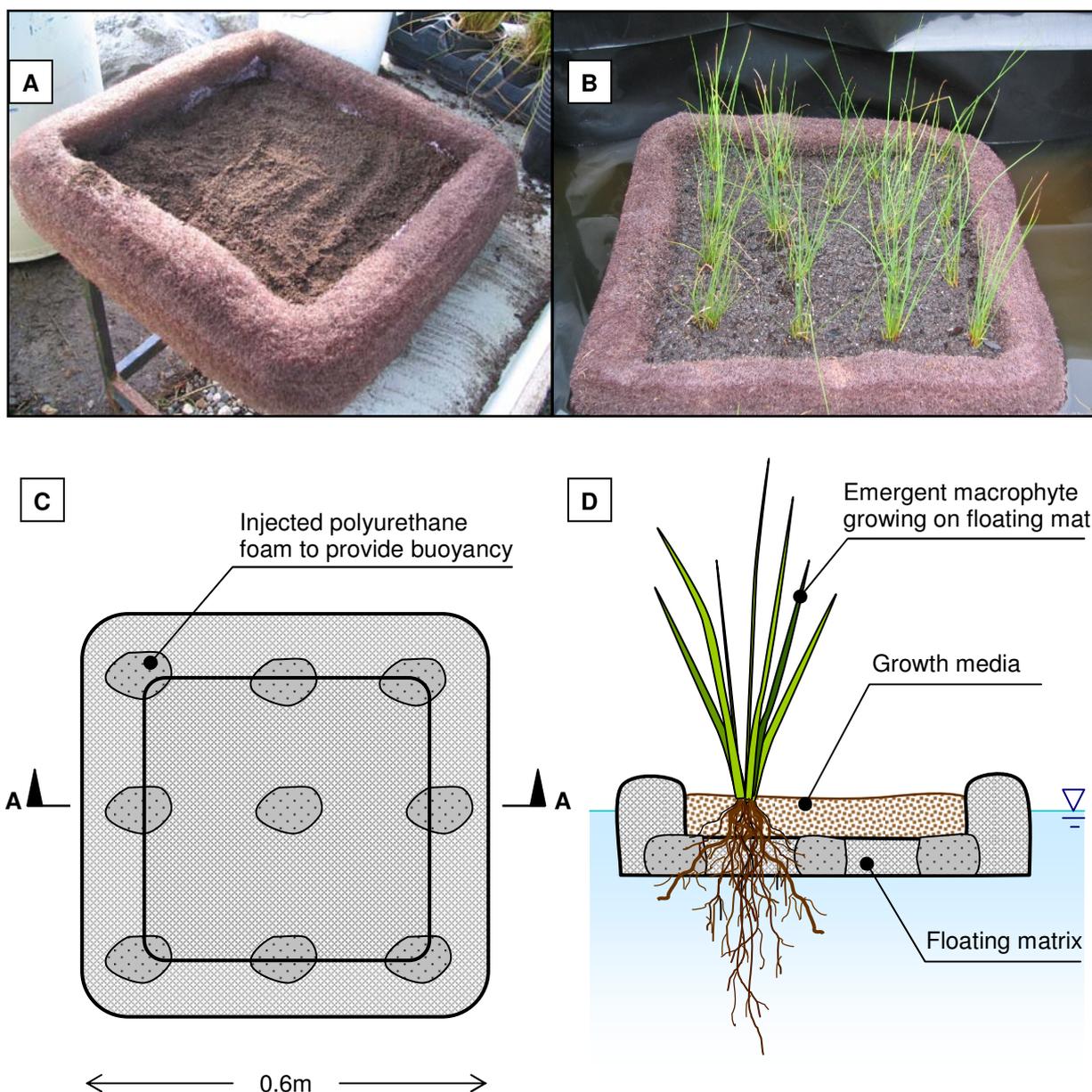
Table 2

Target concentration of key elements in the artificial stormwater.

	Dissolved copper	Dissolved zinc	NH_4-N	NO_3-N	TDP
Mean of the 90th percentile concentration (g/m^3)	0.016	0.485	0.3	3.0	0.1
Nutrient salt added	$CuSO_4.5H_2O$	$ZnSO_4.7H_2O$	NH_4NO_3	KNO_3	KH_2PO_4

Note: TDP = Total Dissolved Phosphate.

3.1.1 Plant biomass measurements

3.1.1.1 Biomass dry weight

The above and below-mat biomass dry weight was determined for each mat 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 sub-sample of between 40 and 300 shoots, depending on the growth habit of each species. Below-mat biomass dry weight 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 dry weight was determined at the end of May 2007 (365 days growth) for the four selected species that were used in subsequent water quality trials. On this occassion 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 substracting the plant biomass (g m^{-2}) 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.

The biomass that had accumulated within the floating matrix or the associated soil media was not readily accessible and was therefore not included in the biomass measurements (hence the terms "above-mat" and "below-mat"). So that the planted mats could be kept for use in subsequent trials, destructive harvesting of the "within-mat" biomass was not conducted. All dry weights were determined as the weight of the plant sample after drying to constant weight (typically at least 48 hours) in an oven at 80 °C.

3.1.1.2 Shoot and root characteristics

Qualitative biomass measurements were made in January (all six species) and May (four species used in water quality improvement trials) of 2007. The maximum and "majority" shoot heights were determined for each mat by measuring from the upper

surface of the mat. The "majority" height was determined by a visual approximation of the height below which the majority (approx. 90 per cent) of shoots occurred. Maximum and "majority" root lengths were determined in the same way as for shoots, except that measurements were taken from the lower mat surface. 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 time of the May 2007 biomass measurements, 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 (excluding fine lateral roots) length and surface area was also made by measuring the length and diameter of a sub-sample of six typical roots from each mat.

3.1.1.3 Evaluation of most suitable species for floating treatment wetlands

The plant biomass data collected in May 2007 was used to evaluate the suitability of the six test species for use in floating treatment wetlands. The main characteristics considered were root length, below-mat dry weight and overall plant vigour in response to growing on the floating mats on the artificial stormwater solution. From this assessment, four of the six species were then selected to be used in the subsequent water quality improvement trials.

3.2 Mesocosm water quality improvement trials

A series of batch loaded mesocosm experiments were conducted between 20 March and 24 April 2007 (Southern Hemisphere autumn) to investigate the effect of floating treatment wetlands, and their various structural components (floating matrix, soil media, plant species), on the removal of fine particulates, dissolved copper and dissolved zinc from stormwater.

3.2.1 Experimental set-up

A series of 12 mesocosm tanks (1 m x 1 m x 0.75 m water depth; operational water volume ≈ 0.7 m^3) were set up under a clear horticultural plastic shelter (≈90 per cent transmission of photosynthetically active radiation) to exlude rain for experimental purposes at the Rukura Research Centre (Figure 4). The mesocosms were connected to a central mixing tank of 10 m^3 capacity so that they could be filled simultaneously from the same batch of artificial stormwater.

The effect of eight different "treatments" on water quality was compared in triplicate during the batch experiments (Table 3, Figure 5). Each treatment was monitored during two batches of seven days, with some batches being allowed to run for 14 days. The mesocosms were loaded with a fresh batch of artificial stormwater on day 0 and then emptied at the end of the batch period. The mesocosm tanks were cleaned in between each batch to remove any sediment or biofilm that had accumulated during the preceeding batch. As there were only 12 mesocosm tanks available during the

study, the treatments were split into two groups and run as separate batches (Group 1 = C, M, MS and CV; Group 2 = AR, CU, JE and ST).

During the second batch of each of the treatments, kaolin ("NZ Halloysite: Premium": a white, ultra-fine china clay mined in Northland, NZ; New Zealand China Clays Ltd; Matauri Bay, Northland, NZ) was added to the stormwater solution at a rate of approximately 160 g per mesocosm ($\cong$200 g m^{-3}) in order to simulate the fine suspended particulate load that typically remains in stormwater following primary sedimentation. According to the manufacturers claims, the particles of the kaolin used are all smaller than 6 micron in diameter. Kaolin was added to the artificial stormwater mixing tank and gently mixed using a small pump for approximately 24 hours prior to filling of the mesocosms. This ensured that the artificial stormwater contained a suspension of only the non-readily settleable, very fine particulate fraction.

Figure 4
Six of the 12 mesocosm tanks used during the batch loading trials.

Two criss-crossed 10 mm thick fibreglass rods were installed horizontally in each mesocosm tank in order to support all of the floating mats at the same level of submergence (half submersed). A 0.6 m x 0.6 m square of black polyethylene sheeting was suspended 100 mm above the water surface in each of the Control treatments in order to provide an equivalent amount of shading to that of the floating mats and avoid algal proliferation. Three of the healthiest looking planted mats for each of the four species selected from the plant assessment trial were used in the mesocosm experiments. The same soil mix (sand: peat :compost = 1:2:1) was used in all treatments containing soil media (MS, AR, CU, CV, JE and ST).

