Reduction of Road Runoff Contaminants: Laboratory Experiments and Monitoring of Treatment Walls

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Executive summary

Project and client

Contamination of freshwater resources and estuaries as a result of runoff from urban development in New Zealand is threatening aquatic life. Many of the pollutants associated with urban runoff are derived from motor vehicles, and territorial and regional authorities in New Zealand have identified stormwater management as a priority environmental issue in urban areas. While sediment and associated contaminants in road runoff can be removed by a range of treatment devices, the removal of dissolved contaminants has proved to be far more challenging. Increasing attention is being paid to the use of various filter systems, such as relatively low-cost treatment wall systems, to reduce the dissolved contaminant load in road runoff. Treatment walls are permeable barriers that allow the passage of water while removing or breaking down pollutants by employing agents such as chelators, sorbents and microbes in the barrier material (media).

Landcare Research evaluated the effectiveness of various potential filtration media for the removal of contaminants from road runoff for Transfund New Zealand (Transfund) between July 1998 and June 2004. Laboratory studies were carried out over the first two years of the contract, with subsequent testing of the most promising medium in two pilot studies at sites identified in consultation with Transfund.

Objectives

1. Determine the capability of locally available materials, individually or in layered combination, such as wood waste and wood ash to remove heavy metals and persistent organics from a surrogate solution approximating the composition of road runoff in laboratory tests (1998–2000).

2. Establish two treatment wall pilot studies that intercept road runoff, using the most promising substrate, or substrate mixture from Objective 1 above. Monitor their effectiveness in removing heavy metals and organics from the road runoff, measure water and solute transport through the walls, and measure heavy metal and organics build-up within the walls (2000–2004).

3. Optimise performance by identifying operational parameters (e.g. frequency of sediment removal or medium replacement) based on the laboratory tests and pilot studies (2003–2004).

Methods

1. A laboratory experiment was set up to assess different filter media. Sphagnum moss, crushed limestone, waste wood pulp, wood ash and waste wool felt were tested for their potential use as substrates in treatment filters/walls by determining their ability to remove the dissolved forms of copper (Cu), zinc (Zn), lead (Pb), pyrene and fluoranthene from artificial road runoff.

2. Treatment walls were constructed at a roundabout at the corner of River Road and Wairere Drive in Hamilton, and on the side of State Highway 1 in Cambridge, to intercept runoff before discharge to the stormwater collection system and, finally, to the Waikato River. The mixed Sphagnum/wood ash combination, which performed best in the laboratory tests, was used as the treatment wall medium. This combination had previously been shown to have excellent success in removing heavy metals and polyaromatic hydrocarbons (PAHs), high numbers of PAH-degrading micro-organisms, and suitable hydraulic conductivity to allow chemical and microbiological reactions to take place. Measurements were made of the input and output concentration of heavy metals and PAHs, as well as accumulation in the walls.

3. Normal routine maintenance was not carried out on the field-tested treatment walls during the experiment to examine overstress of the treatment wall media. This 'worse case' scenario enabled us to characterise the breakthrough of contaminants and the accumulation of sediment, and assess potential longevity and associated operational requirements.

Results and discussion

1. In laboratory leaching experiments the lime and wood-ash columns proved to be very effective, removing >95% of applied dissolved heavy metals and PAHs. The other media, particularly *Sphagnum*, were effective in removing heavy metals, but not PAHs. Although *Sphagnum* had high numbers of PAH degraders, its high hydraulic conductivity did not allow enough time for the micro-organisms to break down the PAHs. Wool felt was the least effective at removing heavy metals so was not tested for PAH removal.

   Two mixed media, *Sphagnum*/lime and *Sphagnum*/wood ash, containing 10% by weight of *Sphagnum*, were also tested. The *Sphagnum*/wood ash column performed well, removing >86% of PAHs and >94% of the heavy metals, and this combination was used in the field trial, as noted previously. There was an initial release of both Cu and Zn from the *Sphagnum*/lime mixture, although it removed >93% of the PAHs.

2. In the field studies, both treatment walls were very effective at removing sediment and associated contaminants. In addition, these field results confirmed those found in laboratory trials - that these walls were also effective at removing dissolved Cu, Pb, Zn and PAHs.

3. A 15-cm sediment layer was observed to accumulate at the Hamilton site while no distinct sediment layer accumulated at the Cambridge site, indicating sediment accumulation is due to site-specific factors. The removal of contaminants by the Hamilton treatment wall was comparable to the laboratory studies for the first 10 to 13 months.

After 13 months the levels of dissolved Zn in the treated runoff at the Hamilton site were as high or higher than the untreated runoff, indicating that the medium was unable to effectively treat further inputs of dissolved Zn. The layer of high-Zn sediment deposited on top of the medium appeared to be the source of Zn.

However, other contaminants are still being removed after 39 months. The Cambridge site is continuing to remove contaminants, despite showing early signs of deteriorating heavy metal removal after 22 months. This site had been subject to truck spills of substances, such as cream, that may have affected media longevity.

Conclusions

1. In laboratory studies, lime and wood ash, and the wood ash/*Sphagnum* mixture, were very effective (>90%) at removing heavy metals and PAHs from artificial road runoff.

2. Field-testing treatment walls containing wood ash/S*phagnum* media showed them to be effective at reducing contamination from road runoff. An appropriate strategy for the use of such treatment walls may be in targeting hot spots, i.e. those areas that, either through heavy industrial use or high traffic density accompanied by high tyre wear (e.g. roundabouts and major intersections), could be expected to have higher levels of contaminated runoff.

3. Periodic removal of sediment from the surface of the treatment wall is needed, as the sediment is a source of dissolved heavy metals that can become distributed in subsequent rain. The length of this period will depend on the sediment load of the site.

4. Breakthrough of dissolved Zn was observed at the Hamilton site after 13 months, while the Cambridge site is only now showing early signs of breakthrough for both Zn and Cu after 22 months.

5. Without removal of the sediment, longevity of the media in treatment walls is about one to two years. Removing sediment will increase this lifespan.

Recommendations

1. Treatment walls containing suitable organic media to remove dissolved contaminants should be used where the contamination load in road runoff is expected to be high (hot spots). The media used could be wood ash, a wood ash/*Sphagnum* combination or green compost, but economic considerations such as cost of transportation and ease of availability should also be taken into account during selection. Hot spots might include car parks, roundabouts, accelerating and de-accelerating zones of roading networks and petrol station forecourts.

2. Sediment build-up in such walls should be removed, probably at six monthly intervals but at least annually. An assessment of the effects of such maintenance on treatment wall life expectancy should be carried out.

3. To promote uptake, trials should continue to monitor the performance of treatment walls under a variety of site characteristics, traffic density and climatic conditions at sites different from those in this study, to optimise road runoff treatment in other parts of New Zealand. This is likely to influence engineering design for stormwater interceptor devices suggested in 2003 by Auckland Regional Council.

4. Other suitable media and a combined treatment train approach should continue to be explored.

Abstract

Sand-filled interception devices are the current industry standard filtration systems to treat road runoff. However, other materials, such as wood ash, wood ash/*Sphagnum* combination, or green compost, could be better at removing stormwater contaminants, particularly dissolved contaminants.

