MEDIA FILTER DRAIN:
MODIFIED DESIGN EVALUATION

FINAL PROJECT REPORT

by

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16. Abstract

The media filter drain (MFD), a stormwater water quality treatment best management practice, consists of media made up of aggregate, perlite, gypsum and dolomite in a trench located along roadway shoulders with gravel and vegetative pre-filtering facilities and optional underdrains. One of the many benefits of MFDs is the effective removal of dissolved zinc and copper from roadway runoff. However, the *existing* design includes use of an aggregate gradation that is no longer readily available (*old* design). A more readily available and economical aggregate gradation has a slightly lower percent of finer material (*new* design). This project evaluates if the *new* design is as effective as the *old* design at enhanced dissolved zinc and copper treatment.

Findings from laboratory research performed on columns filled with *new* media versus columns filled with *old* media indicate that the *new* media initially has similar removal efficiencies as the *old* media for large storm events. Accelerated aging of the *new* media indicates that removal efficiency for dissolved zinc and copper of the *new* media has not decreased after 15 years of simulated use.

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EXECUTIVE SUMMARY

The media filter drain (MFD), a stormwater quality control best management practice used extensively along roadways in Washington state, consists of media made up of aggregate, perlite, gypsum and dolomite in a trench located along roadway shoulders with gravel and vegetative pre-filtering facilities and optional underdrains for discharge. One of the many benefits of MFDs is the effective removal of dissolved zinc and copper from roadway runoff. However, the *existing* design includes use of an aggregate gradation that is no longer readily available (*old* design). A more readily available and economical aggregate gradation has a slightly lower percent of finer material (*new* design). This project evaluates whether the *new* design is as effective at enhanced dissolved zinc and copper treatment as the *old* design.

Laboratory research on columns filled with *new* media versus columns filled with *old* media indicates that the *new* media initially has similar removal efficiencies as the *old* media for large storm events. Accelerated aging of the *new* media indicates that removal efficiency of the *new* media has not decreased after 15 years of simulated aging.

A: INTRODUCTION

The Washington State Department of Transportation (WSDOT) wishes to modify the media filter drain (MFD) design by changing the crushed aggregate specification used in the mix. The WSDOT standard aggregate specification changed in 2008, and the media filter drain aggregate specification is based on the 2004 standard specifications. Aggregate mixes made using the 2008 standard aggregate specification are readily available and thus less expensive. Aggregate mixes made using the 2004 standard specification require a special order and thus significantly more expensive. In order to gain approval for this adjustment from Washington State Department of Ecology (Ecology) and incorporate into the media filter drain specifications, dissolved metal removal rates for the *new* design need to be comparable to the *old* design based on current accepted stormwater doses. The two dissolved metal pollutants of interest are zinc and copper.

The MFD, originally referred to as the Ecology Embankment, has been adopted by numerous states across the nation. Many are based on the *old* WSDOT design, such as the Oregon DOT bioslope. Thus other highway departments will find the additional design efficacy information useful.

B: BACKGROUND

WSDOT developed the MFD, formerly known as the Ecology Embankment, as a stormwater best management practice (BMP) to treat roadway runoff. This linear flow-through water quality treatment method has a narrow footprint conducive to situations where the available right-of-way is limited. The MFD has four basic components: a gravel no-vegetation zone, a vegetated filter strip, the media filter mix, and a gravel-filled underdrain trench. The MFD removes suspended solids, phosphorous, and metals from highway runoff. It is hypothesized that the media filter mix, which consists of crushed aggregate, dolomite, gypsum, and perlite, treats stormwater through physical filtration, chemical precipitation, sorption and cation exchange, and biological uptake and metabolism. The system performance as a whole was initially documented in the Ecology Embankment Report (WSDOT, 2006). A major role of the media filter mix functions as enhanced removal of dissolved metals - specifically copper and zinc. WSDOT's interest lies with the efficacy of the proposed *new* media filter mix designs, with respect to dissolved copper and zinc.

Between 2005 and 2010, WSDOT installed or contracted for installation approximately 38 miles of MFD. The MFD represents one of 3 BMPs approved by Ecology for enhanced treatment of stormwater. It has a narrow footprint, amenable to use in many highly developed or land constrained applications. The proposed modified design, which modifies the gradation of the crushed aggregate added to the mix, may reduce costs significantly. The current (*old* mix) specification for crushed aggregate, not a common gradation, requires a special order for the crushed aggregate. The modification (*new* mix) would allow for a more common gradation. This change, not expected to decrease the dissolved metal removal rates from the media filter mix, requires testing with protocols to determine if the system will perform as specified. In addition, since replacing *existing* MFDs is expensive, WSDOT needs the proposed new media filter mix tested to estimate system longevity.

Highway runoff contains metals, particularly zinc and copper, which if released into sensitive waters, can negatively affect the aquatic ecosystem. The MFD represents a feasible approach to enhanced metals removal. In order to realize cost savings on the installation and replacement of MFDs, WSDOT proposed evaluating a modified design for longevity. One portion of the MFD Research Project with funding from WSDOT and not included herein evaluates the *existing* design for longevity of metals removal and possible rehabilitation options. The other portion of the project, with funding by PacTrans, evaluates the proposed modified (*new*) media filter mix. The research project aims to improve guidelines and specifications as well as reduce installation, operation and maintenance costs. This report covers the findings from the PacTrans portion of the MFD Research Project as performed in the Low Impact Development laboratory at Washington State University (WSU) in Pullman, WA.