Table 3

The treatments compared during the batch experiments.

Treatment	Code	Treatment group
Control (no floating matrix, but equivalent shading)	C	1
Matrix only	M	1
Matrix + soil media	MS	1
Matrix + soil media + Artificial Roots	AR	2
Matrix + soil + *Carex virgata*	CV	1
Matrix + soil + *Cyperus ustilatis*	CU	2
Matrix + soil + *Juncus edgariae*	JE	2
Matrix + soil + *Schoenoplectus tabernaemontani*	ST	2

Figure 5

Examples of the various treatments compared during batch loaded experiments: A = Control (C); B = Matrix only (M); C = Matrix + soil media (MS); and D = planted matrix (*Carex Virgata*, CV, shown).
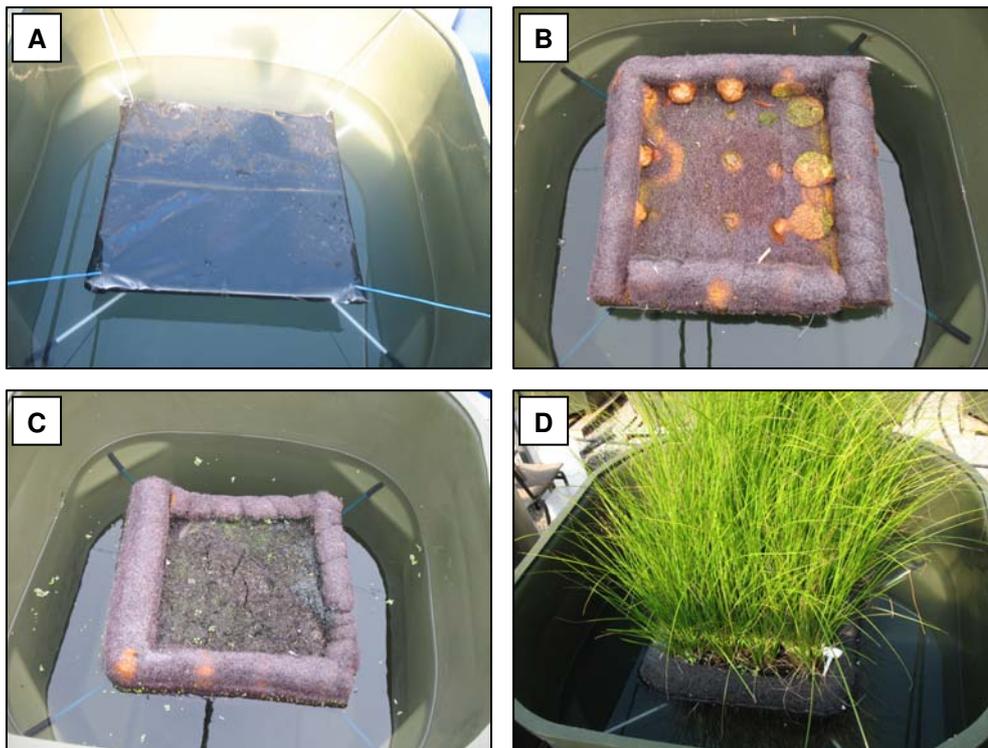
The artificial roots for the AR treatment were created by attaching bundles of branched polyester threads (Plumes Knitting Yarn, Sullivans International Pty Ltd, Auckland, New Zealand) to a plastic mesh secured to the under-side of the floating mats (Figure 6). The polyester thread used contained numerous short (20 mm) lateral threads and therefore resembled the basic structure of a natural plant root. To determine the length and number of artifical roots to be attached under each AR mat, an estimate of the

root density and length was made for the most vigorous plant species at the end of the plant growth assessments (January, 2007). A total of 700 individual polyester strands were attached in bundles of 11 at a spacing of 75 mm under each AR mat to give a final artifical root length of 45 cm (total root length = 875 m per m^2 of floating mat, not including lateral roots).

Figure 6
The artificial roots attached to the floating mat (A), after pre-conditioning for six weeks in artificial stormwater solution (B) and submersed in one of the mesocosm tanks (C).

3.2.2 Water quality sampling and analysis

All water quality sampling and monitoring was conducted on days 0, 1, 3 and 7 of each batch. Depth-integrated samples were collected using a 70 cm length of 50 mm diameter PVC pipe submersed vertically into the upper 50 cm of the water column. The upper end of the pipe was capped with a rubber bung, the pipe drawn up and the lower end capped before being withdrawn from the water. This provided a depth-averaged sample of the upper 50 cm of the 70 cm water column. These samples were taken to the NIWA Hamilton water chemistry laboratory and analysed for pH, electrical conductivity (EC), turbidity, and dissolved organic carbon (DOC) in accordance with APHA (1998). At the time of sampling, two 100 mL sub-samples (one filtered and one unfiltered) were separated into acid washed (5 per cent nitric acid) bottles for analysis of dissolved (filtered) and total (unfiltered) Cu and Zn at Hill Laboratories, Hamilton. The dissolved Cu and Zn samples were filtered in the field using 0.45 μm cellulose acetate disposal syringe filters (Advantec™). All sampling equipment was acid rinsed in 5 per cent nitric acid solution followed by flushing in distilled water prior to sampling. Total Cu and Zn samples were subjected to nitric acid digestion prior to analysis (APHA, 1998). Copper and Zn analysis was conducted using an ICP-MS in accordance with APHA method 3125 (APHA, 1998).

In situ measurements of pH, dissolved oxygen (DO) and temperature were also taken at two depths (20 cm and 50 cm from water surface) within each mesocosm. pH was measured using a TPS™ WP-81 portable meter, while DO and temperature were measured using a TPS™ WP-82Y portable meter. Water samples were also extracted via syringe from 20 cm and 50 cm depths, using tubing attached to a fibreglass rod at the desired depths, and analysed for turbidity using a Hach™ Portable Turbidimeter (Model 2100M, 0-1000 NTU range).

3.2.3 Calculation of Cu and Zn removal and plant uptake rates

Areal mass removal rates for Cu and Zn throughout the batches were determined using equation 1:

$$\text{Mass Removal Rate (g m}^{-2}\text{ d}^{-1}) = \frac{M_i - M_t}{t \times A} \qquad \text{(Eq. 1)}$$

where: M_i = initial mass of metal in mesocosm water at start of a batch (g)

= measured concentration (g m^{-3}) x volume of water in mesocosm (m^3)

M_t = mass of metal in mesocosm water at time t from start of batch (g)

t = time since start of batch (days)

A = surface area of floating mat (m^2)

The likely range of Cu and Zn plant uptake rates (mg m^{-2} d^{-1}) were estimated for each species by multiplying the measured above and below-mat plant biomass growth rates (g m^{-2} d^{-1}) by the maximum and minimum Cu and Zn tissue concentrations (μg g^{-1}) reported for eight emergent wetland plants in Tanner (1996). The plant tissue concentrations reported in Tanner (1996) were considered to be relevant to the present study, because the wetland plants were grown in gravel-bed mesocosms (ie, soil-less culture) and received water with similar Cu and Zn concentrations over a similar period to that of the present study.

4 Results and Discussion

4.1 Plant species growth assessment

The growth characteristics of the six species after 230 days of growth on the floating mats is presented in Table 4 . All of the species had a similar amount of above-mat biomass (377 – 474 g m^{-2}) at the end of the study, with exception of *Carex virgata* which had approximately twice as much (985 g m^{-2}) as the other species. *C. virgata* also had the second highest mean shoot density of nearly 10,000 shoots m^{-2}. *Cyperus ustulatus* and *Eleocharis acuta* had the shortest shoot heights of the six species.

Table 4

Growth characteristrics of six different species measured in January 2007 after 230 days growth. on floating mats (n = 6 for each species). Values in parentheses are standard deviations.