The effectiveness of various potential filtration media for the removal of the contaminants Cu, Pb, Zn and PAHs from road runoff was evaluated between July 1998 and June 2004.

A 2-year laboratory study was followed by field testing of the most promising medium (*Sphagnum*/wood ash mixture) in two pilot studies (treatment walls). Both treatment walls were initially very effective at removing sediment and associated contaminants and confirmed results from the laboratory trials. After 13 months of operation, breakthrough of dissolved Zn occurred at one site. A 15 cm layer of high-Zn sediment deposited on top of the medium appeared to be the source of Zn and this sediment would need periodic removal to maintain performance.

Treatment walls containing the media studied were considered best suited for areas where the contaminant load in road runoff was expected to be high, and could be incorporated as part of a treatment train approach.

1. Introduction

Stormwater generated from road runoff contains contaminants that are either dissolved in stormwater or bound to particulates. Although roading infrastructure may represent only 10 to 20% of an urban catchment, road runoff can contribute as much 35 to 75% of total heavy metals, 16 to 25% of total hydrocarbons and 50% of total suspended solids to a receiving water body (Ellis et al. 1987). Many of these contaminants are potentially toxic and can have detrimental effects on the environment (Ellis & Revitt 1991). Metals are carried in stormwater in both dissolved and particle-bound forms (Robien et al. 1997) and 80% of those in particulate form remain potentially bioavailable and a source for further pollution (Colandini et al. 1995; Mikkelsen et al. 1996). Metals do not decompose; rather, they accumulate in sediments, plants and filter feeding organisms. Elevated metal concentrations cause health issues, and organisms will avoid the affected habitat (ARC 2003). Another group of contaminants that may cause health concerns are polyaromatic hydrocarbons (PAHs). Boxall & Maltby (1997) considered PAHs to be the major toxins in road runoff. Suspended solids may also alter habitats and, after settling, smother aquatic life.

While sediment and associated contaminants can be removed by a variety of strategies (ARC 2003), it is more difficult to remove dissolved contaminants. Treatment walls have the potential to remove dissolved contaminants as well as sediment loads (through filtration), and offer a possible low-cost system for treating runoff.

Treatment walls are permeable barriers that allow the passage of water, while restricting the movement of pollutants, by employing agents such as chelators (ligands selected for their specificity for a given metal), sorbents and microbes in the barrier material. As water is the major vector for waste constituent movement, the contaminant load in a runoff stream can be decreased if the flow is intercepted by constructing a filter treatment wall across the flow path containing a medium that will remove targeted contaminants.

The specific medium chosen for a permeable wall is based on the nature and characteristics of the pollutant stream. Depending on the specific medium, the mechanism of removal of pollutants will follow different chemical processes (US EPA 1996): sorption, precipitation or degradation (Figure 1.1).

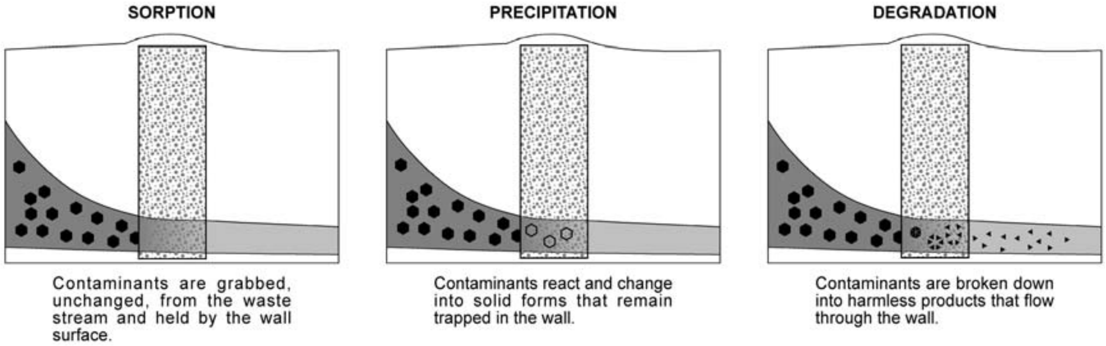

Figure 1.1 Mechanisms of contaminant removal: sorption, precipitation and degradation.

Under laboratory conditions, *Sphagnum* moss, crushed limestone, waste wood pulp, wood ash and waste wool felt were tested for their potential use as media in treatment filters/walls by determining their ability to remove dissolved copper (Cu), zinc (Zn), lead (Pb), pyrene and fluoranthene from artificial road runoff (Pandey et al. 2002, 2003). Based on these results, four field studies were established using the most promising medium, or a combination of media, to construct a treatment wall to intercept runoff directly from the road surface. Input and output solution concentrations of heavy metals and key organics, and their build-up in the treatment walls, have been measured over time to assess field performance and help establish design specifications.

The four treatment walls so far tested were constructed in Hamilton and Cambridge (both funded by Transfund), Waitakere (funded by ARC) and Tauranga (funded by Eastern Bay of Plenty (EBOP)). This report summarises previous reports (Pandey et al. 2002, 2003) and incorporates results from the latest phase of field-testing. It constitutes the final report in this sequence of work funded by Transfund.

Figures 1.2 & 1.3 The Hamilton treatment wall in operation.

Figures 1.4 & 1.5 Cambridge site, State Highway 1, during construction. The catch pit for the treatment wall is behind the white van.

2. Laboratory Experiments

2.1 Methodology

Under laboratory conditions, we have examined five media (Table 2.1) that may be suitable in treatment walls through their ability to remove the heavy metals, copper (Cu), lead (Pb), zinc (Zn) and also selected PAHs (fluoranthene and pyrene) from artificial road runoff. The media tested were commercially available *Sphagnum* moss, crushed limestone, waste wood pulp, wood ash, and waste wool felt. Two media, *Sphagnum*/lime and *Sphagnum*/wood-ash layered one above the other, as well as in mixed configurations containing 10% by weight of *Sphagnum*, were also tested. These materials have previously been shown to be capable of removing pollutants such as heavy metals (Ho et al. 1996), nutrients (Kadlec 1987) and trace organics (Toller & Flaim 1988).

Table 2.1 Media tested under laboratory conditions for pollutant removal capacity.

Media	Origin
Sphagnum moss (floor sweepings)	West Coast Region of New Zealand
Limestone (‘blue-chip’ <25 mm)	McDonald’s Lime, Otorohanga
Waste Wood Fibre	Carter Holt Tissue, Kawerau
Wood Ash	Carter Holt Harvey Pulp and Paper, Kinleith
Felted Waste Wool	Wool Research Organisation of New Zealand, Christchurch

Plastic drainpipes (600 by 60 mm) were filled with each medium (three replicates), and plastic mesh was glued over the ends of the pipes to hold the media in place (Figure 2.1). The *Sphagnum* was packed at a bulk density of approximately 0.04 t m^{-3}, the mixed media at 0.17 t m^{-3} and the remaining single media at 1.18 t m^{-3}. Artificial road runoff (Table 2.2) was applied by a peristaltic pump to the top of each drainpipe at 25 mL min^{-1} for the wood ash and the mixed media, 5 mL min^{-1} for the wood pulp and 100 mL min^{-1} for the other single media. The difference in application rates reflects the infiltration rates of the different media. The runoff was applied in eight applications of 2.25 litres (‘rainfall’ events), with two weeks between each application, giving a total of 18 litres of leachate. Leachate was analysed for heavy metals and PAHs. Analysis for Cu and Pb was carried out using graphite furnace atomic absorption spectrometry with Zeeman background correction, while analysis for Zn was carried out by flame atomic absorption spectrometry. PAHs were determined by gas chromatography.