C: RESEARCH APPROACH AND PROCEDURES

1. Objectives

The following summarizes the objectives of this project.

- Determine whether the *new* design has the same or better metals removal efficiencies as the *old* design using laboratory experiments to:
    - Determine initial removal rates for the *new* and *old* designs over a range of influent concentrations (*Method #1*).
    - Measure infiltration rates for both the *new* and *old* designs to determine whether the infiltration rates were similar.
- Determine a more representative design life of the *new* MFD design by:
    - Completing an extended analysis on the *new* design based on estimated long term high loadings and expected media capacities (*Method #2*).

2. Procedures

The following procedures are based on a Quality Assurance Project Plan (QAPP) as prepared by Cara Poor and Liv Haselbach, submitted and reviewed by the Washington State Department of Transportation and the Washington State Department of Ecology in the summer of 2012, and as revised September 28, 2012. The QAPP was titled: Media Filter Drain: Evaluation of New Media Filter Mix and Existing Design Longevity.

Many laboratory procedures used were common to the two methods. However, some specific procedures were used for each of the methods. All cases involved preparing columns in the laboratory and subjecting them to simulated stormwater loading. In all cases there were two days between the start of two consecutive events or tests on a column to allow for drying as might be experienced between storms, which allowing for testing time, meant at least 43 hours were allowed to lapse between loadings on any one column. The sections covering the common procedures include information on the synthetic rainwater and stormwater used. Preparations included synthetic rainwater and synthetic stormwater solutions made with the synthetic rainwater and the metal stock solutions at various concentrations of dissolved zinc and copper (concentrations at typical, high and accelerated loading metal concentrations). The common procedure section also describes the development of channelization prevention procedures, analysis of influent and effluent samples for component concentrations, and grading and mixing of the *new* and *old* media.

The procedures for the two methods describe the details on combining the synthetic rainwater and the stock solutions to form the synthetic stormwater solutions, preparing the columns, and loading the columns. Table C.2.1 describes how the columns containing the *old* or *new* MFD design media were tested. Note that the procedures are differentiated into two sub-methods: *Accelerated Aging Events* and *Performance Testing*. The *Accelerated Aging Events* artificially load the columns with zinc and copper ions representative of many years of use. The *Performance Testing* sub-methods evaluate how the columns might perform using metals concentrations that fall within the range observed in roadway stormwater. Testing used the low typical, average typical, and high end of the concentration range. In the cases where accelerated loading to mimic long-term use occurred, columns were also periodically subjected to performance testing at high concentrations to evaluate performance after experiencing accelerated aging. This performance testing used either a 25-yr or a modified 25-yr simulated storm. A 25-yr test was defined herein as applying 35 inches (890 mm) of simulated stormwater, or 3.5 inches over ten times the surface area of an MFD (nine times additional runon). A modified 25-yr storm is defined as 1/5th of the volume of the 25-yr storm, due to five times the metal concentration.

Table C.2.1. Research Matrix: Purpose and Description of the Methods

Method	**Objective**	**Metal Concentration Range**	**Precipitation Loading(s)**	**Applied Infiltration Rate (in/hr)**
#1	Compare the *old* and the *new* design	Typical	Five 25-yr tests	30 & 50
		High	Five Modified 25-yr tests	30 & 50
#2	Determine the *new* design longevity	Accelerated*	Accelerated aging loading	10
		High	Periodically: Two Modified 25-yr tests	30

*Usually 40 times the typical concentration. Note that two typical concentrations for copper exists, 10 ppb and 20 ppb. Method #1 uses the lower (10 ppb) to test removal at really low concentrations, and uses the upper (20 ppb) to determine the high (5x) and the accelerated (40x). Typical concentration for zinc were always set at 100 ppb, with high (5x) and accelerated (40x).

Synthetic Rainwater Solution

The researched effort's synthetic rainwater conformed to rainwater samples taken at the Hanford site in Washington (Flury, unpublished data). The rainwater solution was prepared by adding the following to one liter of deionized (DI) water; 2.474 mg NaCl, 0.336 mg $NaHCO_3$, 3.923 mg KNO_3, 0.30 mg $KHCO_3$ and 0.30 mg $CaCO_3$. Table C.2.2 provides the component details for this synthetic rainwater. Table C.2.3 shows results for periodically measuring the rainwater and DI water for dissolved zinc and copper background levels. As the results show, background levels in copper and zinc were relatively low except for the sample taken on 2/27/13. There was likely contamination of the rainwater in this sample and the simulated rainwater was then replaced. In addition, we measured influent concentrations prior to application onto the media. If high background levels resulted in an influent concentration higher than intended, we quantified and accounted for it with the measured influent concentration.