Species	Above-mat				Below-mat			Above-mat
	Biomass dry weight	Majority shoot height	Max. shoot height	Shoot density	Biomass dry weight	Majority root depth	Max. depth	Below-mat biomass ratio
	g m^2	cm	cm	shoots m^2	g m^2	cm	cm	
Carex dipsacia	442 (96)	42 (5)	100 (13)	6193 (891)	91 (42)	17 (3)	42 (8)	5.8
Carex virgata	985 (214)	60 (5)	104 (8)	9819 (2296)	376 (97)	21 (4)	54 (9)	3.1
Cyperus ustulatus	377 (90)	28 (5)	47 (4)	2837 (470)	239 (71)	26 (9)	67 (12)	1.9
Eleocharis acuta	442 (144)	34 (4)	57 (8)	11342 (2681)	37 (5)	8 (4)	32 (9)	14.4
Juncus edgariae	426 (108)	50 (5)	83 (10)	1649 (307)	228 (103)	24 (5)	76 (11)	2.2
Schoenoplectus tabernaemontani	474 (116)	65 (3)	101 (4)	748 (136)	80 (41)	18 (7)	57 (12)	7.1

C. virgata had the greatest amount of below-mat biomass (376 g m^{-2}), followed by *C. ustulatus* (239 g m^{-2}) and *Juncus edgariae* (228 g m^{-2}). The remaining three species had substantially less below-mat biomass (37 – 91 g m^{-2}), with *E. acuta* possessing relatively little below-mat biomass (37 g m^{-2}). *Juncus edgariae*, *Cyperus ustulatus* and *Carex virgata* had the greatest below-mat root depth, with the bulk of the root mass hanging to a depth of at least 21 cm and the longest roots extending beyond 50 cm. In contrast, *Eleocharis acuta* had the shortest roots, the majority of which were less than 8 cm long.

All species had more above-mat biomass than below-mat. In particular, *E. acuta*, due to its relatively poor below-mat growth, developed over 14 times as much biomass above the mat surface than below.

Based on the greater amount and length of below-mat biomass observed for *Juncus edgariae*, *Cyperus ustulatus* and *Carex virgata*, these three species were selected to be used in the subsequent water quality improvement trials. *Schoenoplectus tabernaemontani* was also selected based on provious experience with this species and the fact that it has traditionally been one of the most commonly used species in treatment wetlands for other applications.

4.2 Mesocosm water quality improvement trials

The results of the plant growth and water quality monitoring conducted during the mesocosm batch-loaded trials are summarised in this section.

4.2.1 Plant growth

A range of growth characteristics of the four plant species used in the water quality improvement trials were measured in May 2007 at the end of the batch experiments and are summarised in Table 5. Estimated mean above and below-mat biomass growth rates for the period of the water quality improvement trials (January – May 2007) are also presented. Typical examples of each of the species at the time of the May measurements can be seen in Figure 7.

Of the four species used in the water quality improvement trials, *Carex virgata* had the greatest amount of above and below-mat biomass (2350 and 533 g m^{-2} respectively) at the end of the batch experiments and displayed the greatest rate of above and below-mat biomass growth (10.3 and 1.1 g m^{-2} d^{-1} respectively) throughout the experimental period. *Scoenoplectus tabernaemontani* had the lowest amount of above and below-mat biomass (834 and 184 g m^{-2}) and experienced the lowest above-mat productivity (2.2 g m^{-2} d^{-1}) of the species used. However, *Juncus edgariae* experienced virtually no increase in below-mat biomass (0.05 g m^{-2} d^{-1}) over the course of the experiments, despite the fact that this species had by far the greatest depth of hanging roots and total root length at the time of the May measurements. Some of the *Juncus edgariae* mats that were used had already attained a substantial amount of below-mat biomass by the time of the previous measurements conducted in January 2007 and may have approached a carrying capacity in terms of root biomass.

Table 5

Species	Above-mat					Below-mat						Combined above- and below-mat biomass growth rate	Above-mat: Below-mat biomass ratio
	Biomass dry weight	Biomass growth rate[#]	Majority shoot height	Max. shoot height	Shoot density	Biomass dry weight	Biomass growth rate[#]	Majority root depth	Max. depth	Total root length[*]	Total root surface area[*]		
	$g\ m^{-2}$	$g\ m^{-2}d^{-1}$	cm	cm	$shoots\ m^{-2}$	$g\ m^{-2}$	$g\ m^{-2}d^{-1}$	cm	cm	$km\ m^{-2}$	$m^2\ m^{-2}$	$g\ m^{-2}d^{-1}$	
Cyperus ustulatus	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
Carex virgata	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
Juncus edgariae	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
Schoenoplectus tabernaemontani	834 (128)	2.2 (0.7)	76 (4)	122 (9)	1446 (123)	184 (33)	0.8 (0.48)	24 (2)	62 (6)	##	##	3.0 (1.1)	4.5

Biomass characteristrics of the four species used in the water quality improvement trials as measured in May 2007 after 365 days growth on floating mats (n = 3 for each species). Standard deviations are shown in parentheses.
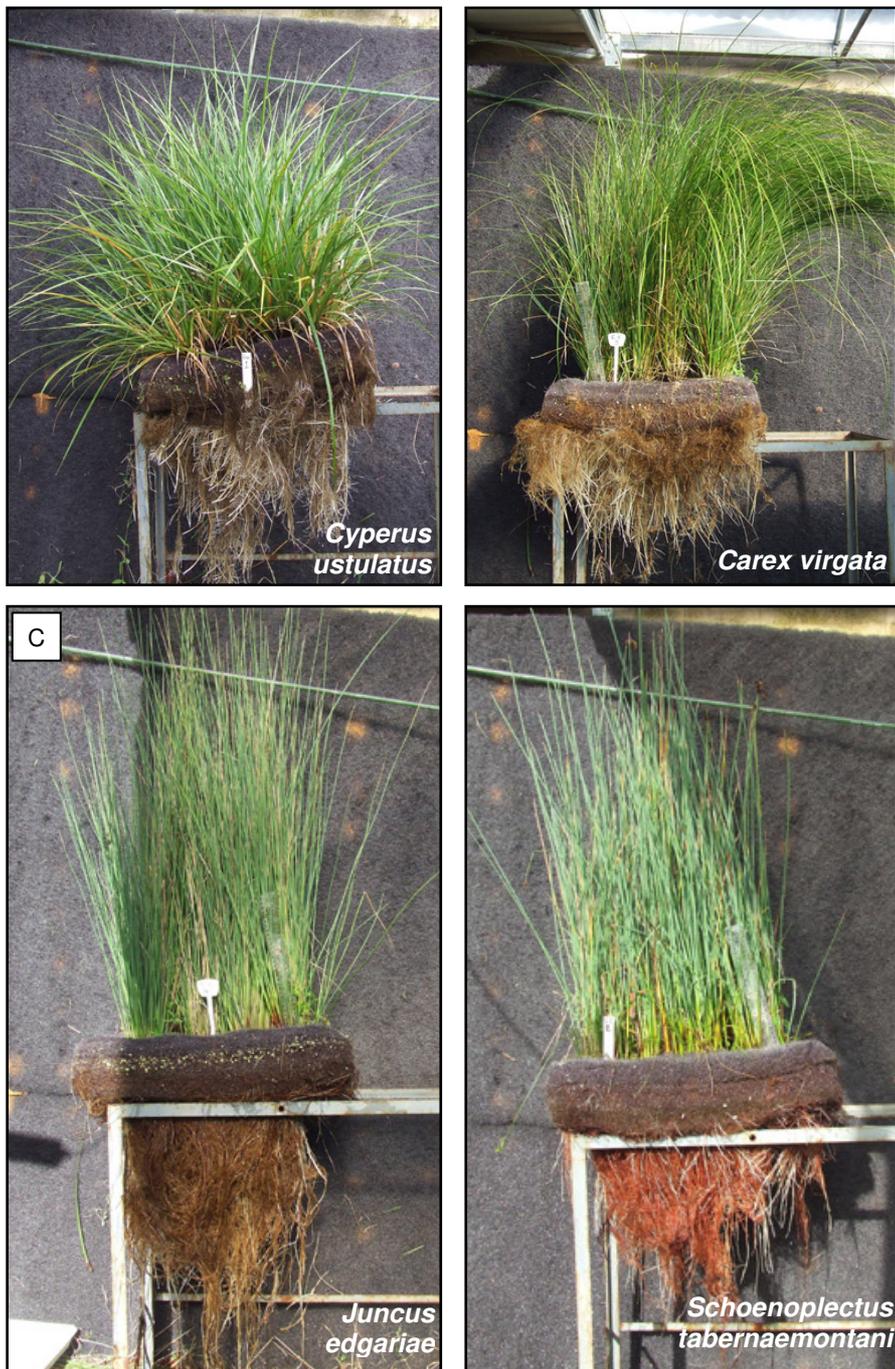
average growth rate for period January to May 2007.
* does not include lateral roots or fine root hairs.
measurements not available.

Figure 7
Typical examples of each of the four species at the time of the May 2007 biomass measurements.