Initial leaching showed that lime and wood ash were much more effective at removing PAHs than *Sphagnum* and waste wood fibre, therefore only these continued to be irrigated with artificial road runoff containing PAHs. Wool felt was not examined for its ability to remove PAHs because it was the least effective at removing heavy metals.

Figure 2.1 Laboratory experiment showing artificial road runoff being applied to six treatment wall columns.

Table 2.2 Concentration of pollutants in artificial runoff (pH = 7.5).

Pollutant	Concentration (µg L^{-1})
Cu	110
Pb	880
Zn	440
Fluoranthene	42
Pyrene	18

2.2 Results and discussion

2.2.1 Individual media

Lime and wood ash removed >98% of Cu and Zn (Figure 2.2), presumably because these metals become less soluble as pH increases. *Sphagnum* was almost as efficient, removing >97% of Cu and Zn, while waste wood fibre removed 85% and 60% of Cu and Zn respectively.

Sphagnum has been shown to have a large number of adsorption sites capable of rapidly binding metals (Gardeatorresdey et al. 1996), and this is the most likely reason for its better performance. The waste wood fibre consisted largely of lignin and would have less adsorption sites available. The behaviour of Pb was slightly different. Lime and wood ash removed >99%, as Pb becomes less soluble with increasing pH, while *Sphagnum* removed >87% and waste wood fibre >82%. The lesser removal of Pb by *Sphagnum* and waste wood fibre could be due to mobilisation of dissolved organic matter, which releases Pb back into solution (Jordan et al. 1997). Wool felt was the least efficient medium at removing heavy metals. The lime and wood ash columns removed more than 96% of the applied PAHs during the experiment. Removal could be due to adsorption of PAHs to the media or microbial decomposition of PAHs. A combination of both processes is most likely. Although the number of PAH degrading micro-organisms in the lime and fly ash was low compared with *Sphagnum* (Table 2.3), both media have higher pH than the *Sphagnum*. Thiel & Brummer (1998) showed that microbial decomposition of PAHs in contaminated soils increased with the addition of lime, probably due to increased pH. Although *Sphagnum* had the highest number of PAH-degrading micro-organisms, the hydraulic conductivity of *Sphagnum* was so high that these micro-organisms had little time to react with the contaminants because the solution passed through the media very quickly (Table 2.4). The lack of time for micro-organisms to react may also have contributed to the high standard deviation associated with this medium.

Waste wood fibre had a much slower conductivity and was not suitable for treating large volumes of road runoff. There was an initial release of dissolved carbon from each medium except lime (up to 250 mg L^{-1} for a single sample), which would have resulted in increased Chemical Oxygen Demand (Figure 2.3). Levels reduced rapidly to background levels after three rainfall events. After the initial wetting, drying and re-wetting had no further effect on the release of carbon. Wool felt was not examined for dissolved carbon because it had already been rejected as a suitable medium, as it was the least effective at removing heavy metals.

Table 2.3 PAH degrading micro-organisms found on media.

Medium	Number of PAH degraders (colonies g^{-1})
Sphagnum	13622
Lime	73
Wood waste	73
Wood ash	136

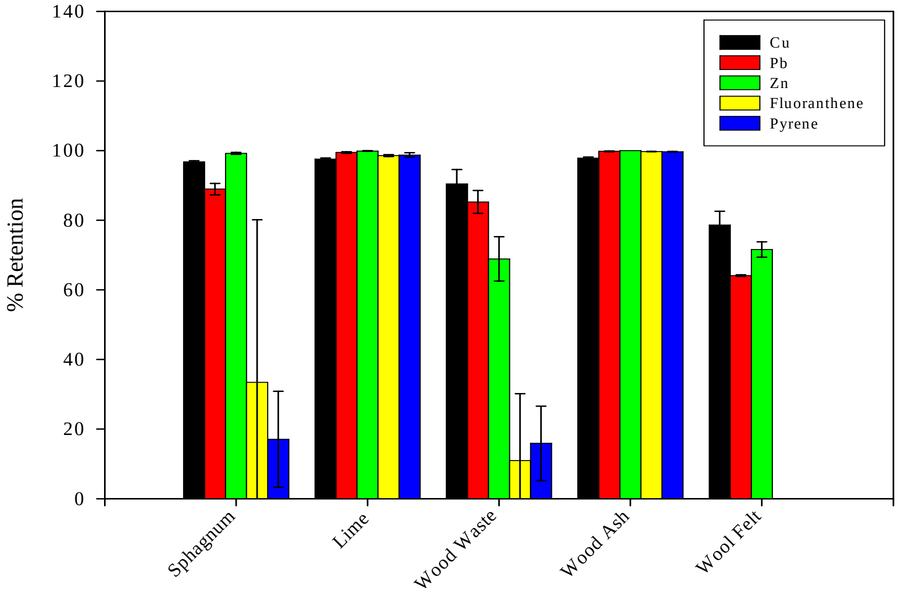

Figure 2.2 Average removal of pollutants from artificial road runoff by individual media.

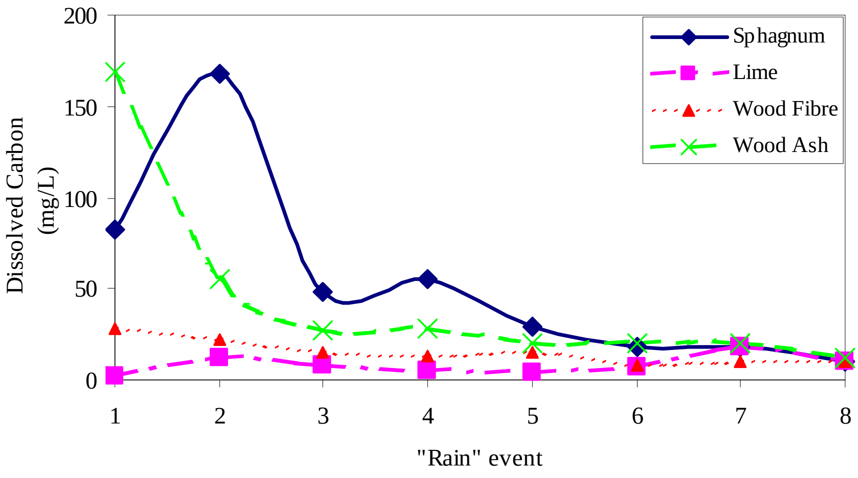

Figure 2.3 Average dissolved carbon release from individual media.

2.2.2 Combined media

The mixed media had higher hydraulic conductivity than the layered media and wood ash alone, but not as high as *Sphagnum* alone (Table 2.4). The *Sphagnum*/wood ash mixture performed well, removing over 99% of the PAHs added, 94% of the copper, and 99% of the Zn (Figure 2.4).

Table 2.4 pH values of leachates and saturated hydraulic conductivity (Ksat) of media.