Table C.2.2. Chemical Composition of the Synthetic Rainwater Solution

Chemical Composition	
Major Constituents	Concentration (M)
Na^+	4.63E-05
K^+	4.17E-05
Ca^{2+}	3.00E-06
Cl^-	4.23E-05
NO_3^-	3.88E-05
TIC : initial total inorganic carbon (HCO_3^- + CO_3^{2-}) 1.0E-5 M pH(measured) : 6.4	

Table C.2.3. Dissolved Zinc and Copper in Synthetic Rainwater and DI Water

Rainwater		
Date	**Zn (ppb)**	**Cu (ppb)**
1/14/2013	24.0	1.0
1/26/2013	18.3	0.6
2/13/2013	11.9	1.6
2/15/2013	24.0	1.0
2/27/2013	97.8	13.1
3/13/2013	14.8	0.5
3/20/2013	21.9	0.3
3/4/2013	43.0	1.9
4/24/2013	21.8	3.4
5/8/2013	36.4	0.8
5/24/2013	30.8	1.4
7/6/2013	32.5	1.8
7/31/2013	15.8	3.3
DI Water		
Date	**Zn (ppb)**	**Cu (ppb)**
3/25/2013	23.7	1.1
4/12/2013	15.0	0.3

Detection limits are 0.1 ppb for Cu and 1 ppb for Zn.
Quantification is approximately 1 ppb for Cu and 10 ppb for Zn.

Metal Stock Solutions

For this particular project, when a typical concentration is specified for the influent as in Method #1, the copper concentration is around 10 ppb and the zinc concentration is around 100ppb, therefore the zinc concentration in the stock solution is ten times the copper concentration. Whereas when a high or up to eight times high concentration (accelerated) is specified, the copper concentration is around 100ppb and 500ppb respectively and the zinc concentration is approximately 800ppb and 4000ppb respectively. Therefore for the typical metal solutions, the zinc concentration is approximately ten times the copper concentration and for the high or accelerated solutions, the zinc concentration is five times the concentration of copper. Since two different ratios were used for different methods, two metal stock solutions were made and are referred to as Metal Stock Solution A and Metal Stock Solution B, respectively. During the course of the project some precipitation was noticed in the stock solution containers and may have contributed to influent concentration variability. After this was noticed, influent solutions were stirred more vigorously for consistency. However, all influent concentrations were measured so actual results are accurate, and the variability provided additional information on removals for a range of concentrations.

The Metal Stock Solution A consisted of 8mg/L of copper and 40mg/L of zinc. The solution was made by adding 21.46 mg of cupric chloride dihydrate ($CuCl_2.2H_2O$) and 83.38 mg of zinc chloride ($ZnCL_2$) to a liter of DI water. Metal Stock Solution A was used for both the Accelerated Aging Events and the High Concentration Performance Tests as described in later sections.

The Metal Stock Solution B consisted of 2mg/L of copper and 20mg/L of zinc. It was made by adding 41.69 mg of zinc chloride ($ZnCL_2$), and 5.346 mg of cupric chloride dehydrate ($CuCl_2.2H_2O$) to a liter of DI water. Metal Stock Solution B was used for the Typical Concentration Performance Tests as described in later sections.

Sample Preparation and Component Concentration Testing Procedures

All sample bottle cleaning, sample preservation, and storage of samples followed Standard Method Section 3010 (Eaton et al. 2005). During each experiment, the influent and effluent samples were collected in glass beakers. 15 mL of each sample was transferred to an HDPE sample bottle for metal analysis. The sample number, size, column, and date were recorded in the official laboratory record. To preserve the sample, 23 μL of 15.8M concentrated nitric acid was added to bring the pH to less than two. Samples were stored in a refrigerator (kept at 6^oC) until delivery to the Geoanalytical Laboratory on the WSU campus. The lab uses an Agilent Technologies 7700 Series Inductive Coupled Plasma – Mass Spectrometer (ICP-MS) machine to analyze metals. Results in the form of metals concentrations and detection limits were provided electronically to the WSU Low Impact Development Laboratory. Concentrations were then further recorded in the official laboratory record.

Periodically a sample was taken from the influent, effluent or other solutions and tested for pH. The samples were tested for pH with a HACH HQ411d pH meter according to standard procedure.

Channelization Prevention Procedures

An unforeseen occurrence that was uncovered in early testing for the WSDOT portion of the research, was possible channelization within the column after the column was made. Channelization refers to faster flow through a portion of the column where the aggregate and other media are not distributed evenly until subsequent water flow and associated settling lessen this impact. It is hypothesized that this resulted in highly variable removal rates that were sometimes much lower than the norm through approximately the first five events applied to the column. This is not as important in the longevity testing where a column is subjected to many events, but in performance testing where there are only five planned events total, this settling period would not produce reliable results. In order to allow the column to settle, a channelization prevention method was developed

Channelization Procedure A involved running five “metal-less” events through the columns of approximately 770 mL of DI water at 10 in /hour. This allows the aggregate to settle and aids in removing the subsequent variability that was observed in earlier experiments. In addition, the use of DI water avoids the possibility of loading the virgin columns with metals and/or aids in leaching out pre-existing metals from the *new* or *old* design mix prior to being tested at low concentrations.

Aggregate Grading Procedure and Column Preparation

In all cases, preparation of each of the 6” diameter by 12” deep columns with either the *new* or the *old* aggregate gradation mix involved adding 0.0729 lbs of dolomite, 0.0108 lbs of gypsum, 0.065 cubic feet of perlite and approximately 0.196 cubic feet of the respective aggregate (*new* or *old* gradation) to the column (Methods #1 and #2). (The amounts of dolomite and gypsum added are approximately three times the amounts used in the MFD design mix originally specified by WDOT, but less than the amounts currently specified by WSDOT which are four times the existing for dolomite, and eight times the existing for gypsum. Thus the tests should provide conservative results.)

