Sustainability **2015**, *7*, 3721-3733; doi:10.3390/su7043721

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Long-Term Metal Retention Performance of Media Filter Drains for Stormwater Management

Agatha Thomas [1], Liv Haselbach [1,*], Cara Poor [2] and Maxwell Freimund [1]

[1] Department of Civil and Environmental Engineering, Washington State University, P.O. Box 642910, Pullman, WA 99164-2910, USA; E-Mails: agathe.thomas@email.wsu.edu (A.T.); maxwell.freimund@email.wsu.edu (M.F.)

[2] Civil and Environmental Engineering, Portland State University, P.O. Box 751—CEE, Portland, OR 97207-0751, USA; E-Mail: cpoor@pdx.edu

* Author to whom correspondence should be addressed; E-Mail: haselbach@wsu.edu; Tel.: +1-509-335-4874.

Academic Editor: Marc A. Rosen

Received: 22 December 2014 / Accepted: 24 March 2015/ Published: 30 March 2015

Abstract: Stormwater runoff, a substantial source of nonpoint pollution, can be treated using Best Management Practices (BMPs), such as the Media Filter Drain (MFD). An MFD is a trench filled with an engineered media mix, usually with a grass overlay, that receives runoff from the paved roadway next to it. The MFD was shown to remove dissolved metals (zinc and copper), typical pollutants from vehicles and urban areas, which might negatively impact aquatic species in receiving waters, but its long-term effectiveness was not known. Existing media filter mixes of different ages were collected from two different sites in the Pacific Northwest of the United States. Columns made with these media mixes received concentrated copper and zinc loading to simulate accelerated aging for estimated total lifespans from 14 to 22 years of copper and zinc loading, with little or no decrease in sorption. Throughout the aging process, some columns were subjected to performance testing with higher levels of typical runoff concentrations and average concentration decreases from influent to effluent were found to be greater than 90% for both copper and zinc. Based on this study, the MFD's lifespan for zinc and copper treatment is significantly greater than the initial ten-year estimate.

Keywords: stormwater; urban roadway pollution; media filter drain; runoff; copper; zinc

---

1. Introduction

Stormwater runoff from highways may contain many pollutants and is a large contributor to nonpoint source pollution [1]. Best Management Practices (BMPs) are a suite of structural and nonstructural installations or practices that can be used for stormwater quantity control and/or stormwater quality control. Many of these practices provide both water quantity and water quality control such as bioretention systems. These systems can remove many pollutants, such as total suspended solids (TSS), hydrocarbons, and metals [2]. However, these systems do not always fit well in a highway setting and there are alternative BMPs for water quality control along highways, which have not been as well studied as bioretention systems. One of these is the Media Filter Drain (MFD), formerly known as the Ecology Embankment [3].

The MFD is a narrow footprint Best Management Practice (BMP) designed by the Washington State Department of Transportation (WSDOT) to treat roadway runoff. It is a linear flow-through water quality treatment method that can be used when available right-of-way is limited. The MFD is made by digging a trench parallel to the roadway in the shoulder or median and filling with an engineered media filter mix. It is typically 0.30 m deep and at least 0.90 m wide. The MFD may be covered with grass. The media filter mix is made of crushed aggregate and three active ingredients: perlite, dolomite and gypsum. Details of the MFD and proportions of these ingredients in the media mix can be found in the WSDOT Highway Runoff Manual. The original design is in the 2011 version of this manual, with changes and more details in the 2014 version [4,5]. Table 1 is a listing of the mix design from the 2011 manual.

Table 1. Approximate Composition of Media Filter Drain (MFD) Mix [4].

Material	Type	Sieve Percent Passing by Mass	Amount
Aggregate	Manufactured from ledge rock, talus, or gravel.	1/2" square 100 3/8" square 90–100 US No. 4 30–56 US No. 10 0–10 US No. 200 0–1.5	3 cubic yards
Perlite	Horticultural Grade. Free of any toxic materials.	US No. 18 0–30 US No. 30 0–10	1 cubic yard
Dolomite	Agricultural Grade. Free of any toxic materials.	US No. 8 100 US No. 16 0	10 pounds
Gypsum	Agricultural Grade. Free of any toxic materials. (hydrated calcium sulfate)	US No. 8 100 US No. 16 0	1.5 pounds

The MFD is efficient at removing suspended solids, oil, and phosphorus, and has enhanced capabilities to remove dissolved metals such as zinc and copper [3]. In some locations it is important to treat for dissolved zinc and copper prior to discharge into receiving waters, as zinc and copper can be harmful for fish and amphibians at low concentrations [6–9]. One study on juvenile coho salmon showed that copper impacts their olfactory system's responsiveness and therefore their ability to avoid predators [10]. Metal removal from stormwater runoff is especially of interest when discharging to urban streams that support salmonid species.

The minimum effective life of the MFD has been initially set at 10 years by WSDOT. Many MFDs have been in use for several years in Washington and in other states and there is a need to determine if the MFD can be used for a longer period of time. It has been hypothesized that the MFD can have a significantly longer life with respect to metal removal. The main mechanisms involved in metal removal are sorption, ion exchange and complexation. Perlite adsorbs metal ions (Cu^{2+}, Zn^{2+}) with its silicon and alumina atoms. At room temperature, the silicon and alumina atoms at the surface tend to keep their coordination with oxygen by attachment to monovalent hydroxyl groups (OH^{-}), creating adsorbent negative ions that bond with the metal ions [11]. Dolomite and gypsum adsorb metals from runoff by exchanging calcium and magnesium cations with metals including zinc and copper [3]. Zinc and copper concentrations in roadway runoff are on the order of magnitude of parts per billion; copper concentrations typically range from 5 to 200 ppb, and zinc concentrations from 20 to 5000 ppb and typical concentrations are 20 ppb and 100 ppb for copper and zinc, respectively [12]. In terms of mass for typical runoff volumes, there are many sorbent sites available as well as particulates in the MFD to complex with, possibly making the effective life of the MFD for dissolved metal removal much longer than initially established.