By the end of the batch experiments the plants had accrued substantial total root length and surface areas (no data currently available for *S. tebernaemontani*). For example, *Juncus edgariae* had amassed 3.0 km of root length and 9.3 m^2 of root surface area per m^2 of floating mat. This was triple and twice the root length and surface area respectively attained by *Cyperus ustulatus*. Smith and Kalin (2000)

reported a root surface area of 15 m^2 m^{-2} for a two-year-old FTW planted with *Typha angustifolia*, compared to a seven-year-old system that had 114 m^2 of root surface area per m^2 of FTW. This suggests that the root biomass parameters observed in the present study (following one year of growth) are likely to increase further over subsequent years.

4.2.2 Water quality effects

The water quality results from the batch loaded mesocosm trials are presented below. With the exception of turbidity (kaolin was only added to half of the batches) the data from the two repeated batches for each of the treatments have been grouped together because negligible adsorption of metals to the kaolin occurred and loss rates were similar with- and without kaolin. Due to slight variations between batches in the starting concentration of some parameters, the concentration data has generally been normalised by dividing by the initial concentration (C_{in}) for comparative purposes. Hence, graphs depict the proportion of the initial concentration that remains in the water at time = t since the start of the batch (C_t/C_{in}).

For two of the batches it was possible to continue running them for 14 days (due to logistical reasons), and samples were therefore also collected on day 14. Thus, data for day 14 is presented for some of the treatments, although the number of replicates is only three (not six) for these data points.

4.2.2.1 pH, electrical conductivity and temperature

There was very little variation in pH, EC and DOC both between treatments and throughout the batches (Table 6) . The pH remained circum-neutral throughout the experiments. The EC concentrations were within the range typically observed for urban stormwater within the Auckland region and elsewhere in New Zealand (Williamson, 1986). There was effectively no DOC added to the artificial stormwater solution. The DOC generally remained low throughout the study and displayed no clear trends between treatments or over time within the batches.

The water temperature remained between 12° and 23° C for all treatments throughout the entire study, with a mean of 17.5° C (Table 6). The mean daily diurnal variation in water temperature was 2.8° C. Although water temperatures varied during the batches due to ambient weather conditions, there was very little variation in water temperature between the various treatments at any given point in time. There was also virtually no difference between the temperature measured at the two depths (20 cm below upper water surface and 20 cm above the tank bottom) at any given time of measurement, showing that the tanks generally remained unstratified.

Table 6

Summary statistics for pH, electrical conductivity and temperature throughout the batches. Statistics are based on individual measurements from all treatments.

Parameter	pH	EC	DOC	Water temperature
		µS cm⁻¹	g m⁻³	°C
Mean	7.2	253	0.9	17.5
Standard deviation	0.3	5.5	0.67	0.75
Maximum	7.7	265	3.7	22.7
Minimum	6.5	226	<0.25	11.9

4.2.2.2 Dissolved oxygen

The mean dissolved oxygen (DO) per cent saturation in the stormwater solution at a depth of 20 cm from the tank bottom for each treatment throughout the batches are presented in Figure 8. Only results for the bottom 20 cm depth are presented as the DO at the top 20 cm depth was almost identical during the batches.

These results show that conditions within the water column of all treatments remained aerobic throughout the batches. The DO saturation in the treatments that did not include soil media (C and M) were similar throughout the batches with measured DO remaining above 80 per cent saturation. The MS treatments experienced a slight reduction in DO saturation during the batches, decreasing from an initial DO of 91 per cent to 74 per cent on day seven. The mean DO saturation in the AR treatments was almost identical to that of the MS treatments after seven days, but continued to decrease over the next seven days to reach a DO of 60 per cent on day 14. Dissolved organic matter leaching from the organic rich soil media included in these two treatments (MS and AR) is likely to have contributed biochemical oxygen demand, causing the gradual decrease in DO over time. The sustained reduction in DO in the AR treatments (which also included the organic-rich soil media) may have been due to additional respiration by heterotrophic bacteria within biofilms attached to the artificial root substrate.

All of the treatments that included plants exhibited a greater reduction in DO over time than the non-planted treatments. The most rapid reduction in DO occurred during the first day, with all planted treatments decreasing from 91 per cent saturation down to 63 – 69 per cent. The mean DO of the JE and ST treatments were similar throughout and decreased steadily to a DO of 50 – 52 per cent after 14 days. The CU and CV treatments experienced a more substantial reduction in DO, decreasing to 43 and 36 per cent saturation respectively after seven days, from which point the DO stabilised. This observed reduction in DO under the planted treatments is somewhat contrary to the findings of other studies which report that wetland plants have the ability to leak oxygen through their roots and suggests that whatever oxygen was released by the

roots was more than outweighed by the oxygen demand imparted by the respiration of heterotrophic bacteria within the root-associated biofilms.

Figure 8

Mean per cent saturation of dissolved oxygen (DO) in the water 20 cm from the bottom of the mesocosm tanks throughout the batches. Error bars represent +/- one standard error of the mean. $n = 6$ for days 0 to 7. $n = 3$ for day 14.
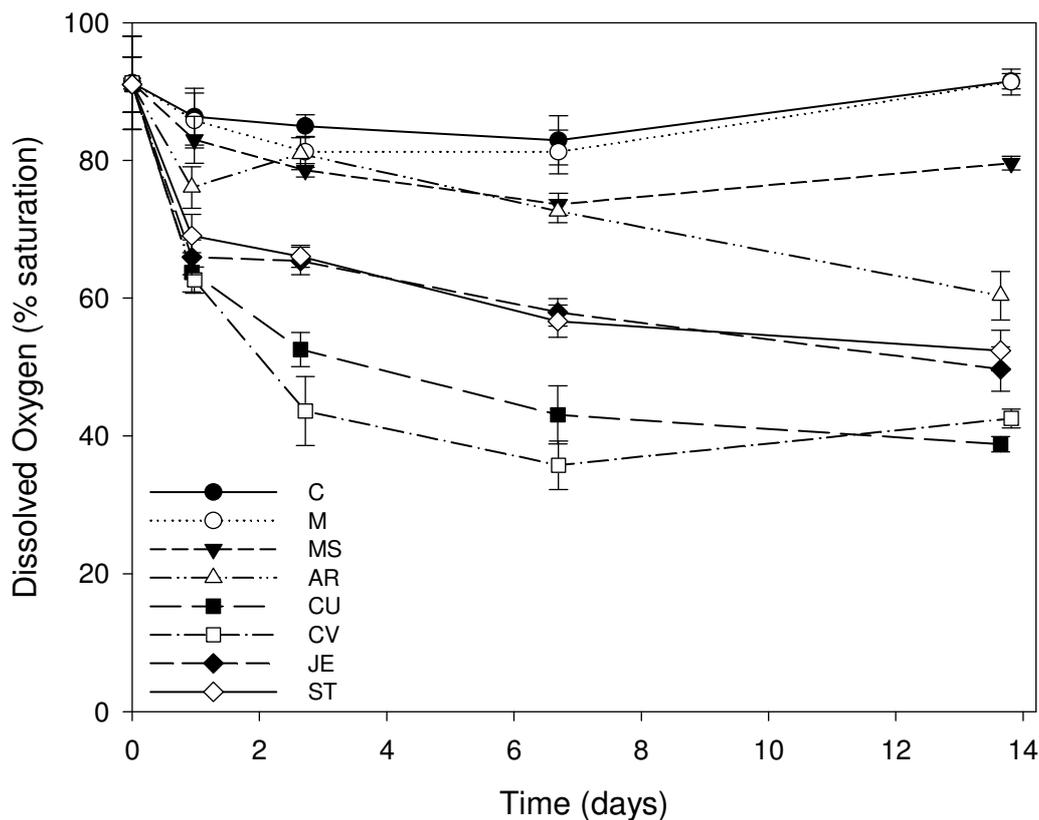
4.2.2.3 Copper

The mean concentrations of total copper (Cu) remaining (C/C_{in}) in the stormwater solution throughout the batches are presented in Figure 9. The initial total Cu concentration in the artificial stormwater ranged between 10 and 17 mg m^{-3} for the various batches. Monitoring of the dissolved Cu fraction demonstrated that typically more than 90 per cent of the total Cu was in the non-particulate form throughout the batches (even for batches with kaolin added to the stormwater solution). For brevity, only results for total Cu (representing primarily dissolved Cu) are therefore presented here.

The initial total Cu concentrations (10 – 17 mg m^{-3}) were within the event-mean concentration ranges summarised in ARC's TP237 (2004) from a number of studies of of stormwater from residential and commercial catchments in New Zealand. However, these studies indicate that approximately only one third of the total Cu typically occurs

in the dissolved phase. Thus, the initial dissolved Cu concentrations in the artificial stormwater used in the current study can be considered to be at the high end of the range.

Minimal reduction in total Cu occurred within the control mesocosms over the seven day batches. All other treatments generally showed a more rapid decline in total Cu concentration during the first one to three days, with the removal rate declining from days three to seven.