A local supplier provided the aggregate for all of the *new* mix columns. That supplier also provided a set of sieve analyses on the aggregate obtained in the summer of 2012 as noted in Table C.2.4 as Eastern Washington 3/8”. Two samples of this local *new* mix aggregate were also sieved at the Washington State University (WSU) laboratories in the summer of 2012 as also noted in Table C.2.4. These sieve analyses are compared to both the *old* mix design specification and the *new* WSDOT standard in Table C.2.4. Note that the main difference in the two standards is the decreased amounts of finer aggregates passing the US#4 sieve in the *new* WSDOT standard. The first loads of *new* aggregate obtained had fairly low amounts of aggregate at the lower end of the range for passing the US#4 sieve (or even less) than the WSDOT standard. This represents the limiting case as it is expected that less fine aggregate would be a less dense mix and therefore might have decreased retention times in the columns for sorption.

The same supplier provided additional *new* aggregate over the course of the testing. In August 2013 the remainder of the *new* aggregate stored in the WSU laboratory and many buckets of additional local *new* aggregate were sieved for the fraction passing the US#4 sieve since additional masses of the finer fraction were needed to prepare the *old* mix gradation. The results of this sieving process are presented in Table C.2.5 and show the variability in the *new* gradation mix, with these samples having masses passing the US#4 sieve in the 16-28% range. The *old* mix aggregate was made by adding the appropriate masses from the Table C.2.5 of aggregate not passing the US#4 sieve with aggregate passing the US#4 sieve to bring the percent passing the US#4 sieve to 40%.

Table C.2.4. Gradations of Aggregate (Mass Percent Passing)

Sieve	Old MFD Design	WSDOT Standard	E. WA 3/8"*^	WSU LabAnalysis A*	WSU LabAnalysis B*
1/2"	100	99-100	100	100	100
3/8"	90-100	85-100	97.98-99	99	99
1/4"	-	-	23.3-38.7	29	30
#4	30-56	10-30	4.2-11.7	5	6
#8	-	0-10	2.92-4.4	2	3
#10	0-10	-	2.89-4.5	2	3
#16	-	0-5	2.82-4.4	2	3

*Aggregate from supplier. ^Analysis provided from supplier.

Table C.2.5. Sieving to Increase Fines in Aggregate used to Prepare Old Media Mix

Sample	Total Mass (g)	Mass Passing #4 (g)	% Passing #4
Bottom of lab bin^	22467	4935	22.0
New Aggregate 1*	10500	2000	19.1
New Aggregate 2*	7000	1500	21.4
New Aggregate 3*	8300	1800	21.7
New Aggregate 4*	7800	1600	20.5
New Aggregate 5*	9000	1900	21.1
New Aggregate 6*	8400	1900	22.6
New Aggregate 7*	7600	2000	26.3
New Aggregate 8*	8700	1600	18.4
New Aggregate 9*	8300	1400	16.9
New Aggregate 10*	7000	1600	22.9
New Aggregate 11*	7900	1600	20.3
New Aggregate 12*	7700	1600	20.8
New Aggregate 13*	8900	2100	23.6
New Aggregate 14*	10900	3100	28.4
New Aggregate 15*	10800	2200	20.4
New Aggregate 16*	10100	1900	18.8
New Aggregate 17*	9800	2600	26.5

^Remaining aggregate from the supplier received from summer through fall 2012
*New batch of aggregate obtained 8/20/2013 from supplier.

Method #1

Method #1 consisted of sixteen 6” diameter by 12” deep columns of *new mix* and eight 6” diameter by 12” deep columns of *old mix*, each subjected to five sequential performance tests. These performance tests were conducted after *Channelization Procedure A* had been performed on each column to ensure more consistent results. The initial plan was for two columns of each mix to be tested at typical (10 and 100 µg/L for copper and zinc, respectively) and high (100 and 500 µg/L for copper and zinc, respectively) concentrations at infiltration rates of 30 inches per hour and 50 inches per hour for a total of four different tests on two columns of each mix. However, due to the variability in the finer gradations in the *new mix* aggregate evidenced from looking at the pile at the supplier and in the laboratory storage bin where the aggregate was taken, the number of *new* mix columns was doubled.

The typical concentration performance tests performed on each column were a series of five 25-year, 24-hour storms as typical in some areas of western Washington using the target concentrations and infiltration rates as follows. Typical concentration tests consisted of 16.2 liters total, prepared with 16.135 liters of synthetic rainwater and 81 mL of Metal Stock Solution B dispensed over 70 minutes for the 30 in/hr infiltration rate and over 45 minutes for the 50 in/hr infiltration rate. For high concentration performance tests the volumes of the 25-year, 24-hour storm from the typical concentration performance tests were reduced to one fifth the total volume, referred to in Table C.2.1 and C.2.15 as the Modified 25-year Test. Therefore 3.20 liters of synthetic rainwater and 40.5 mL of Metal Stock Solution A were used for each test. This was dispensed over 14 minutes for the 30 in/hr infiltration rate and over 8 minutes for the 50 in/hr infiltration rate.

After all the Performance Tests were completed on the columns in Method #1, the columns were subjected to a set of infiltration tests. These were based on a modified ASTM c1701, with the modification that 2 liters of tap water was used for all the tests. Three consecutive infiltration tests were performed on each column as per the method.