Treatment Media	Ksat ($m\,s^{-1}$) Mean and standard deviation	pH Range (Mean)
Sphagnum	$1.62 \times 10^{-3} \pm 4.80 \times 10^{-4}$	5.0-5.9 (5.5)
Lime	$2.56 \times 10^{-4} \pm 1.62 \times 10^{-4}$	7.6-8.2 (8.0)
Waste wood fibre	$3.17 \times 10^{-7} \pm 2.25 \times 10^{-7}$	7.0-7.6 (7.3)
Wood ash	$1.45 \times 10^{-4} \pm 2.09 \times 10^{-5}$	8.1-8.4 (8.3)
Mixed wood ash/*Sphagnum* 1:0.05 kg	$1.95 \times 10^{-4} \pm 8.69 \times 10^{-5}$	7.1-8.0 (7.5)
Mixed lime/*Sphagnum* 1:0.05 kg	$2.36 \times 10^{-4} \pm 1.60 \times 10^{-4}$	7.1-7.9 (7.4)
Layered wood ash/*Sphagnum* 1:0.05 kg	$8.04 \times 10^{-5} \pm 9.90 \times 10^{-5}$	6.5-8.0 (7.7)
Layered lime/*Sphagnum* 1:0.05 kg	$4.29 \times 10^{-5} \pm 2.03 \times 10^{-5}$	4.2-7.9 (6.7)

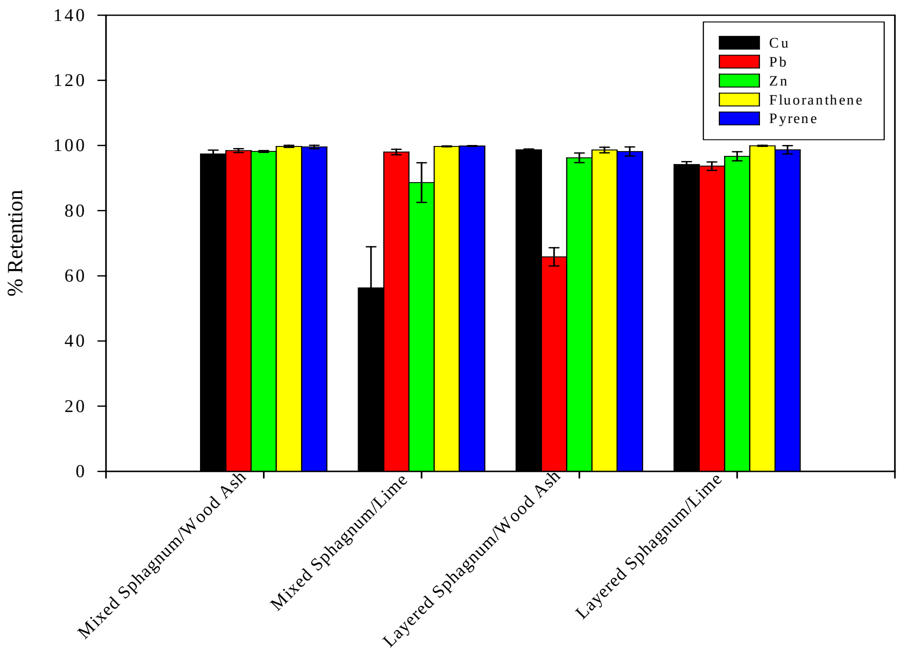

Figure 2.4 Removal of pollutants from artificial road runoff by mixed media.

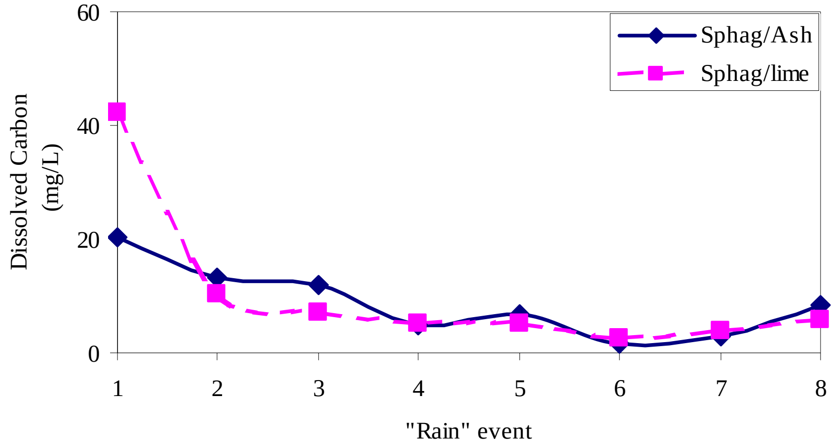

Figure 2.5 Average dissolved carbon release from mixed media.

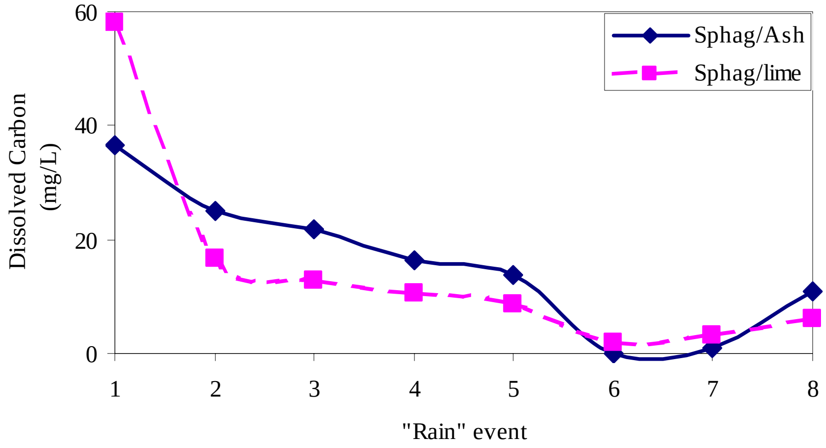

Figure 2.6 Average dissolved carbon release from layered media.

The *Sphagnum*/lime mixture proved marginally better in removing PAHs, but did not perform so well with Cu and Zn. Here, there was an initial release of these two metals from the mixture, associated with the release of carbon (Figure 2.5). The cumulative total of Cu removed was still negative after three applications because more Cu was released from the media than was added with the artificial road runoff. The effect on the Zn was not so marked, the initial release resulting in a cumulative total removal of 86%. The initial leachate from the *Sphagnum*/lime mixture was coloured, due to dissolved organic carbon (DOC). The elevated levels of DOC could be from readily available carbon released with the initial wetting of dry media. Carbon-entrained Cu and Zn would then be released with the leachate generated from the initial wetting. The colouration had gone by the time of the third application or 'rainfall' event, which coincided with much lower levels of Cu and Zn in the leachate. The layered media performed similarly to the mixed media but had slower hydraulic conductivity and had a wider range of pH (Table 2.4, Figures 2.4 and 2.6). The pH was lower when *Sphagnum* was the bottom layer, compared with when lime or wood ash comprised the bottom layer.

2.2.3 Ranking of media

The individual, mixed and layered media were ranked according to their contaminant removal efficiency, with 1 being the best performance (Table 2.5). The lowest total score gives the best-performing media over the five contaminants studied. The best-performing media overall were the mixed *Sphagnum*/wood ash combination, wood ash alone and lime alone.

Table 2.5 Ranked treatment matrix: 1 being the best performed in each category, lowest total being best overall.