Figure 9

Mean proportion of Total Copper concentration remaining (C/C$_{in}$) for each treatment throughout the batches (n = 6). Initial concentrations (C$_{in}$) ranged from 0.010 to 0.017 g m^{-3}. Error bars represent +/- one standard error of the mean. Note that 14 day samples were only collected for some treatments (AR, CU, JE and ST) during one batch (n = 3).
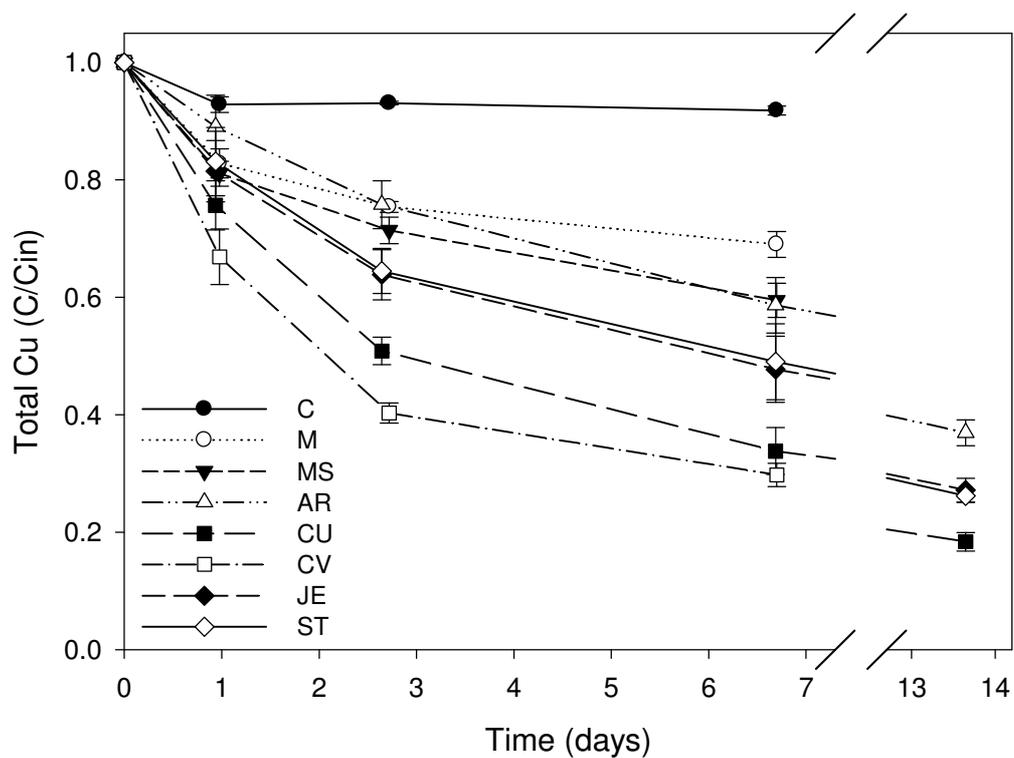
The planted mats (CU, CV, JE and ST) all removed total Cu at a faster rate than the unplanted mats (M, MS, and AR) and the control (C). After seven days, the total Cu concentration in the mesocosms containing *Cyperus ustulatus* (CU) and *Carex virgata* (CV) had been reduced to 4.2 and 4.3 mg m^{-3} respectively (approximately 65 per cent removal). The total Cu concentration in the *Juncus edgariae* (JE) and *Schoenoplectus tabernaemontani* (ST) mesocosms was reduced to 6.0 and 6.1 mg m^{-3} respectively after seven days, equating to approximately 50 per cent removal. The floating mats containing soil media (MS) and with artificial roots attached (AR) had removed

approximately 40 per cent of the total Cu after seven days. The data available for day 14 indicates that removal continued over the subsequent seven days.

The data indicates that the presence of a planted FTW provides a substantial improvement in the removal of dissolved Cu, and that there may be some differences between plant species. The efficacy of the planted FTWs at removing dissolved Cu may be due to a number of reasons, including:

- plant uptake of dissolved Cu;

- uptake of dissolved Cu into the biofilm community that is likely to have been present on the plant roots;

- complexation with humic compounds released by the plant roots (root exudates or decomposing biomass) or associated biofilms, followed by flocculation or binding to particulate organic matter and subsequent settling or entrapment, sorption, or precipitation within the root biofilms;

- provision of a physical surface area for sorption of dissolved Cu; or

- adsorption onto iron oxyhydroxide plaques that may have formed on the plant roots.

Given that conditions in the water column remained oxic throughout the batches, formation of insoluble metal sulphides is unlikely to have occurred within the mesocosms.

4.2.2.4 Zinc

The mean concentrations of total zinc (Zn) remaining (C/C_{in}) in the stormwater solution throughout the batches are presented in Figure 10. The initial concentration of total Zn in the artificial stormwater ranged between 440 and 490 mg m^{-3} for the various batches. Monitoring showed that more than 95 per cent of the total Zn was in the non-particulate form throughout the trials (even for batches with kaolin added to the stormwater solution). Hence, the total Zn results presented here essentially relate to dissolved Zn.

Minimal reduction in total Zn occurred within the control mesocosms over the seven day batches. All treatments generally showed a more rapid decline in total Zn concentration during the first day compared to the subsequent days.

The M, CV, JE and ST treatments all achieved between 9 and 15 per cent removal of total Zn by day seven. The two unplanted treatments that included soil media (MS and AR) and the mats planted with *Cyperus ustulatus* (CU) performed better than the other treatments, removing between 27 and 35 per cent of the total Zn by day seven. The MS treatment generally performed best, achieving a 35 per cent reduction in the total Zn concentration by day seven (day seven concentration = 305 mg m^{-3}). The available data for day 14 indicates that the observed removal rates would continue with increased contact time.

It is unclear why the removal of Zn was greater in the MS, AR and CU treatments than the others. Although Zn is generally more available for plant uptake under aerobic

conditions (Jugsujinda and Patrick, 1977; Sims and Patrick, 1978), removal in the planted treatments appears to have been highest for the species that showed the lowest DO levels. This, and the high rates of Zn removal exhibited by un-vegetated treatments suggests that other mechanisms of Zn removal are likely to have dominated in these systems.

Figure 10

Mean proportion of Total Zinc concentration remaining (C/C_{in}) for each treatment throughout the batches ($n = 6$). Initial concentrations (C_{in}) ranged from 0.44 to 0.49 g m^{-3}. Error bars represent +/- one standard error of the mean. Note that 14 day samples were only collected for some treatments (AR, CU, JE and ST) during one batch ($n = 3$).
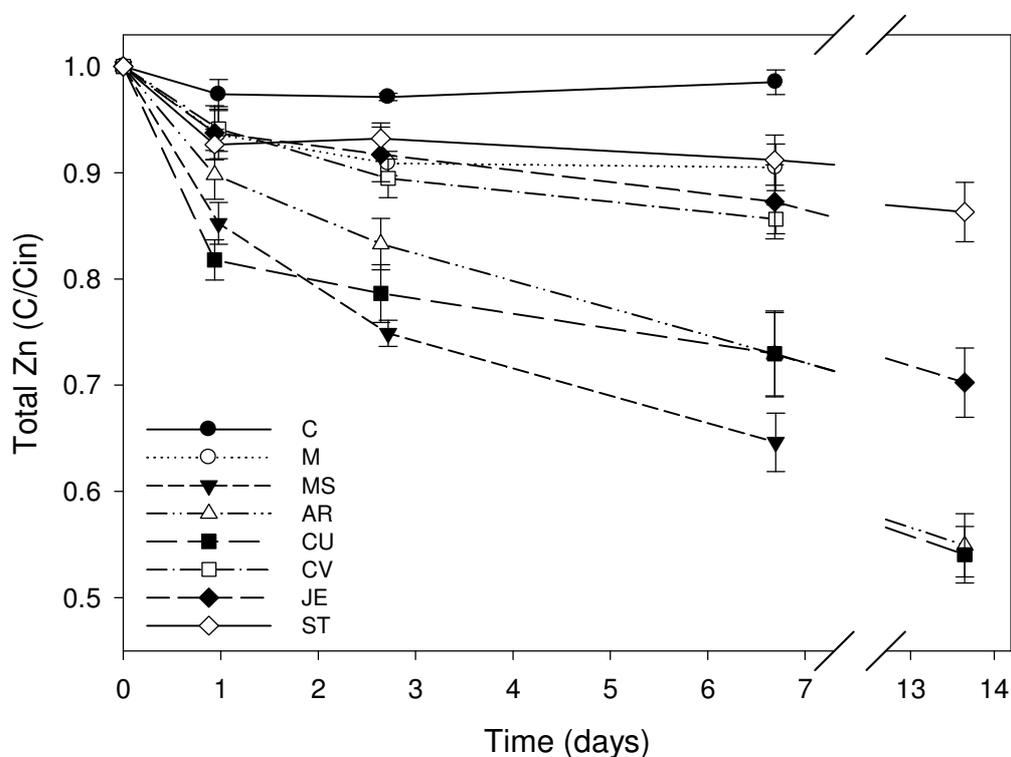

4.2.2.5 Turbidity

Turbidity was used as an indicator of the amount of fine particulate material suspended in the artificial stormwater. Only data from the batches where kaolin was added to the artificial stormwater are presented here. The kaolin was added to the artificial stormwater and mixed for 24 hours before being added to the mesocosms. Despite the stirring provided in the artificial stormwater mixing tank, substantial amounts of kaolin settled to the bottom of the mixing tank prior to addition to the mesocosms. Thus, only the very fine and slow to settle fraction of the kaolin remained in suspension when added to the mesocosms. The mean proportion of turbidity remaining (C/C_{in}) in the stormwater solution throughout the batches are presented in Figure 11.