The objectives of this study were to make laboratory columns filled with existing media mix from the field and further "age" the media by adding dissolved zinc and copper in concentrations which are much higher than the concentrations found in roadway runoff, and then analyze if the media is still effective in removing dissolved zinc and copper at roadway concentrations, *i.e.*, performance tests. The performance tests were planned periodically during the aging process. This experimental protocol is summarized in the following:

(1). Load the columns with extremely concentrated metal solutions much higher than found in roadway runoff to simulate additional years of use in just months in the laboratory (accelerated aging).

(2). Periodically load the columns with high metal concentration stormwater solutions typical to dense urban or "hotspot" areas to test for long-term effectiveness or possible leaching (high performance test). These performance tests are labeled as "high" performance tests, since the concentrations and flows used would be representative of some of the worst conditions that an MFD might be exposed to, *i.e.*, roadway concentrations in the higher range, and volumes typical of larger storms.

2. Experimental Section

Existing media were collected from the field and used to prepare laboratory columns. These columns were used to perform the accelerated loading and the high performance tests. The media was collected prior to 2014 and it is therefore assumed that the field media were designed as per the WSDOT design in the 2011 version of the Highway Runoff Manual [4]. The methods for column preparation, solution preparation, loading and testing are described in the following sections.

Samples from existing MFDs were collected from two sites (Site A and Site B) both located in Western Washington, east of Puget Sound, which has a maritime climate characterized by wet winters. A typical 2-year 24 h storm in this region results in approximately 90 mm of precipitation [13]. Site A was located on the side of State Route (SR) 167 in Auburn, where the 2012 average daily traffic volume was 100,000 vehicles [14]. When sampling was performed, the MFD at Site A had been in use for 12 years and a vegetation layer had grown on top of it. Site B was located on 244th Street SE, in Maple

Valley slightly up road from the SR 18 overpass. 244th Street SE has a relatively low traffic volume (around 1000 ADT), and SR 18 average daily traffic volume was 60,000 vehicles in 2012 [14]. Site B was located at a shoulder with a hill next to it and appeared to receive runoff from both the highway and the hill. There was no vegetation layer on top of the media at Site B. Media at Site B had been in use for 5 years prior to sampling. During field sample collection, media mix was collected separately from the top 100 mm of each MFD, the middle 100 mm of the MFD and the bottom 100 mm of the MFD. At each site, media from these layers were placed into separate buckets and transported to the laboratory.

Six columns were prepared for each site. The columns were filled to 300 mm of depth, and were made of three 100 mm layers of media mix using the respective layer mix from the field for that site. Three of the columns for each site were 150 mm in diameter and three were 200 mm in diameter. (Two different diameters were used in order to see if the smaller diameter column would be as effective as a larger diameter column. The larger diameter column would represent a larger sample, and therefore possibly less error, but was cumbersome and required copious amounts of simulated stormwater for loading. There did not seem to be any difference in the results from either size, so the smaller diameter was then selected for use in other related studies in the laboratory.)

To obtain the different stormwater solutions to load the columns with, a metal stock solution containing zinc and copper ions and a synthetic rainwater stock solution were mixed together. The synthetic rainwater solution was made based on the chemical composition of rainwater samples taken at the Hanford site in Washington [15]. The metal stock solution was made using cupric chloride dihydrate and zinc chloride, and contained 8 ppm of copper and 40 ppm of zinc.

Accelerated aging was performed by pouring extremely concentrated solutions of dissolved zinc and copper prepared with the simulated rainwater and the metal stock solution on top of the columns in a downflow mode. An event was defined as pouring a set amount of extremely concentrated metal solution at a controlled rate on top of each column. At least 48 h lapsed between the start of each event to simulate drying time between precipitation events. Throughout the accelerated aging events, the columns were loaded with different influent levels of very concentrated zinc and copper stormwater to gather more sorption rate information. The approximate influent concentration levels used are provided in Table 2 and noted as Phases 1 through 3. Actual influent concentrations varied due to experimental variability and were measured and are reported with the results. (The ranges of influent concentrations used for the accelerated aging events were chosen in order to simulate approximately 10 years of use in the timeframe of the project in the laboratory.)

Table 2. Approximate influent dissolved metals concentrations.

Sequence	Accelerated Aging Events	Zinc Concentration [ppb]	Copper Concentration [ppb]
Phase 1	Events 1–4	4000	800
Phase 2	Events 5–39	1880	240
Phase 3	Events 40–100	4000	800

The accelerated aging events were applied at a low surface infiltration rate of 250 mm/h to simulate runon from typical rain events in Western Washington and allow time for sorption. Note that the media is essentially an aggregate bed with some additional ingredients, and has a hydraulic conductivity that would be well above any surface infiltration rates. Therefore the surface infiltration rates were controlled at the simulated runon rate by flowing through a separatory funnel and dripping onto the top surface of the columns. The solution was allowed to freely flow through the columns and drip into beakers below the columns with an air gap at all times. Thus the media was never fully saturated as would be found in the field conditions. The field design typically has an underdrain to allow for free flow.