Method #2

Method #2 consisted of six 6” diameter by 12” deep columns of the *new mix*. The channelization procedure was not used on this method because when these columns were started, we were unaware channelization was an issue. Consequently, the first five events on the columns are considered to have significant channelization and their results are not included in the performance evaluations, although the results are presented and the metal masses retained considered in the calculations.

The main testing in Method #2 has two main components, frequent accelerated loading of the columns with very concentrated zinc and copper solutions to mimic many years of absorption of the metals (*Accelerated Aging Events*) and periodic removal from the Accelerated Aging Event sequence for stormwater performance testing at the upper end of metal concentration levels found in stormwater runoff (*High Concentration Performance Testing*). Two High Concentration Performance Tests were conducted each time on a pair of columns using a similar procedure as in Method #1 with high concentrations and a 30 in/hr loading rate.

After High Concentration Performance Testing, some of the columns were returned to the Accelerated Aging Event Sequence for additional aging as per Modification A to the Objectives. Of the six columns used in Method #2, four were returned to the Accelerated Aging Sequence for additional aging after each High Concentration Performance Testing sequence. (The original laboratory plan for Method #2 did not have any of the columns returning to the Accelerated Aging Sequence after Performance Testing, but the metal analysis results obtained after discarding the first pair of columns indicated essentially no change in metal removal due to aging and it was decided to keep aging the remaining four columns beyond the original plan.) The following sections outline both the Accelerated Aging Event sequences and the High Concentration Performance Testing sequences. Also included are details of which columns received the additional aging, and when and how often the performance testing was performed on them.

The accelerated aging event sequence for Method #2 did not always use the same level of very concentrated zinc and copper influent solutions for each event, and this variation has provided information on the effectiveness of the media over a range of influent concentrations. Table C.2.6 lists the approximate concentration levels used. Actual concentrations varied due to experimental variability and are provided in the results. The volumes used were 0.77L for these six inch diameter columns, dispensed to the columns over 10 minutes. Of this 0.77L, 0.697 L was synthetic rainwater, and 0.077L was stock solution.

Table C.2.6. Approximate Influent Concentrations for Method #2: Accelerated Aging

Events	**Zn [ppb]**	**Cu [ppb]**
1-18, 21	200	20
19-20, 22-24	1850	250
25-112	4300	850

The accelerated loading event sequence can be used to estimate the equivalent age for metal loading in various regions based on rainfall amounts and typical copper and zinc concentrations in the stormwater runoff. The zinc and copper accelerated loading concentrations of 4000 ppb and 800 ppb, respectively are based on an initial calculation estimating that six accelerated aging events (herein referred to as Events) are equivalent to one typical year in Western Washington. This calculation is based on typical stormwater runoff concentrations of 100ppb and 20 ppb for zinc and copper, respectively, with stormwater runoff volumes of ten times an annual precipitation of 40 inches, to provide for significant runon from paved surface areas. Note that the loading is the zinc and copper equivalent loading, not the equivalent volumes of water.

The basis of the design was the equivalent number of years corresponding to forty times the typical concentration using 1/6th of a year per event (800 and 4000 ppb for copper and zinc, respectively). The Accelerated Aging Event Sequence is applied at a slow infiltration rate of 10in/hr. It takes 10 minutes for the stormwater to flow onto a column. Thus the calculation for the stormwater volume applied to the columns for an Accelerated Aging Event with the forty times typical concentration was calculated as follows:

(40 in rain/year)(runon from 10 times the MFD area) = 400 inch runon/year C.2.1

(400 in runon/year)/(40 times typical concentration/ accelerated concentration)

= 10 inch accelerated concentration runon/year C.2.2

Assuming that a year would be equivalent to 6 events, the applied solution per event would be:

(10 in accelerated concentration runon/year)/(6 events/year)

= 1.67 inch accelerated runon/event C.2.3

Thus, in Method #2 through the final Event 112, the approximate age of the media for runon from 10 times the MFD surface based on metal loadings in a region that received 40 inches of rain per year, was approximately 15 years (14.5 years for the copper and 15.8 years for the zinc).

The High Concentration Performance Testing consists of loading the columns with high concentrations found in runoff after a number of Accelerated Aging Events to see how the columns might perform after several years or more of metal loading. The concentration target for High Performance Testing was 100 ppb and 500 ppb for copper and zinc, respectively. As previously mentioned, this was achieved using 3.24 L of solution, dispensed to the six inch diameter columns over 14 minutes. The solution consisted of 3.20 liters of synthetic rainwater and 40.5 mL of Metal Stock Solution A.

The experimental design allows for two columns to be subjected to the High Concentration Performance Testing at three different times which were after 40, 60 and 80 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 that the columns used in the second and third High Concentration Performance Tests were returned for additional Accelerated Aging, up to 112 events. Table C.2.7 gives the number of the columns for the three High Concentration Performance Test sequences, summarizes their correlation to aging, and outlines the testing procedure. Actual concentrations varied due to experimental variability and are provided in the results.