The initial turbidity of the artificial stormwater was 10.2 NTU throughout the batches. The turbidity reduction in the control (C) treatment provides an indication of the ambient settling rate of the fine particles within a static open water body (approximately 25 per cent reduction after seven days). The rate of turbidity reduction was slightly improved in the treatments that contained a floating mat without any roots or root-like material hanging beneath them (M, MS). The rate of turbidity reduction was greatest in the mesocosms containing the planted mats (CU, CV, JE and ST), ranging between 58 and 67 per cent reduction after seven days. The turbidity in the treatment containing mats planted with *Carex virgata* (CV) declined to less than 1 NTU by day 14, while it was still at 6.8 NTU in the control. Smith and Kalin (2000) reported that the roots hanging beneath FTWs treating mine drainage accumulated between 0.3 and 2.2 kg of suspended solids per m^2 of FTW per year, with the higher rates being for a seven-year-old system with substantially more root development.

These results provide clear evidence that a pond with a FTW over it will achieve a substantially greater removal of fine suspended particulates from stormwater than a pond alone. Under the relatively sheltered, non-turbulent conditions within the mesocosms, it seems likely that it was the root mat and associated biofilms hanging beneath the floating mats that played the major role in enhancing the removal of fine suspended particulates. The "sticky" biofilms growing on the dense network of roots of FTWs filter and entrap particles suspended in the water column. Biofilms growing on the artificial roots appeared to be less effective at trapping suspended solids than natural roots. Although the characteristics of the biofilms were not directly investigated in the present study, those forming on plant roots are likely to have access to root exudates providing an organic substrate and bioactive compounds which may stimulate biofilm growth and promote floc formation (Neori et al. 2000).

Figure 11

Mean proportion of Turbidity remaining (C/C) at 20 cm from the bottom of the mesocosms for each treatment throughout the batches ($n = 6$). Initial concentrations (C) were 10.2 NTU. Error bars represent +/- one standard error of the mean. Note that 14 day samples were only collected for some treatments (AR, CU, JE and ST) during one batch ($n = 3$).
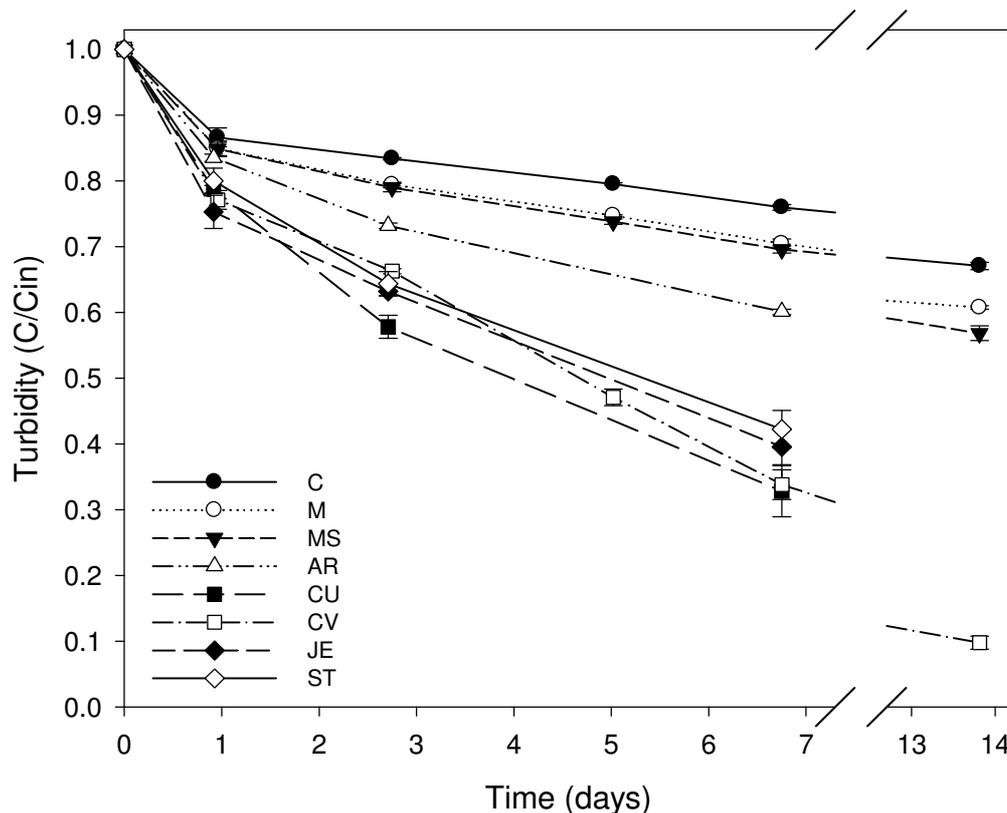
4.2.2.6 Ammonium nitrogen

The mean concentrations of ammonium-N (NH_4-N) remaining (C/C_{in}) in the stormwater solution throughout the batches are presented in Figure 12. The initial concentration of NH_4-N in the artificial stormwater ranged between 0.18 and 0.25 g m^{-3} throughout the batches.

The mean concentration of NH_4-N in the control mesocosms remained virtually unchanged throughout the seven day batches. In contrast, the concentration of NH_4-N in the M and MS treatments increased slightly during the batches. The concentration in the AR treatment increased slightly after one day before steadily decreasing to 0.173 g m^{-3} (21 per cent reduction) and 0.061 g m^{-3} (70 per cent reduction) after seven and 14 days respectively.

The fastest rate of NH_4-N reduction occurred in the planted treatments, particularly during the first three days. After 2.7 days the mean concentration reduction in the planted treatments ranged from 52 per cent for ST (down to 0.112 gN m^{-3}) 89 per cent for CU (down to 0.026 gN m^{-3}). The planted mesocosms continued to remove NH_4-N during the subsequent days, although at a slower rate, with concentration reductions

after 6.7 days ranging from 72 per cent for ST (down to 0.064 g N m^{-3}) to 96 per cent for CU (down to 0.009 g N m^{-3}). From the batch that was allowed to run for 14 days it was observed that the NH_4-N concentration in the planted treatments (CU, JE and ST) had decreased to 0.005 – 0.016 g m^{-3} after 13.6 days. The substantially higher removal of NH_4-N in the planted treatments compared to the others is likely a result of plant uptake or enhanced nitrification due to the additional surface area and biofilms provided by the roots.