The volumes of stormwater applied to the different columns for the accelerated aging events are given in Table 3 and were calculated based on rainfall amounts and on typical copper and zinc concentrations in the stormwater runoff. These volumes represent the same areal loading rate. A year of rainfall was set to be equivalent to approximately 6 accelerated events for Phases 1 and 3, proportioned appropriately for Phase 2. According to the Stormwater Management Manual for Western Washington [13] the average annual precipitation in Western Washington is 1020 mm in many communities in the Puget Sound region. The runon plus direct precipitation was assumed to be 10 times the surface area of an MFD (*i.e.*, a MFD accepts runoff from several highway lanes). Hence, an MFD receives 10,200 mm/year of precipitation. The typical concentrations of copper and zinc in stormwater runoff were 20 ppb and 100 ppb, respectively, with higher typical concentrations in more polluted areas approximately five times greater. The accelerated aging events consisted of loading the columns with extremely high copper and zinc concentrations, which were selected to be approximately 40 times the typical concentrations (800 ppb and 4000 ppb, respectively).

Table 3. Influent volumes used for the accelerated aging event sequence.

Diameter of the Column (mm)	Volume [L]
150	0.77
200	1.38

The high concentration performance testing consisted of test sequences of loading the columns with high concentrations found in runoff to test for longer-term performance or possible leaching after a number of accelerated aging events. The experimental procedure allows for two columns from each of the sites to be removed from the accelerated aging events procedure for the high concentration performance testing at three different times which were after 20, 40, and 60 accelerated aging events have occurred. Initially, it was not intended for the columns to return to accelerated aging after removal to the high concentration performance test. However, the results from the accelerated aging events had such high removal rates through the first twenty events, indicating the capacity limit had not been reached, that the columns used in the second and third high concentration performance tests were returned for additional accelerated aging. The high concentration performance tests were applied at a surface infiltration rate of 760 mm/h through a separatory funnel. (Note that this loading rate is higher than the accelerated loading rate, as the performance tests were intended to examine functionality under extreme conditions of high flow through, while the accelerated aging events were intended to allow for metal sorption to the media for which the slower rate would increase.) The effluent was allowed to freely flow through the columns and was collected in beakers beneath the column with air gaps in between. Table 4 gives details of the columns used for the three high concentration performance test sequences, and outlines the testing procedure. Again, the dissolved zinc and copper concentrations used in the high performance tests are in the higher ranges found in roadway runoff, but much lower than those applied for aging in the accelerated aging events. Actual influent concentrations varied, and are provided in the results.

Table 4. High concentration performance testing procedure summary.

Test Sequence	Number columns per site and diameters (mm)	Post "High Tests" Columns Continued Aging?	Pre-"High Tests" Aging Event Numbers	Number of High Concentration Performance Tests	Volume of 'High Tests'	Approx. Influent Zn Conc. (ppb)	Approx. Influent Cu Conc. (ppb)
1	1–150	No	1–20	2	0.77 L	250	30
	1–200	No	1–20	2	1.38 L	250	30
2	1–150	Yes	1–40	2	0.77 L	500	100
	1–200	Yes	1–40	2	1.38 L	500	100
3	1–150	Yes	1–60	2	3.24 L	500	100
	1–200	Yes	1–60	2	5.77 L	500	100

Volumes of both the influent and the effluent solutions were recorded for each experiment, except for the effluent volumes for the first 17 accelerated aging events. These volumes were estimated as the average from the later events. pH values were also taken periodically. A 15 mL influent solution sample and a 15 mL effluent solution sample were collected in HDPE sample bottles from each column for each accelerated aging event and each high performance test. These samples were extracted from the fully mixed applicable influent or effluent volumes. In order to preserve the samples, 23 μL of 70% concentrated nitric acid was added to each sample to bring the pH below 2 [16]. Samples were then kept refrigerated at 6 °C until analysis. The samples were analyzed for dissolved copper and zinc using an Agilent Technologies 7700 Series Inductive Coupled Plasma—Mass Spectrometer (ICP-MS).

To assess the effectiveness of the existing media filter mix at removing dissolved metals from stormwater, two different calculations were performed. The percent decrease in concentration (Equation (1)) was computed, and a mass balance was performed to find the percent of mass retained in the column (Equation (2)).

$$\text{Percent Concentration Decrease} = 100(C_{in} - C_{out})/C_{in} \quad (1)$$

$$\text{Percent Mass Retained} = 100(C_{in}V_{in} - C_{out}V_{out})/(C_{in}V_{in}) \quad (2)$$

where C_{in}, C_{out}, V_{in}, and V_{out} are the dissolved metal concentrations and the volumes of the influent and effluent solutions, respectively. These two ratios are different because of evaporation, water retention and potential metal leaching from the columns.

3. Results

Results for the accelerated aging events and the high concentration performance tests are presented in the figures in the following subsections in the form of concentrations, percent decrease in concentration, and percent mass retained for each event or test. For the accelerated aging events, the different influent concentration phases previously referenced in Table 2 are annotated on the time series. Results for zinc and copper are presented separately and each figure includes both data from Site A and Site B. On the figures, the markers correspond to average values and the error bars correspond to the standard deviation of the average.

3.1. Accelerated Aging Events

For the first 20 events the concentrations were averaged over 6 columns for each event and for the following 80 events, the concentrations were averaged over 4 columns for each event since two of the columns from each site had been removed following the first high performance tests. Figure 1 shows the influent and effluent dissolved zinc concentrations for Sites A and B. Variability occurs during the 5 first events, due to possible channelization from uneven initial compaction of the media, or from fine particles being dislodged during column preparation and flowing into the beaker. Therefore, the results from these earlier events are still included in metal mass loading, but are not necessarily indicative of anticipated performance.