Media	Copper	Lead	Zinc	Fluor-anthene	Pyrene	PAH Degraders	Hydraulic Conductivity	Total
Sphagnum	1	3	1	2	2	1	5*	15
Lime	1	1	1	1	1	3	3	11
Wood Fibre	2	4	4	3	2	3	6	24
Wood Ash	1	1	1	1	1	2	2	9
Sphagnum/ Ash mixed	1	2	1	1	1	1	1	8
Sphagnum/ Lime mixed	3	2	1	1	1	1	3	12
Sphagnum/ Ash layered	1	4	3	1	1	1	4	15
Sphagnum/ Lime layered	1	3	2	1	1	1	4	13

* *Sphagnum* had excessively fast hydraulic conductivity, which allowed insufficient time for chemical or biological reactions to occur.

3. Treatment wall pilot studies

3.1 Site location and establishment

The mixed *Sphagnum*/wood ash combination, which performed best in the laboratory tests, was used as the treatment wall medium. This combination had excellent removal of heavy metals and PAHs, high numbers of PAH degrading micro-organisms and suitable hydraulic conductivity to allow chemical and microbiological reactions to take place.

Two pilot studies were established in Hamilton and Cambridge with support from Transfund. This report relates to these two treatment walls. We have included other treatment wall data for comparison. The Hamilton treatment wall was constructed at the corner of River Road and Wairere Drive in December 2000 to intercept the runoff from a portion of a roundabout (Figures 3.1 and 3.2). The treatment wall was housed in two stormwater pipes (1.5 m deep by 1.05 m in diameter), placed side by side. Each pipe receives road runoff entering at the top and percolating through the medium by gravity. The treated runoff exiting the treatment wall re-joins the normal flow path for the stormwater system and finally enters the Waikato River. A mixture of *Sphagnum*/wood ash, at a ratio of 1:1 by volume, 1:10 by weight, was chosen as the medium for this site. Mixed media have higher hydraulic conductivity than layered media (Table 2.4). Measurements were made for input and output concentration of heavy metals and PAHs, as well as for accumulation of contaminants in the media. Subsequently, an additional wall was constructed in Cambridge on the side of State Highway 1. In contrast to the Hamilton trial, it was testing an increased ratio of *Sphagnum* (20% by weight). The Cambridge treatment wall is configured in a similar fashion to that at the Hamilton site.

Figure 3.1 The Hamilton site. The orange hazard fence surrounds the treatment wall.

Figure 3.2 The Hamilton site.

A third treatment wall site was constructed at the Henderson recreation centre and swimming pool complex in Waitakere City (funded by ARC), intercepting runoff from a car park. Here we tested wood ash, sand and green-waste compost, as filter media. Sand is the standard medium in sand filters and the other two media were compared with it. Wood ash performed well in the laboratory experiments and the other medium, compost, was included as it is readily available and the humified organic matter should have high adsorption capacity for contaminants. The media are 'housed' in standard sand-filter units supplied to Waitakere City Council by Hynds, arranged in parallel and received similar amounts of runoff through the pre-treatment chamber. The outflows join the Henderson Creek.

A fourth treatment wall site has recently been established in Mount Maunganui (Tauranga) at the Hewletts Road/Tasman Quay roundabout (funded by EBOP). We are testing layered *Sphagnum*/wood ash media (no mixing) housed in a shallow 'box' with the *Sphagnum* sitting on top of wood ash (1:1 by volume, 1:20 by weight) in a 'removable basket'.

3.2 Results and discussion

3.2.1 Input road runoff

Average concentrations of both total and dissolved contaminants in road runoff were higher at the Hamilton site than the Cambridge site, except for dissolved Zn (Table 3.1). The Hamilton site is at a roundabout, while the Cambridge site is an intersection. Roundabouts have been shown to contribute higher concentrations of contaminants than intersections (O'Riley 2002). The lower concentrations of pyrene at the Cambridge site are possibly due to the makeup of the traffic. Larger numbers of diesel vehicles, particularly trucks (7% of vehicle count), have been observed at the Cambridge site, while a larger portion of the vehicle count at the Hamilton site consists of cars. Diesel trucks tend to emit lower molecular weight PAHs than petrol engines (Rogge et al. 1993).

These low molecular weight PAHs are more likely to be lost by volatilisation into the atmosphere (Hewitt & Rashed 1990) rather than be deposited on the road. Similar concentrations of PAHs to those at Cambridge are also found at our Tauranga site, which also has high numbers of trucks using it (Taylor et al. 2004, Table 3.1).

Table 3.1 Comparison of contaminant concentrations ($\mu g\ L^{-1}$) in road runoff from the Hamilton and Cambridge sites.

Site	Total Cu	Total Pb	Total Zn	Dissolved Cu	Dissolved Pb	Dissolved Zn	Dissolved Fluoranthene	Dissolved Pyrene
Hamilton	27	25	286	16	10	121	0.18	0.12
Cambridge	12	13	194	6	3	230	0.14	0.04

Concentrations of total suspended solids (TSS) are high at the New Zealand sites compared with overseas sites (Table 3.2), especially when the lower vehicle numbers using the roads in New Zealand are considered. The high TSS could be caused by rougher road surfaces in New Zealand. TSS is an important indicator of potential pollution, as concentrations of total and dissolved heavy metals (Cu, Pb and Zn) increase with increasing TSS.

3.2.2 Results from the Hamilton site after 39 months

Performance of the Hamilton treatment wall in removing dissolved contaminants over 12, 22, 32 and 39 months is summarised in Figure 3.3. The results obtained over the first 13 months confirmed laboratory results discussed in the previous section.

After 13 months of operation, the percent retention for Zn dropped (Figure 3.3) and Zn concentration in the effluent increased markedly (Figure 3.4), indicating that the filter medium had reached its capacity for Zn removal and was unable to remove more. It was likely that sediments trapped on top of the medium were acting as a source of Zn. Under normal operating conditions, this sediment layer would have been removed in the same way the sediment layer from stormwater sand filters is removed. However, as we wished to observe the timing of the breakthrough of other contaminants, we left the sediment layer intact. Analysis of the sediment revealed very high concentrations of zinc (Table 3.3). The used, underlying medium also showed greatly enhanced concentrations of Cu, Pb, and Zn compared with new medium, indicating that it has removed contaminants from the runoff (Table 3.3).

Table 3.2 Average concentrations of total copper, lead, and zinc, dissolved copper, lead, zinc, fluoranthene and pyrene, total suspended solids and pH in road runoff from different sites (in µg L^{-1} unless otherwise stated).