Figure 12

Mean proportion of ammonium-nitrogen (NH_4-N) remaining (C/C$_{in}$) for each treatment throughout the batches (n = 6). Initial concentrations (C$_{in}$) ranged between 0.18 and 0.25 g m^{-3}. Error bars represent +/- one standard error of the mean. Note that 14 day samples were only collected for some treatments (AR, CU, JE and ST) during one batch (n = 3).
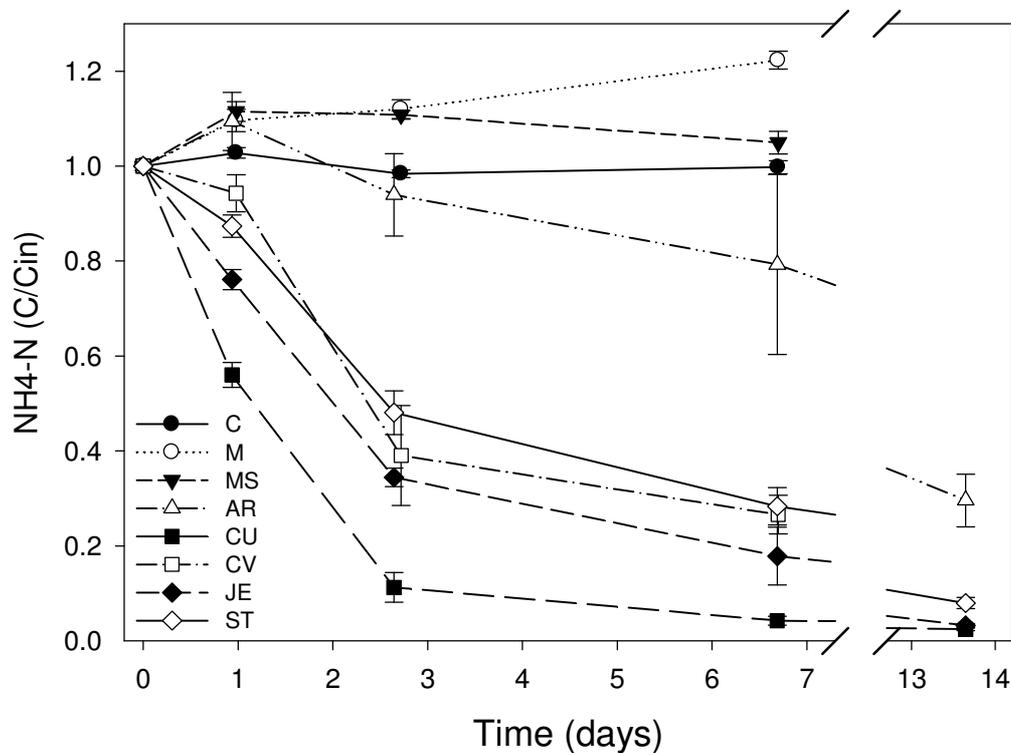
4.2.2.7 Dissolved reactive phosphorus (DRP)

The mean concentrations of dissolved reactive phosphorus (DRP) remaining (C/C$_{in}$) in the stormwater solution throughout the batches are presented in Figure 13. The initial concentration of DRP in the artificial stormwater ranged between 0.09 and 0.12 g m^{-3} throughout the batches.

Figure 13

Mean proportion of dissolved reactive phosphorus (DRP) remaining (C/C$_{in}$) for each treatment throughout the batches (n = 6). Initial concentrations (C$_{in}$) ranged between 0.09 and 0.12 g m^{-3}.

Error bars represent +/- one standard error of the mean. Note that 14 day samples were only collected for some treatments (AR, CU, JE and ST) during one batch ($n = 3$).
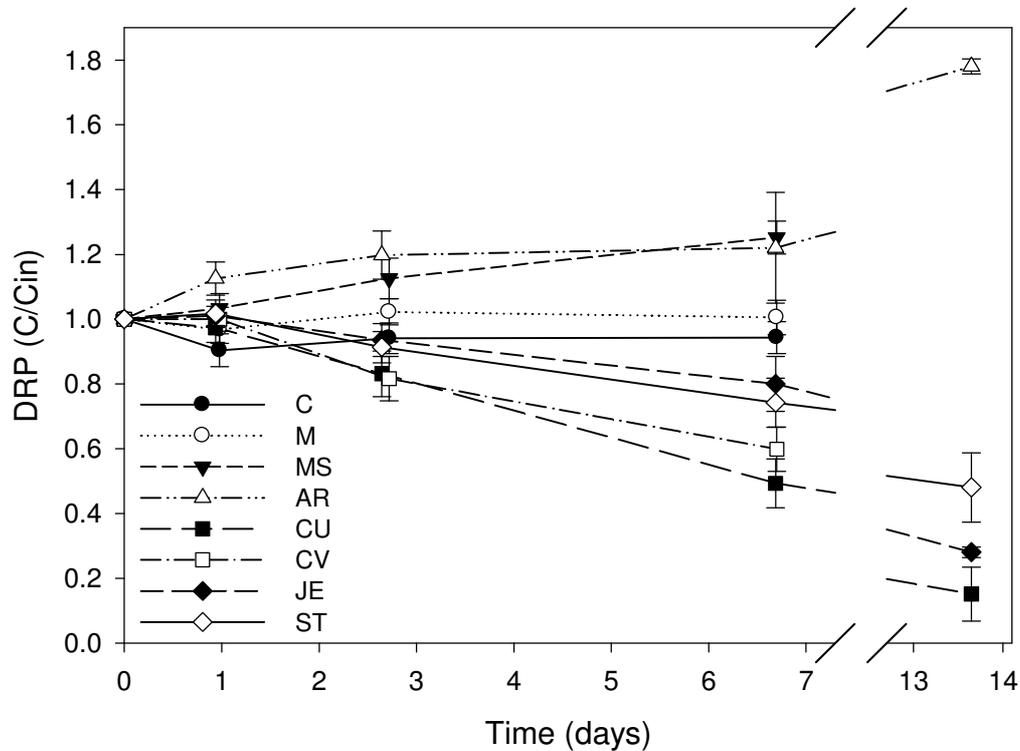

The mean concentration of DRP in the control (C) and matrix only (M) treatments remained almost constant throughout the seven day batches. The mean concentration in the planted treatments remained unchanged after one day, but then decreased steadily over time, with mean concentration reductions after 6.7 days of 20 per cent, 26 per cent, 40 per cent and 51 per cent for JE, ST, CV and CU respectively. In those planted treatments that were monitored for 14 days, removal of DRP continued, with mean reductions of 72 per cent, 52 per cent and 85 per cent achieved after 13.6 days in the JE, ST and CU treatments respectively.

In contrast, the mean DRP concentrations in the treatments containing the floating mat with soil (MS) and the artificial roots (AR) increased steadily over time (approximately 25 per cent increase after 6.7 days). After 13.6 days the mean DRP concentration in the AR treatment had increased by 78 per cent; an increase almost equal to the decrease observed in the planted treatments. Possibly, the break-down of the organic soil media used in the experiments provided an internal source of DRP, but was not apparent in the vegetated treatments due to plant uptake.

4.2.3 Removal rates

The mean Cu and Zn areal mass removal rates and fine particulate (turbidity) percentage reductions for the various treatments over the first three days of the batches are presented in Table 7. Removal rates for the first three days were selected because two to eight days is the common average recurrence interval for rainfall events in the Auckland region (2 to 2.5 days in winter, five to eight days in summer; ARC TP10, 2003). Also, the three day removal rates represent approximately average performance, as the most rapid removal rates occurred within the first day of each batch, whilst removal typically slowed after day three. The amounts of particulate Cu and Zn were negligible throughout the batches. Hence, the total Cu and total Zn removal rates presented in Table 7 primarily represent the removal of the dissolved metal fraction, whereas the turbidity reduction provides an indication of the amount of metals associated with very fine particulates that would be removed after three days.

Table 7
Mean copper and zinc areal removal rates and fine particulate (turbidity) percentage reductions over the first three days of the batches for the various treatments. Values in parentheses are one standard error of the mean.

Treatment	Cu removal rate		Zn removal rate		Fine particulate (turbidity)	
	mg m^{-2} d^{-1}		mg m^{-2} d^{-1}		% reduction	
Control (C)	0.73	(± 0.05)	10.0	(± 1.3)	16.6	(± 0.17)
Matrix (M)	2.7	(± 0.28)	32.1	(± 4.7)	20.6	(± 0.40)
Matrix + Soil (MS)	3.1	(± 0.43)	87.7	(± 6.1)	21.0	(± 0.62)
Artificial Roots (AR)	2.7	(± 0.71)	60.4	(± 10.6)	26.8	(± 0.42)
Cyperus ustulatus (CU)	5.1	(± 0.84)	77.0	(± 12.3)	42.2	(± 1.76)
Carex virgata (CV)	6.4	(± 0.60)	35.9	(± 5.5)	33.7	(± 0.40)
Juncus edgariae (JE)	3.9	(± 0.84)	30.4	(± 9.9)	36.8	(± 0.69)
Schoenoplectus tabernaemontani (ST)	3.8	(± 0.81)	24.8	(± 5.9)	35.6	(± 1.84)

The planted FTWs achieved Cu and Zn mass removal rates in the order of 3.8 – 6.4 mg m^{-2} d^{-1} and 24.8 – 77.0 mg m^{-2} d^{-1} respectively (Table 7) . These removal rates are higher than those reported for conventional constructed wetland systems receiving similar Cu and Zn loading rates to the FTWs in the present study. For example, Kadlec and Knight (1996) report Cu and Zn removal rates of 0.19 – 2.25 mg m^{-2} d^{-1} and 3.1 – 10.9 mg m^{-2} d^{-1} for similarly loaded surface flow and sub-surface flow wetlands. Furthermore, the Cu and Zn removal rates observed in the present study represent the removal of only the dissolved metal fraction, as the FTW mesocosms received minimal quantities of particulate metals. The planted FTWs removed approximately one third of the fine particulate load within three days, as indicated by the observed turbidity

reductions (Table 7). Given that the proportion of Cu and Zn associated with fine particles can be high in urban stormwater, especially as the distance from source increases (Griffiths and Timperley, 2005), potentially higher total Cu and Zn removal rates than those observed in the present study are conceivable. It is worth noting that only the very fine, slow to settle, fraction of suspended solids was added during these experiments in the form of kaolin, and that the actual removal of the suspended solids (and associated particulate metals) load in typical stormwater is likely to be much higher due to the rapid settling of larger particles. Whilst the results from the present study are encouraging, some caution needs to be excercised when comparing the removal rates observed from mesocosms during relatively short batch experiments to those derived from long-term studies of full-scale wetland systems. These results need to be verified at pilot- or full-scale over long-term operation under field conditions.