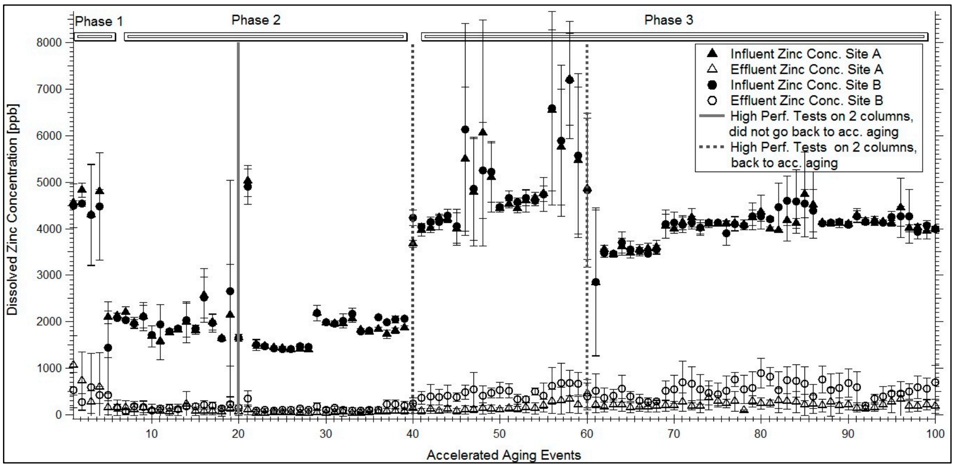

Figure 1. Influent and effluent dissolved zinc concentrations for both Site A and Site B.

Figure 2 shows the percent dissolved zinc concentration decrease and percent metal mass retained in the columns. The percent concentration decrease and the percent retained are relatively constant during the three different phases for Site A, and exhibit more variability for Site B.

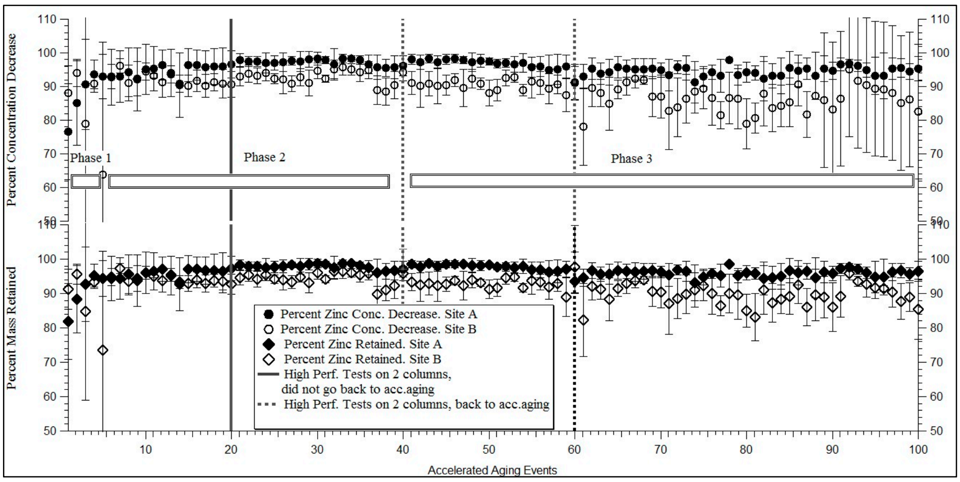

Figure 2. Dissolved zinc removal indicators for both Sites A and B.

The results for copper removal are given in Figures 3 and 4. Variability is again seen in the first few events. The removal efficiencies are very high throughout, with the Site A results again the least variable.

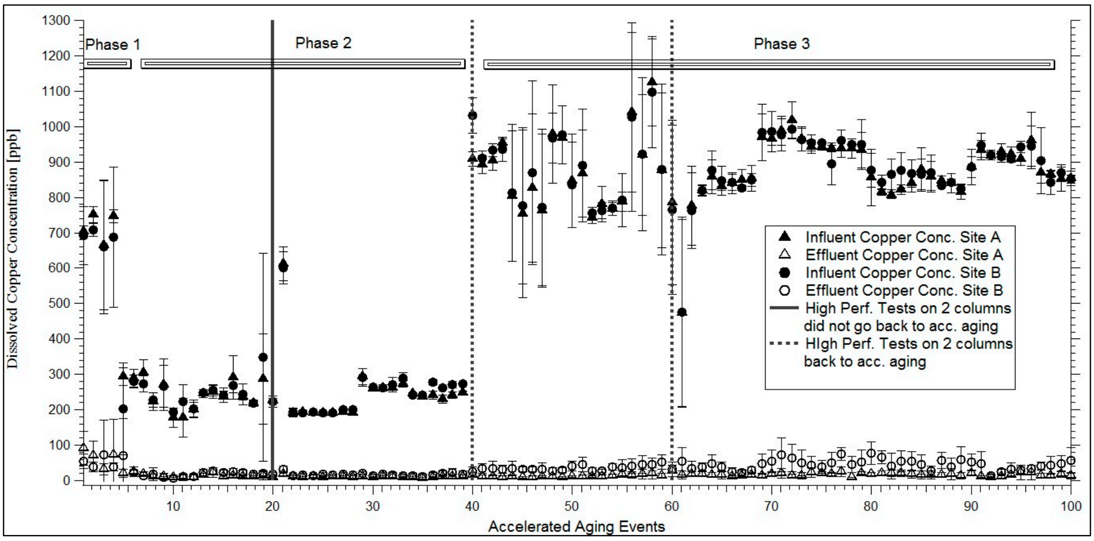

Figure 3. Influent and effluent dissolved copper concentrations for both Sites A and B.