Table C.2.7. High Performance Testing Procedure Summary in Method #2

Test Sequence	**Number of Columns**	**Post Test Columns Continued Aging?**	**Pre-Test Aging Event Numbers**	**# of High Performance Tests on Each Column**	**Target Influent Zn Concentration (ppb)**	**Target Influent Cu Concentration (ppb)**
1	2	No	1-40	2	500	100
2	2	Yes	1-60	2	500	100
3	2	Yes	1-80	2	500	100

Methods Summary

Table C.2.8 recaps the two methods used in this study. (Estimated ages pre and post High Performance Testing, based on typical concentrations of zinc and copper found in 400 inches of runon, are provided for Method #2.) Tests are listed sequentially with accelerated aging in italics (*AA*) and performance testing (PT).

Table C.2.8. Actual Testing Matrix of Columns (*AA-Accelerated Aging* and PT-Performance Testing)

Method	**MFD Mix Design**	**Test and Rate (in/hr)**	**Target Copper Conc. (ppb)**	**Target Zinc Conc. (ppb)**	**Estimated Copper Loading and Performance Tests**	**Estimated Zinc Loading and Performance Tests**
#1	***New* – 4 columns**	PT 30	10	100	Five 25-yr tests	Five 25-yr tests
	***New* – 4 columns**	PT 30	100	500	Five Modified 25-yr tests	Five Modified 25-yr tests
	***New* – 4 columns**	PT 50	10	100	Five 25-yr tests	Five 25-yr tests
	***New* – 4 columns**	PT 50	100	500	Five Modified 25-yr tests	Five Modified 25-yr tests
	***Old* – 2 columns**	PT 30	10	100	Five 25-yr tests	Five 25-yr tests
	***Old* – 2 columns**	PT 30	100	500	Five Modified 25-yr tests	Five Modified 25-yr tests
	***Old* – 2 columns**	PT 50	10	100	Five 25-yr tests	Five 25-yr tests
	***Old* – 2 columns**	PT 50	100	500	Five Modified 25-yr tests	Five Modified 25-yr tests
#2	***New* – 2 columns**	*AA 10* PT 30	*30-800* 100	*200-4000* 500	*3.2 yrs* Two Modified 25-yr tests	*3.5 yrs* Two Modified 25-yr tests
	***New* – 2 columns**	*AA 10* PT 30 *AA 10*	*30-800* 100 *800*	*200-4000* 500 *4000*	*6.7 yrs* Two Modified 25-yr tests *+7.8 yrs*	*7.0 yrs* Two Modified 25-yr tests *+8.8yrs*
	***New* – 2 columns**	*AA 10* PT 30 *AA 10*	*30-800* 100 *800*	*200-4000* 500 *4000*	*10.4 yrs* Two Modified 25-yr tests *+4.1 yrs*	*10.6 yrs* Two Modified 25-yr tests *+5.2 yrs*

D: FINDINGS AND DISCUSSION

Influent and effluent concentrations, and percent removal for both zinc and copper calculated on a concentration and also on a mass basis, are presented for the results as applicable for the various experimental methods. Due to possible channelization, the five first events for Method #2 were not included in the summary results for percent removals, but are included for metal loading calculations. For Method #1, five “metal-free” channelization prevention procedures were applied to the columns prior to the actual testing sequences. The following sections provide the results of the two methods.

1. Method #1 Results

Method #1 analyzed copper and zinc loading onto columns made with both *new* and *old* media for very large storm events. One pair of testing sequences used typical concentrations of both metals, with extremely low copper representing the low range of concentrations typically observed. The simulated storm events were based on a 25-year storm as previously discussed with two different runoff loading rates (30 or 50 in/hr). Eight columns were tested for the *new* mix and four columns were tested for the *old* media. Of the eight columns used for the *new* media, one has been disregarded from the results due to possible metal contamination, probably from laboratory error. The results for the typical concentration tests for the *new* media columns are presented in Figures D.1.1 and D.1.2 for copper. Note in Figure D.1.1 that three of the tests had higher than normal effluent concentrations. These were the first test after the channelization prevention methods. It is hypothesized that channeling was still likely occurring, so these three tests are excluded from the results presented in Figure D.1.2.