The mats with artificial roots (AR) achieved a mean Cu removal rate of approximately half that of the mats containing living plants, and were no better than the treatment containing only floating mats (M) or mats with soil media (MS). This provides strong evidence that the living plants played a broader role in the removal of Cu than simply providing a physical surface area for biofilm growth or adsorption on the roots. The estimated Cu and Zn plant uptake rates indicate that uptake into plant biomass accounted for less than 0.5 per cent of the observed Cu removal during the study (Table 8). Thus, other plant-mediated removal pathways must have been responsible. These pathways may have included flocculation or complexation of Cu with organic compounds exuded by the plant roots, followed by sorption or sedimentation, and/or the modification of the physiochemical environment immediately surrounding the roots through release of oxygen or organic compounds possibly favouring the formation of relatively insoluble complexes, such as with iron oxyhydroxides plaques around the roots.

The removal of Zn between the treatments was much more variable than for Cu, indicating that different removal processes are likely to operate for the two metals. The results suggest that the presence of living plants may impede the removal of Zn when compared to an unplanted floating mat. However, this is confounded by the fact that the FTWs planted with *Cyperus ustulatus* (CU) achieved Zn removal rates comparable to the unplanted mats with soil (MS) and artifical roots (AR). Possibly, the three other plant species were more effective at modifying the conditions in the root zone through oxygen leakage. Whilst this was not evident in the measured dissolved oxygen values (Figure 8), with CU having similar DO levels to the other plant species, the non-planted treatments did have higher DO concentrations than the planted treatments. It is probable that there were species specific effects on the DO conditions in micro-sites immediately surrounding the roots that were not apparent in the the bulk water where the DO was measured in the present study. Significantly more detailed investigations would be required to attempt to explain these observed differences in Zn removal between treatments. In any case, it is clear that a FTW, whether planted or unplanted, is capable of removing substantial amounts of Zn, particularly when compared to the performance of the control mesocosms (C) without any floating mats. It would also seem wise to include *Cyperus ustulatus* where possible when planting a FTW if Zn removal is important. Given that full-scale FTWs would typically be planted with a

range of species and include a mosaic of conditions, Zn removal rates in practice are likely to lie somewhere in the middle of those observed in the present study.

Table 8

Estimated ranges of plant uptake rates of Cu and Zn and the percentage that these represent of the overall Cu and Zn removal rates measured in the present study for the four species tested.

			Cyperus ustulatus	*Carex virgata*	*Juncus edgariae*	*Schoenoplectus tabernaemontani*
Copper uptake#	Above-mat	mg m² d¹	0.008 - 0.016	0.010 - 0.021	0.005 - 0.010	0.002 - 0.004
	Below-mat	mg m² d¹	0.002 - 0.006	0.003 - 0.009	0.0001 - 0.0004	0.002 - 0.007
	Total	mg m² d¹	0.010 - 0.022	0.014 - 0.030	0.005 - 0.010	0.005 - 0.011
	as % of removal rate		0.2 - 0.4	0.2 - 0.5	0.1 - 0.3	0.1 - 0.3
Zinc uptake#	Above-mat	mg m² d¹	0.163 - 0.570	0.206 - 0.720	0.100 - 0.349	0.044 - 0.154
	Below-mat	mg m² d¹	0.041 - 0.237	0.065 - 0.380	0.003 - 0.016	0.048 - 0.280
	Total	mg m² d¹	0.203 - 0.806	0.271 - 1.100	0.102 - 0.365	0.092 - 0.434
	as % of removal rate		0.3 - 1.1	0.8 - 3.1	0.3 - 1.2	0.4 - 1.8

[#] calculated using the minimum and maximum Cu and Zn concentrations reported for eight different wetland plants in Tanner (1996).

The turbidity reductions achieved by the planted FTWs after three days were approximately 1.5 – 2 times greater than in the unplanted mesocosms, indicating that the plants played an important role in the removal of fine suspended particulates. This supports the notion that the mat of roots and associated biofilms hanging beneath a FTW provides an effective filter for trapping very fine suspended solids. The fact that the mats containing artificial roots (AR) were not as effective at reducing turbidity as the mats containing living plants suggests that it is more than just the physical presence of the surface area provided by the roots that is important. In this regard, the plant roots may facilitate better biofilm growth due to the fact that they are a biological, rather than synthetic, substrate and also have the potential to modify the environment immediately surrounding the roots through the release of oxygen and soluble organic compounds. Another factor may have been the "transpiration pump" effect of the living plants (Martin et al, 2003); actively drawing water towards the roots as the plants transpire in the otherwise quiescent conditions, thereby enhancing contact between the roots and suspended particles. More detailed investigations of these factors are desirable.

5 Concluding Remarks

This study has provided encouraging results which support the application of FTWs for removal of Cu, Zn and fine suspended particulates from urban stormwater. The presence of living plants played a key role in the removal of Cu and fine suspended sediments. However, the role of plants in Zn removal is less clear. The results indicate that FTWs are capable of achieving dissolved Cu and Zn mass removal rates in the order of 3.8 – 6.4 mg m^{-2} d^{-1} and 25 – 88 mg m^{-2} d^{-1} respectively, which compare favourably to removal rates reported for conventional surface flow and subsurface flow constructed wetlands at similar loading rates. Full- or pilot-scale studies are desirable to investigate long-term treatment performance under field conditions. 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 one third of the very fine suspended particulate load within three days.

All four of the native New Zealand plant species used in the water quality trials (*Carex virgata*, *Cyperus ustulatus*, *Juncus edgariae* and *Schoenoplectus tabernaemontani*) can be recommended for use in FTWs. *Carex dipsacea*, which diplayed a reasonable growth response during the initial plant trial but was not used in the subsequent water quality trials, is probably also suitable for use in FTWs. Conversely, *Eleocharis acuta*, which experienced rapid and dense, albeit short, shoot development during the plant trial, displayed minimal root development beneath the floating mat and is not likely to have a substantial effect on treatment performance in FTWs. It is likely that other wetland-adapted species from the same genera as the four species used in the water quality trials will also be suitable for use in FTWs. The larger growing species such as *Typha orientalis* (Raupo) and *Baumea articulata*, may also be potentially suitable in larger FTWs where there is minimal risk of the floating mats tipping over during high winds or waves.

5.1 Recommendations for further work

Field scale trials are considered to be an important next step in assessing the feasibility of FTWs for providing improved stormwater treatment. Field testing will enable practical issues to be identified and will overcome some of the limitations imposed in using "artificial" stormwater at the mesocosm-scale. A key factor in the adoption and implimention of the technology will be the degree to which FTWs provide an improvement in treatment efficiency over conventional (less expensive) ponds. Thus, any future trials should provide a clear comparison of the performance of a conventional pond against that of an equivalently loaded FTW system.

It is recommended that a FTW be established in a stormwater pond in the Auckland region that recieves significant loads of metals and fine particulates (ie a catchment with commerical and/or industrial land uses). In order to provide a comparison between pond and FTW performance, a number of options exist, such as:

- splitting an existing pond into two parallel, equi-sized ponds using an impermeable barrier and establishing a vegetated floating mat on one side to provide a direct side-by-side comparison of treatment performance (preferred option);

- constructing a pond and FTW in two side-by-side basins within a newly developed or proposed stormwater treatment system; or

- monitoring the performance of a pond "before" and "after" retro-fitting a FTW over it. This may be the easiest option to set up, but is likely to require the longest period of monitoring due to the need for baseline monitoring. Monitoring of a large number of events will also be required in order to obtain conclusive results due to the inherent variability in stormwater quantity and quality. This monitoring requirement may be reduced if a pond can be used for which extensive baseline monitoring already exists.

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