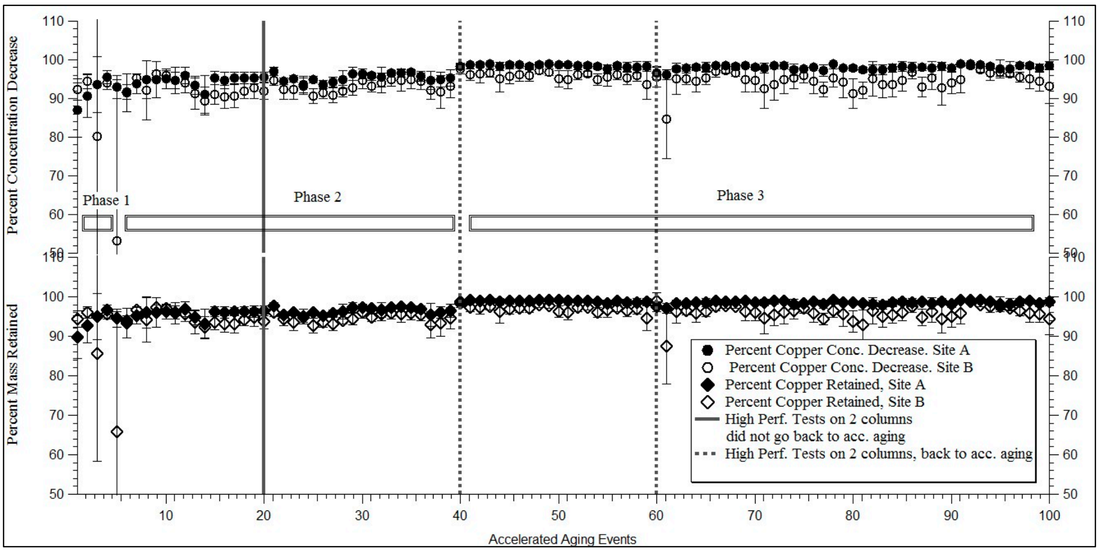

Figure 4. Dissolved copper removal indicators for both Sites A and B.

3.2. Accelerated Aging Equivalent Years of Metal Loading

Based on the rainfall values for the eastern Puget Sound area and 10:1 area ratio for runon as previously described, the equivalent years of metal loading for both zinc and copper are given in Table 5. The years provided include the actual age of the existing media prior to testing. The estimated years of simulation are for metal loading passing through the columns, and not for the volume of water passing through the columns.

Table 5. Chronological cumulative number of metal loading equivalent years.

		Years at Accelerated Aging Event Number for Zinc				Years at Accelerated Aging Event Number for Copper			
Site	Site Age	20	40	60	100	20	40	60	100
A	12	13.9	15.6	18.9	22.2	13.5	14.6	17.9	21.3
B	5	6.9	8.6	11.9	15.2	6.5	7.6	10.9	14.3

3.3. High Concentration Performance Testing

Figures 5–8 show the results from the high concentration performance tests that were performed at three separate times during the accelerated aging events, each time on different columns. On these graphs the first high performance testing sequence corresponds to the set of tests performed after 20 accelerated aging events. The second high performance testing sequence is the set of tests performed after 40 accelerated aging events and the third high performance testing sequence corresponds to the set of tests performed after 60 accelerated aging events. The results of the high concentration performance tests for zinc removal are summarized in Figures 5 and 6. The results of the high performance tests for copper removal are summarized in Figures 7 and 8.

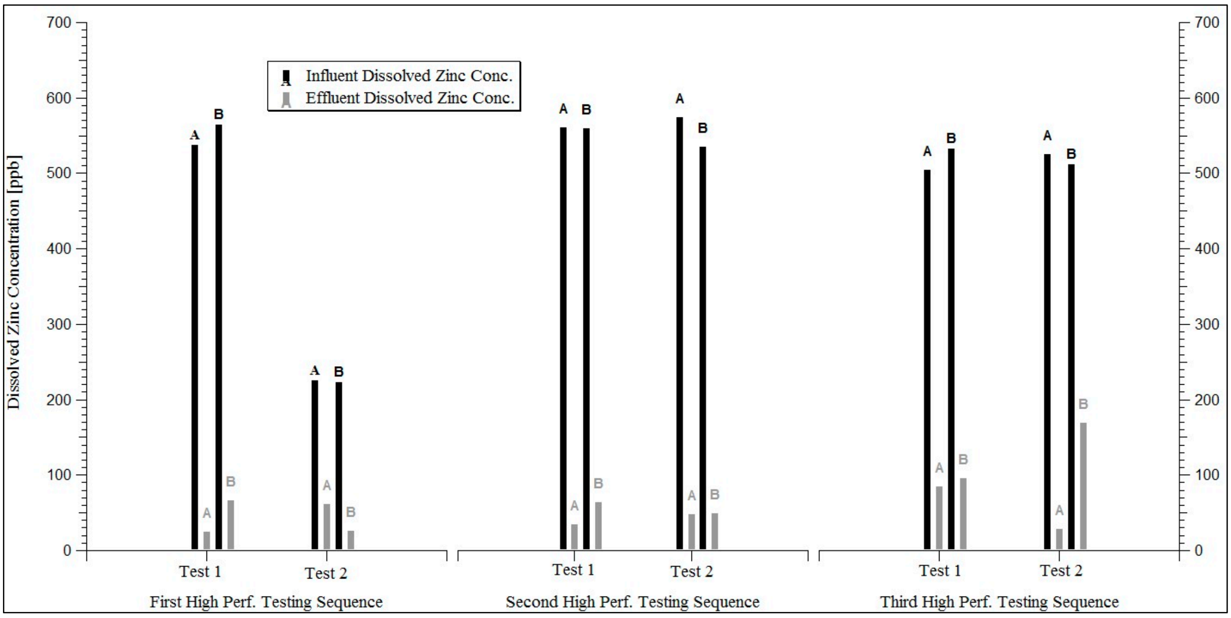

Figure 5. Dissolved zinc influent and effluent concentrations for Both Sites A and B.