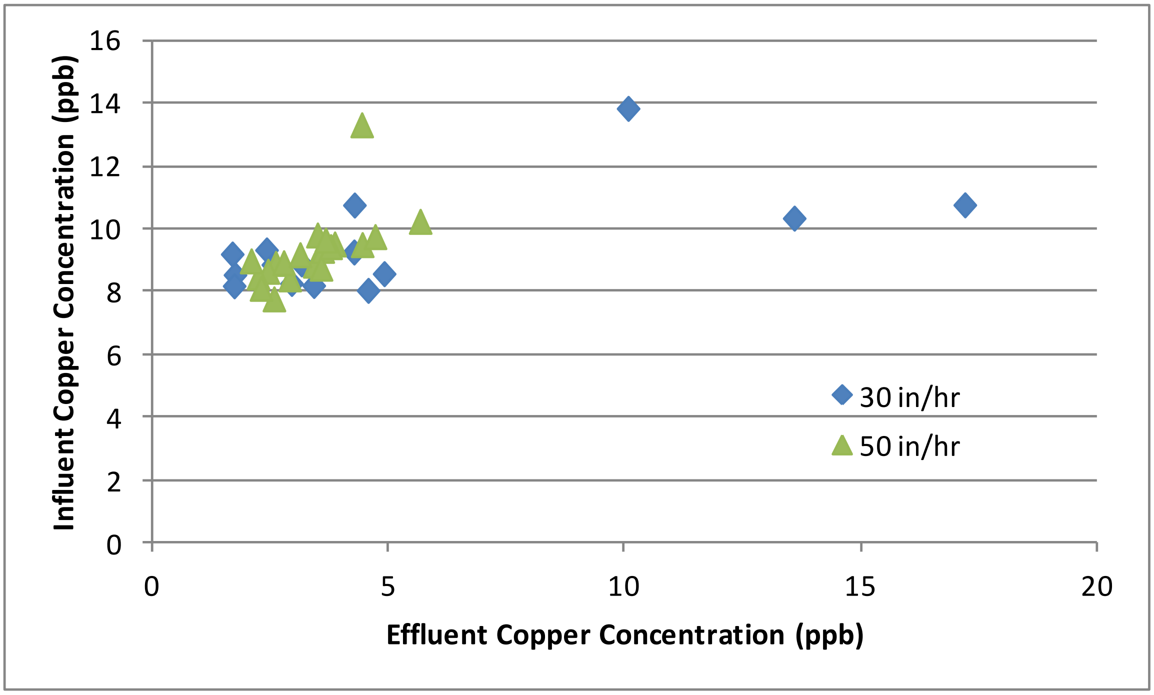

Figure D.1.1. Influent and effluent concentrations for typical performance tests of 25 year storm for copper on *new* media columns. Loading rates are as noted.

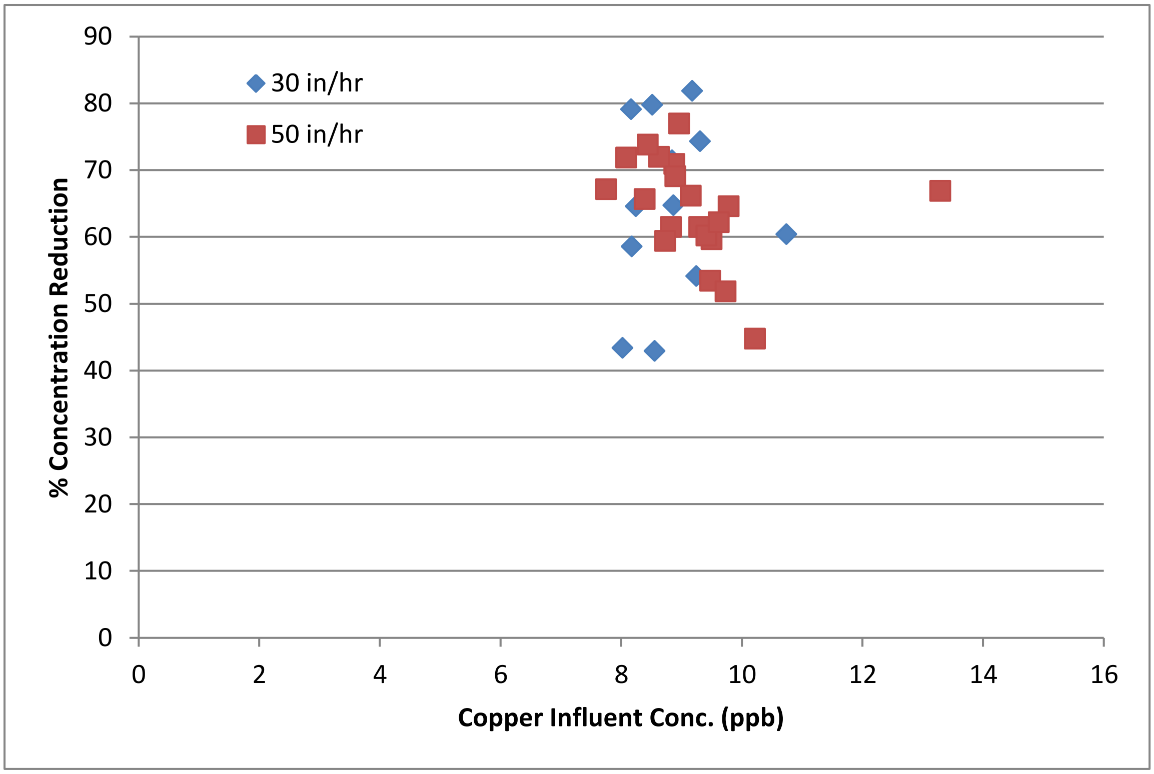

Figure D.1.2. Percent concentration reduction for typical performance tests of 25 year storm for copper on *new* media columns. Loading rates are as noted. (The first three tests on three of the columns are excluded due to assumed channelization still occurring.)

The results for the typical concentration tests for the *new* media columns are presented in Figures D.1.3 and D.1.4 for zinc. Again as noted previously for copper in Figure D.1.1, three of the tests had higher than normal effluent concentrations. All three of these were the first test after the channelization prevention methods and are the outliers in Figure D.1.3. It is likely that channeling was still occurring, so these three are excluded from the percent concentration decrease results presented in Figure D.1.4.