Site	Reference	Vehicles/ day^{-1}	Total Cu	Total Pb	Total Zn	Dissolved Cu	Dissolved Pb	Dissolved Zn	Dissolved fluoranthene	Dissolved pyrene	TSS mgL [1]	pH unit
Hamilton		10300	27±	25±	284±	16±18	10±13	119±110	0.18±0.20	0.12±0.12	123±39	7.2±0.3
Cambridge		7500	12±	13±	195±	7±5.4	3±4.5	141±123	0.14±0.08	0.04±0.04	101±117	7.1±0.2
Tauranga	Taylor et al. 2004	24000	96	106	718	2	1	80	0.17	0.03	337	6.4
Henderson Summer	Pandey & Taylor 2004	carpark	–	–	–	6	3	112	0.16	0.15	80	7.0
Henderson Autumn/winter	Pandey & Taylor 2004	carpark	–	–	–	3	1.1	51	0.04	0.03	50	7.3
Adelaide Residential	Kumar et al. 2002	<1000	25	56	241	14	7	67	–	–	76	–
Adelaide Arterial	Kumar et al. 2002	>17000	116	182	867	32	5	144	–	–	344	–
Osaka	Shinya et al. 2000	75000	66	34	648	12	6	93	0.03	0.02	63	–
Paris Residential	Gromaire-Mertz et al. 1999	–	61	133	550	17	4	138	–	–	93	–
Nantes Motorway	Legret & Pagotto 1999	24000	45	58	356	25	4	222	–	–	71	7.3
Bayreuth	Wust et al. 1994	25000	149	224	373	53	5	74	0.51	–	224	7.9
Amsterdam	Berbee et al. 1999	513000	–	–	–	31	2	108	–	–	–	–
MoPac Expressway	Barrett et al. 1998	8800	7	15	44	–	–	–	–	–	91	–
MoPac Expressway	Barrett et al. 1998	60000	37	53	222	–	–	–	–	–	127	–
Cincinnati	Sansalone & Buchberger 1997	150000	135	64	4274	93	16	4054	–	–	–	6.4

– Not determined

Table 3.3 Cu, Pb, Zn, Fluoranthene and Pyrene in media and sediment from the Hamilton and Cambridge sites in March 2002 and June 2004 (in *µg g*$^{-1}$).

Sample	Total Cu	Total Pb	Total Zn	$Ca(NO_3)_2$ Soluble Cu	$Ca(NO_3)_2$ Soluble Pb	$Ca(NO_3)_2$ Soluble Zn	Total Fluoranthene	Total Pyrene	pH
Hamilton site									
Fresh medium	5	<DL	56	–	–	–	<DL	<DL	8.9
Sediment March 2002	41	28	658	–	–	–	–	–	
Used medium March 2002 0–5 cm	59	52	816	–	–	–	–	–	
Course debris 15–0 cm	14	66	722	1.10	0.22	23.6	0.05	0.11	6.9
0–5 cm	51	94	1026	2.60	0.15	169.0	0.05	0.16	6.9
5–10 cm	46	80	929	2.01	0.10	176.9	0.07	0.18	6.7
10–20 cm	31	40	519	0.72	0.15	90.0	0.03	0.04	6.4
20–40 cm	31	38	469	0.17	0.06	50.1	0.03	<DL	5.9
40–70 cm	18	20	221	0.12	0.05	52.0	<DL	<DL	5.7
Cambridge site									
Fresh medium	12	<DL	81	–	–	–	<DL	<DL	9.4
0–5 cm	13	48	217	0.72	0.29	104.8	0.56	0.57	6.1
5–10 cm	18	44	264	0.61	0.24	78.3	0.25	0.26	6.2
10–20 cm	28	45	331	0.82	0.09	89.6	0.08	0.10	6.2
20–40 cm	26	32	285	0.90	0.05	82.9	<DL	<DL	5.9
40–55 cm	32	24	216	0.71	0.07	78.9	<DL	<DL	6.0

– Not determined
<DL Below detection limit

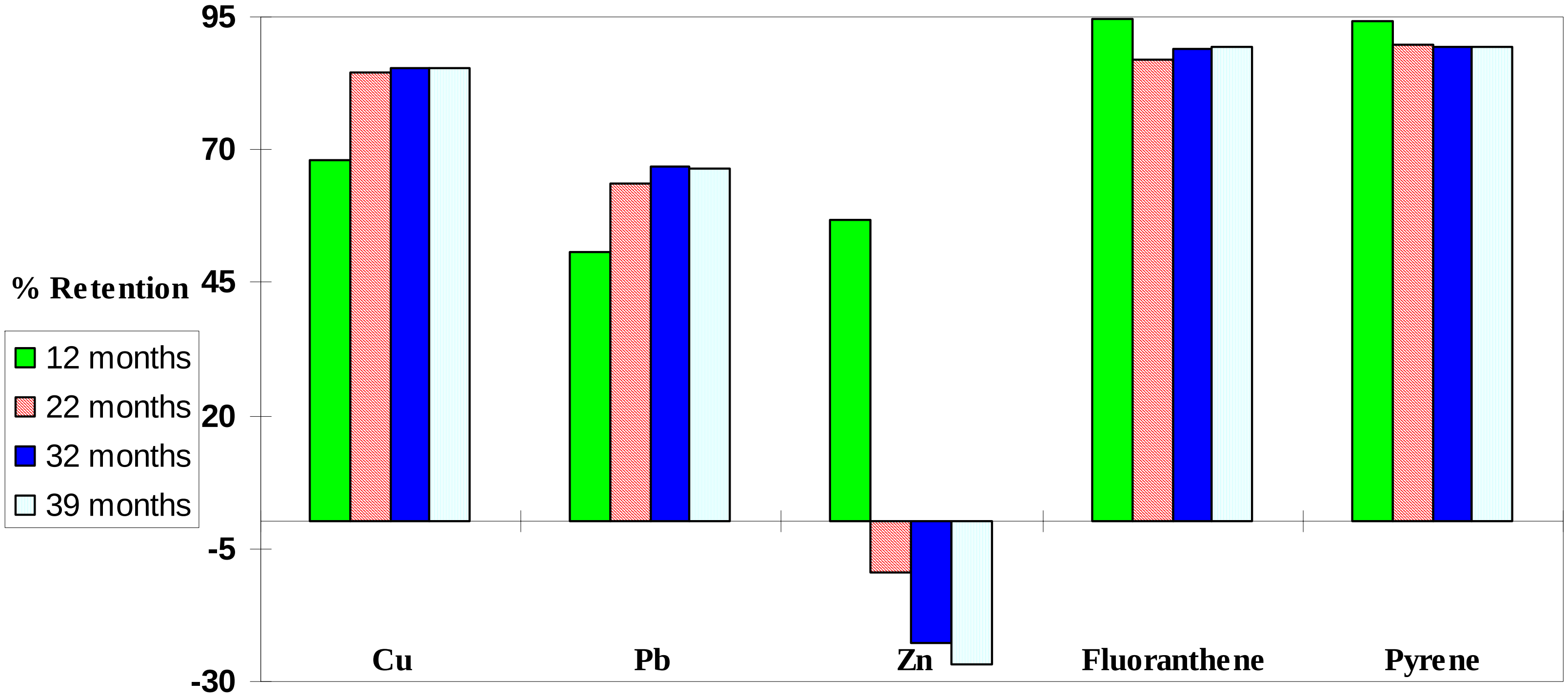

Figure 3.3 Removal of dissolved contaminants from road runoff by mixed media at the River Road site, Hamilton, after 12, 22, 32 and 39 months.