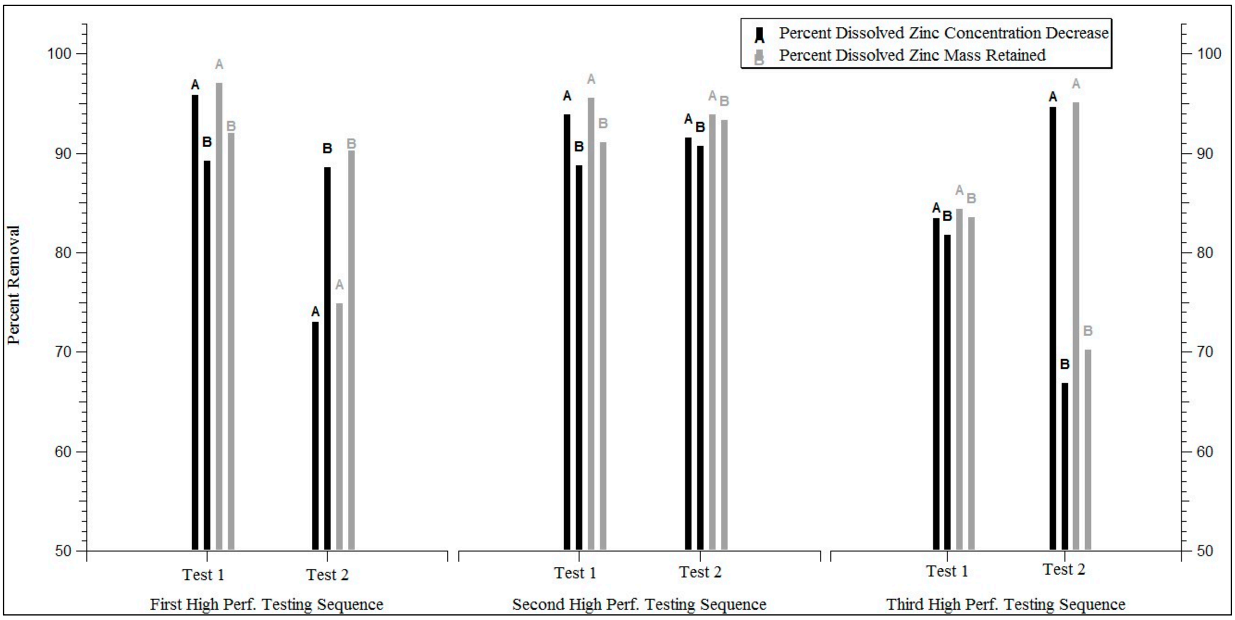

Figure 6. Dissolved zinc removal indicators for both Sites A and B.

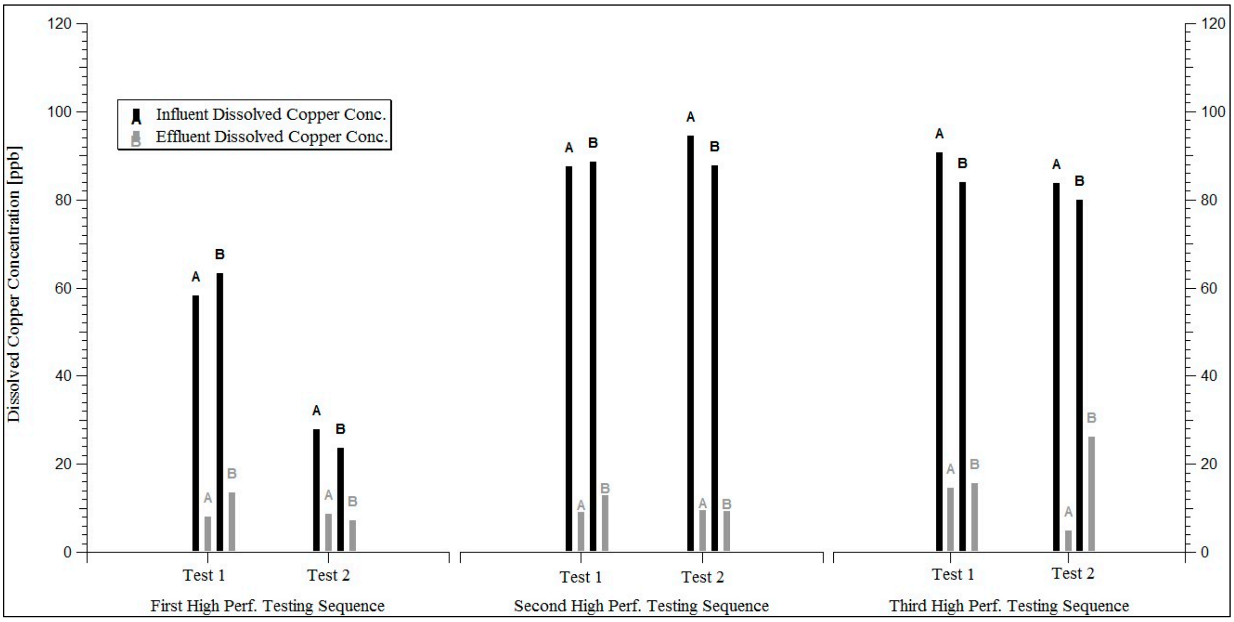

Figure 7. Dissolved copper influent and effluent concentrations for both Sites A and B.