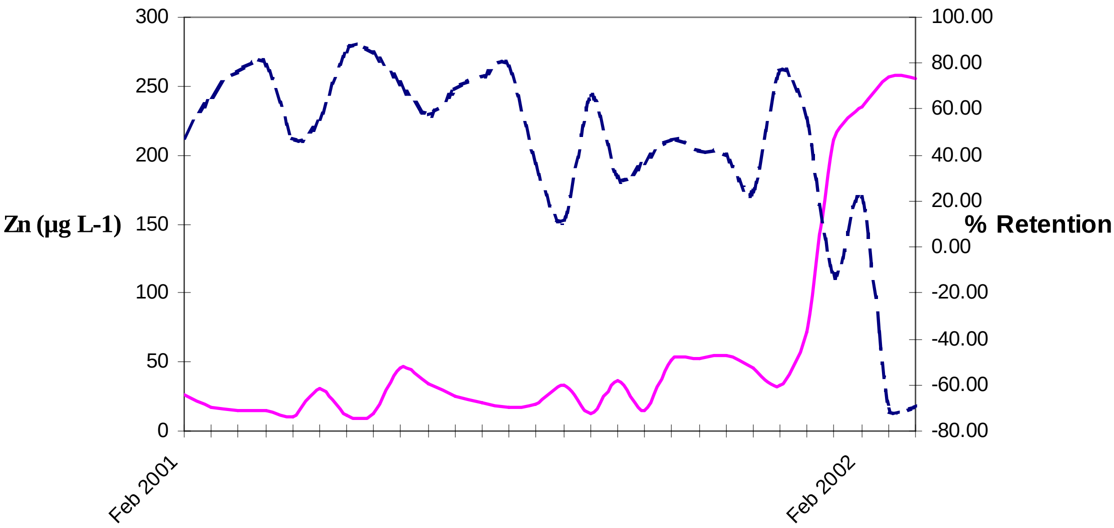

Figure 3.4 Changes in Zn effluent concentration (——) and % retention (— —) over the first 13 months at Hamilton.

3.2.3 Results from the Cambridge site after 22 months

The increased proportion of *Sphagnum* in the Cambridge wall has been used to test whether this has any influence on Zn retention. Results obtained at the Cambridge site over the first 22 months were similar to those found for the first 13 months (Figure 3.5) at the Hamilton site. These results were also similar to those found in the laboratory tests (Figure 2.2).

However, this treatment wall remained effective throughout the study period, although performance appeared to be decreasing, as the figures for Cu and Zn retention after 11 and 22 months were lower than those after 6 months. This site had received high concentrations of pollution from truck spills. One notable spill in October 2002 resulted in about 200 litres of cream passing through the treatment wall (Figure 3.6). The treatment wall was observed to retain the cream and there appeared to be no impact on the operation of the treatment wall. Such truck spills make it difficult to assess the effect of changing the ratio of *Sphagnum* and wood ash.

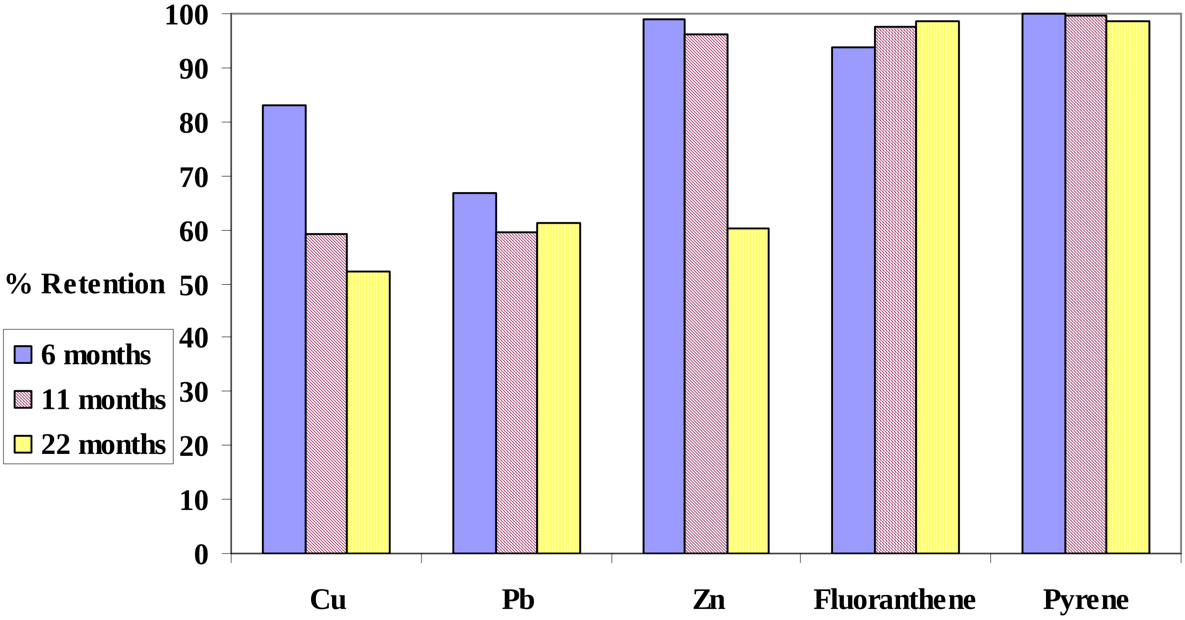

Figure 3.5 Removal of dissolved contaminants from road runoff by mixed media at the State Highway 1 site, Cambridge after 6, 11 and 22 months.

A B C

Figure 3.6 Samples of cream-polluted input (A), normal input immediately before the cream spill (B) and treated output (C).

3.2.4 Analysis of filter media

The media were sampled at Hamilton after 39 months of operation and at Cambridge after 22 months of operation and analysed for total Cu, Pb, Zn, fluoranthene and pyrene, and $Ca(NO_3)_2$-soluble Cu, Pb, and Zn. Concentrations of total Cu, Pb and Zn had increased in the media at both sites, indicating retention of these contaminants from the road runoff. The Hamilton site had 15 cm of coarse debris including leaves, litter, sand and gravel on top of the treatment wall. This was sampled at the same time as the media. Except for this coarse debris layer, total and $Ca(NO_3)_2$-soluble metal concentrations at the Hamilton site decreased with depth (Table 3.3). In contrast, the Cambridge site had the highest Cu concentrations lower in the profile, and Zn concentrations increased with depth to 20 cm, then declined with further increasing depth. This increase indicates movement of these metals within the treatment wall. It is possible that breakthrough of Cu and Zn will occur shortly at the Cambridge site, in the same way that Zn did at the Hamilton site after 13 months. Zn is able to move down the treatment wall when all the sites available for Zn retention in the media have been filled and/or other cations are competing for the limited numbers of retention sites.

Mobility, bioavailability and toxicity of heavy metals are determined largely by their chemical form, which also determines potential for environmental pollution (Jong & Parry 2004). Metals soluble in weak salt solutions, such as $Ca(NO_3)_2$, are considered readily soluble (McLaren & Crawford 1973, McLaren et al. 2003) and therefore are less likely to be retained by filter media. Less than 6 % of total Cu and less than 1% of the lead would be considered readily soluble at both sites (Tables 3.3 and 3.4). However, a much greater proportion of Zn would be considered readily soluble and the highest percentage was found below 40 cm for the Hamilton site, indicating movement of Zn. The proportion of Zn considered readily soluble at the Cambridge site was higher than at the Hamilton site and was highest above 5 cm. These results further support the likely breakthrough of Zn at Cambridge in the near future.

Table 3.4 Percent of total metal (Cu, Pb, Zn) in used filter media considered readily soluble, at Hamilton and Cambridge sites.