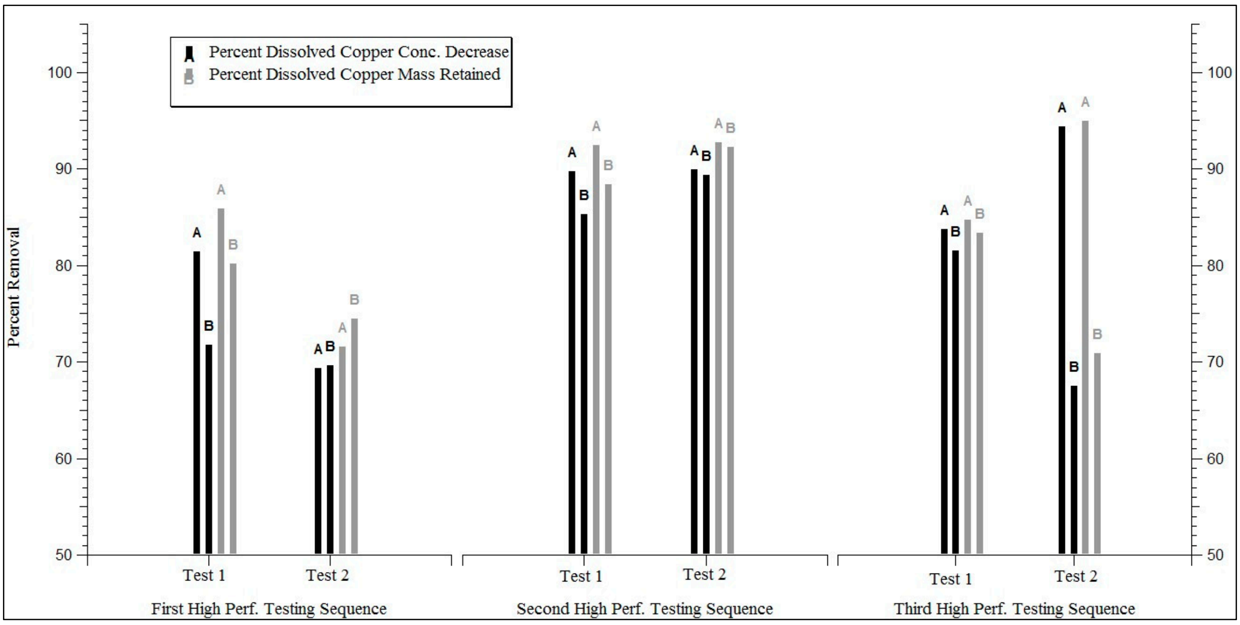

Figure 8. Dissolved Copper Removal Indicators for Both Sites.

3.4. pH Testing

The pH was measured periodically during both the accelerated aging events and the high performance tests. Influent pH measurements were variable ranging from 3.93 to 6.86 for the high performance tests, and 4.65 to 7.93 for the accelerated aging events. However effluent pH levels were always close to neutral ranging from 6.29 to 7.70. Note that the influent samples were from simulated rainwater with only the metal stock added, not other contaminants, such as dissolved organics, *etc.* Thus, the influent solutions may not have been well buffered. Based on the effluent pH levels being very consistent, the media apparently acted well as a buffer, keeping the solutions near neutral.

4. Discussion

According to the results for zinc removal in the accelerated loading events, the media mix from Site A removed slightly more zinc than the one from Site B. The two sites represent vastly different applications, with more traffic at Site A and possibly more runon at Site B. There were also differences in vegetation over the media at both sites, with thick grass at Site A and little or no vegetation at Site B. The improved performance of the Site A columns after removal of the existing media from the site was possibly due to the grass layer on top of the MFD at Site A, which may have helped pre-filter the runon at the field site and keep additional particulates laden with the metals from entering the media in Site A. However, after 100 accelerated aging events, equivalent to 15.2 years of metal loading, there is still a significant amount of zinc removed by the MFD at Site B with an 82% decrease in zinc concentration and 86% retained in the column. Similar results were found for copper removal at both sites, with slightly higher removal rates and less variability at Site A than at Site B. Except for initial event variability, the percent concentration decrease for copper always exceeded 80% with a greater than 86% mass retained. For both metals, the first few events had more variable results, likely due to channelization. Even after years of simulated metal loading, both sites still have substantial capacity for metal sorption as observed by the results of the accelerated loading sequences.

The accelerated aging event results indicate that there may be a decrease in performance after many years as observed for both copper and zinc, but this was seen in Figures 2 and 4 mainly only for Site B. In addition to the aforementioned differences in site characteristics, the media within each column was not laboratory controlled, but instead was taken directly from the sites, and it is unknown if during construction there was significant variability in the active ingredients between various sections of the media. However, there is still substantial sorption to the media. Most likely, the adsorption rates have decreased as the media becomes slightly more saturated with the two metals and there are fewer sorption sites available. Future experiments with laboratory controlled media mixes, different loading rates, column depths and various levels of metal loading may provide more information on removal mechanisms and rates. There may also be varying levels of saturation with column depth, which may impact removal.

The results from the high performance tests indicate that the media has the capacity for significant metal removal at various ages as seen in Figures 5 through 8. The lowest concentration decreases for both metals was 67% with lowest percent mass retained at 70, and these were all for Site B in the second test of the third high performance sequence. Therefore, there may be a slight decrease in performance for both metals for the media from Site B at later ages, but more testing is needed to confirm this.

The mechanisms for the dissolved metal removals were not studied specifically during these experiments. However, other research has indicated that the metals might be removed by adsorption to the perlite [11]. In addition, it is very likely that the copper and zinc complex with the ligands in both the dolomite (carbonate species) and the gypsum (hydroxy and sulfate) [17].

5. Conclusions

The accelerated aging events and the high performance loading tests indicate that the existing media mix has capacity for long-term use, well beyond the initial ten year estimate, resulting in longer life of the media and significant cost savings to communities and agencies that use similarly designed MFDs.

Additional long-term testing is needed to more accurately estimate extended lifespans beyond the tests already conducted. These lifespans will be dependent on needed removal efficiencies, precipitation levels, the catchment areas that provide additional runon and the uses in these catchment areas, depending on the application. In, addition, it is likely that an MFD which has a vegetated layer on top may have a longer lifespan for dissolved metal removal based on the better performance of the media from the site with a vegetated cover even though it had more traffic, and therefore possibly more metal loading, than the site without a vegetated cover and less traffic. An MFD, with its small footprint may be a viable best management practice for stormwater metal removal in both urban and rural areas.

Acknowledgments

The authors are grateful for funding provided for this project by the Washington State Department of Transportation (WSDOT) and PACTRANS (The Pacific Northwest Transportation Consortium) for material provided by Motley—Motley Inc., and for laboratory assistance from Erica Iverson, Andrew Hoover, Vincent McIntyre, Taha Kabbaj and the GeoAnalytical Laboratory at Washington State University.

Author Contributions

Agathe Thomas and Maxwell Freimund were graduate research assistants who performed the column tests and analyzed the data. Haselbach and Poor designed and directed the research, interpreted the results and worked with developing and editing the paper.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Walsh, P.M.; Barrett, M.E.; Malina, J.F., Jr.; Charbeneau, R.J. Use of Vegetative Controls for Treatment of Highway Runoff, Master's Thesis, University of Texas at Austin, Austin, TX, USA, 1997.
2. Hunt, W.; Davis, A.; Traver, R. Meeting Hydrologic and Water Quality Goals through Targeted Bioretention Design. *J. Environ. Eng.* **2012**, *138*, 698–707.
3. WSDOT. *Ecology Embankment Study*; Washington State Department of Transportation: Olympia, WA, USA, 2006.
4. WSDOT. *Highway Runoff Manual*; Washington State Department of Transportation: Olympia, WA, USA, 2011.
5. WSDOT. *Highway Runoff Manual*; Washington State Department of Transportation: Olympia, WA, USA, 2014.
6. Horne, M.T.; Dunson, W.A. Effects of Low pH, Metals, and Water Hardness on Larval Amphibians. *Arch. Environ. Contam. Toxicol.* **1995**, *29*, 500–505.
7. EPA. *Wildlife Exposure Factors Handbook*; US Environmental Protection Agency: Washington, DC, USA, 1993; Volume I.

8. Sandahl, J.F.; Baldwin, D.H.; Jenkins, J.J.; Scholz, N.L. A sensory system at the interface between urban stormwater runoff and salmon survival. *Environ. Sci. Technol.* **2007**, *41*, 2998–3004.
9. Baldwin, D.; Tatara, C.; Scholz, N. Copper-induced olfactory toxicity in salmon and steelhead: Extrapolation across species and rearing environments. *Aquat. Toxicol.* **2011**, *101*, 295–297.
10. Ebrahimpour, M.; Alipour, H.; Rakhshah, S. Influence of water hardness on acute toxicity of copper and zinc on fish. *Toxicol. Ind. Health* **2010**, *26*, 361–365.
11. Ghassabzadeh, H.; Mohadespour, A.; Torab-Mostaedi, M.; Zaheri, P.; Maragheh, M.G.; Taheri, H. Adsorption of Ag, Cu and Hg from aqueous solutions using expanded perlite. *J. Hazard. Mater.* **2010**, *177*, 1–3.
12. Davis, A.P.; Shokouhian, M.; Ni, S. Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. *Chemosphere* **2001**, *44*, 997–1009.
13. *Stormwater Management Manual for Western Washington*; Washington State Department of Ecology: Olympia, WA, USA, 2005.
14. WSDOT. *2012 Annual Traffic Report*; Washington State Department of Transportation: Olympia, WA, USA, 2012.
15. Liu, Z.; Flury, M.; Zhang, Z.F.; Harsh, J.B.; Gee, G.W.; Strickland, C.E.; Clayton, R.E. Transport of Europium Colloids in Vadose Zone Lysimeters at the Semiarid Hanford Site. *Environ. Sci. Technol.* **2013**, *47*, 2153−2160.
16. Eaton, A.D.; Clesceri, L.S.; Rice, E.W.; Greenberg, A.E. *Standard Methods for the Examination of Water & Wastewater*; American Public Health Association: Washington, DC, USA, 2005.
17. Stumm, W.; Morgan, J.J. *Aquatic Chemistry: Chemical Equilibria and Rates in Natural Waters*; Wiley: New York, NY, USA, 1996.