Hamilton	Cu %	Pb %	Zn %
0–5 cm	5.1	0.2	16.5
5–10 cm	4.4	0.1	19.0
10–20 cm	2.4	0.4	17.3
20–40 cm	0.6	0.1	10.7
40–70 cm	0.6	0.2	23.6

Cambridge	Cu %	Pb %	Zn %
0–5 cm	5.5	0.6	48.4
5–10 cm	3.5	0.5	29.7
10–20 cm	3.0	0.2	27.1
20–40 cm	3.5	0.2	29.0
40–70 cm	2.2	0.3	36.5

Concentrations of total fluoranthene and pyrene in the media are lower at the Hamilton site than the Cambridge site, even though the Hamilton site receives more dissolved fluoranthene and pyrene (Table 3.3). It is likely that micro-organisms are breaking down the fluoranthene and pyrene at both sites, as concentrations in the treated runoff in the output remained low (Table 3.5), and PAH degraders were observed in media during another similar study at Waitakere City (Gillian Lewis, Auckland University, Auckland, pers. comm.). These results show the treatment wall is reducing fluoranthene and pyrene concentrations in road runoff, and the presence of PAH degraders indicates that this process is likely to continue and limit accumulation in the wall itself.

Table 3.5 Comparison of input road runoff and treated output from the Hamilton and Cambridge sites, and with ANZECC guidelines. Results in *µg L^{-1}*.

Site	Total Cu	Total Pb	Total Zn	Dissolved Cu	Dissolved Pb	Dissolved Zn	Dissolved Fluor-anthene	Dissolved Pyrene
Runoff Hamilton	27	25	286	16	10	121	0.18	0.12
Output Hamilton (first 12 months)	2	4	37	2	3	33	0.03	0.02
Output Hamilton (after 39 months)	2	5	154	2	3	141	0.02	0.01
Runoff Cambridge	12	13	194	6	3	230	0.14	0.04
Output Cambridge	3	4	55	3	1	45	>0.01	>0.01
ANZECC Guidelines	–	–	–	1.4	3.4	8.0	–	–

The pH of the media at both sites has decreased by two to three units compared with fresh media, and also decreased with depth (Table 3.3). Decreasing pH reduces the capacity of the media to retain metals. The decrease in pH could be caused by decay of organic debris, such as leaves and grass clippings, forming organic acids, as a larger quantity of leaves/organic debris was observed entering the treatment wall system at Hamilton, compared with the Cambridge site. The road runoff is not directly decreasing the pH, as it is approximately neutral (Table 3.2).

3.2.5 Overall performance

Comparison of both total and dissolved contaminants in road runoff and treatment wall output show that both treatment walls greatly reduce the quantity of these contaminants (Table 3.5). The Cu retention at the Hamilton site remained higher than retention at the Cambridge site, possibly due to high amounts of humic material from decayed leaves and other organic matter observed entering that site. Cu has a high affinity for sorption by organic colloids (Baker & Senft 1995).

Dissolved metal concentrations were compared with the ANZECC water quality guidelines trigger values for freshwater ecosystems (ANZECC and ARMCANZ, 2000) (Table 3.5). These trigger values have been derived from acute and chronic data for single toxins, and are used to determine theoretically safe concentrations of contaminants in the receiving environment. Input concentrations of dissolved Cu and Zn at both sites and dissolved Pb at Hamilton clearly exceed these 95% confidence trigger values. At both sites, output concentrations of dissolved Cu were slightly above, Pb below and Zn considerably over trigger values (Table 3.3). However, dilution in the receiving environment will quickly bring these metals to within safe concentrations. Also, our main focus was only on treating the runoff at the 'top-end' rather than measuring the effects on the receiving environment. The treatment walls are still achieving >75% of pollutant removal. We also recognise the need for continued exploration of a combined treatment train approach, where different low-impact treatment technologies (e.g. raingardens, grass swales, treatment ponds, permeable pavers, etc.) will remove specific pollutants, depending upon site-specific characteristics, traffic and weather conditions.

Figures 3.7 & 3.8 Runoff volume at the Cambridge site is measured in the weir before flowing into the treatment wall in the concrete riser below the weir.

4. Conclusions

1. In laboratory studies, lime and wood ash were very effective (>90%) at removing dissolved heavy metals and PAHs from artificial road runoff. *Sphagnum* moss was also effective at removing dissolved heavy metals, but largely ineffective at removing dissolved PAHs due to its high hydraulic conductivity, which led to short contact time between the PAHs and *Sphagnum*. Both the wood waste and wool felt removed over 60% of applied heavy metals, but were not as effective as the other media. The wood waste was poor at removing PAHs. An initial release of carbon and associated metals occurred in the lime/*Sphagnum* mixture but the wood ash/*Sphagnum* mixture was very effective (>90%) at removing heavy metals and PAHs.

2. Comparison of both total and dissolved contaminants in road runoff and output show that both treatment walls greatly reduced the quantities of contaminants being discharged into the aquatic environment. Both pilot study treatment walls were very effective at removing particulates in runoff and in lowering concentrations of particulate-bound contaminants. In addition, they were also very effective at removing dissolved contaminants for the first year of operation. Except for the litter layer, metal concentrations in the media at the Hamilton site decreased with depth. In contrast, the Cambridge site had the highest Cu concentrations lower in the profile, and Zn concentrations increased with depth to 20 cm then declined with further increasing depth, indicating movement of these metals within the treatment wall and probable breakthrough of these contaminants in dissolved form in the near future.

3. A mixture of *Sphagnum* and wood ash, used in Hamilton, showed similar results to those of the laboratory studies over the first 13 months of operation for the removal of dissolved contaminants, but subsequently allowed breakthrough of dissolved Zn. The source of this Zn appears to be a layer of high-Zn sediment deposited on top of the medium. We left this sediment layer in place to observe if breakthrough of other contaminants would occur (unlike normal operational practice where the sediment layer containing this extra source of Zn would be removed). No further breakthrough of the other monitored contaminants has been observed. While output concentrations of dissolved Cu and Zn still exceed ANZECC guideline trigger values, dilution in the receiving environment will quickly bring these metals to within safe concentrations. As pointed out in the previous point, both treatment walls greatly reduce the quantity of these contaminants being discharged into the aquatic environment.

5. Recommendations

1. Treatment walls containing suitable organic media to remove dissolved contaminants should be used where the contamination load in road runoff is expected to be high (hot spots). The media used could be wood ash, wood ash-Sphagnum combination, or green compost, but economic considerations, such as cost of transportation, and ease of availability should also be taken in to account during the selection. Hot spots might include car parks, roundabouts, accelerating and de-accelerating zones of roading networks and petrol station forecourts.

2. The sediment build-up in such walls should probably be removed at 6-monthly intervals, but at least annually. An assessment of the effects of such maintenance on treatment wall life expectancy should be carried out.

3. To promote uptake, trials should continue to monitor the performance of treatment walls under a variety of site characteristics, traffic density and climatic conditions different from those at the sites in this study to optimise road runoff treatment in other parts of New Zealand. This is likely to influence engineering design for stormwater interceptor devices suggested by Auckland Regional Council (ARC 2003).

4. Other suitable media and a combined treatment train approach should continue to be explored.

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