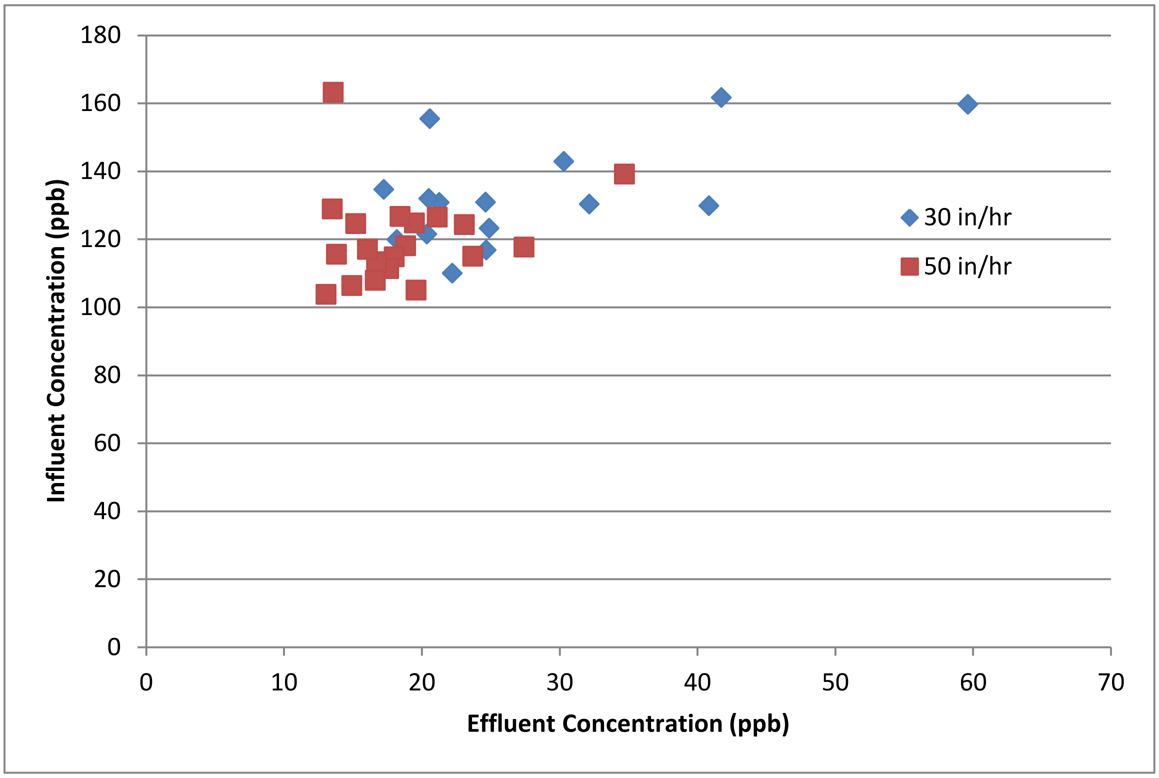

Figure D.1.3. Influent and effluent concentrations for typical performance tests of 25 year storm for zinc on *new* media columns. Loading rates are as noted.

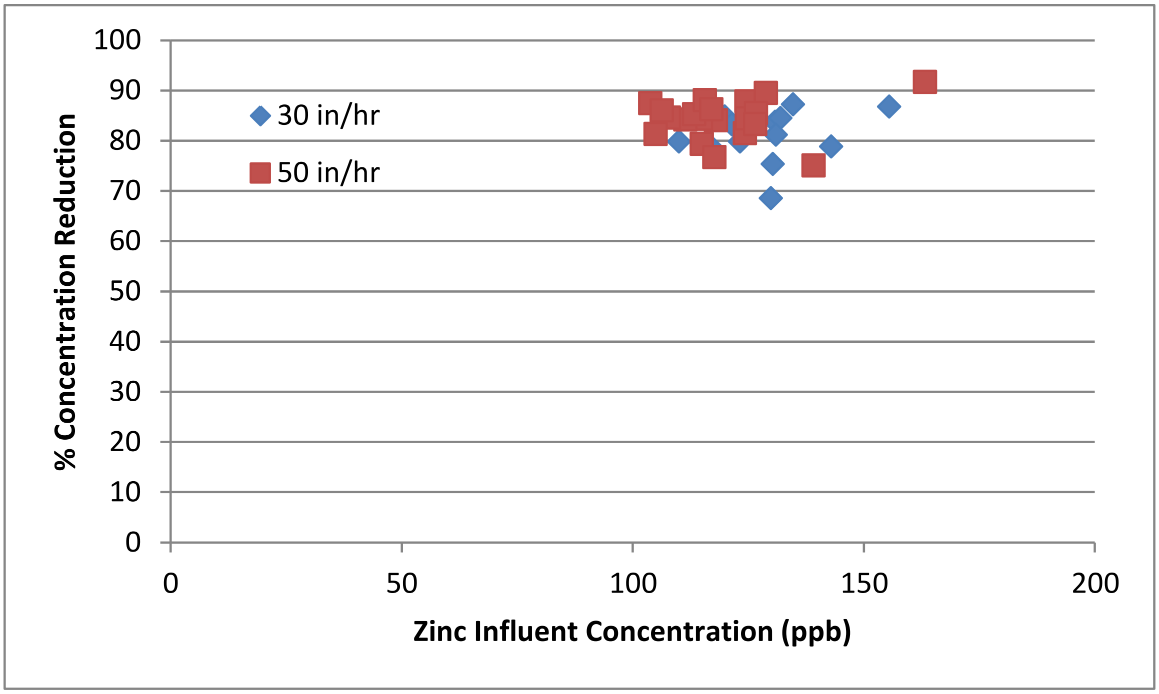

Figure D.1.4. Percent concentration reduction for typical performance tests of 25 year storm for zinc on *new* media columns. Loading rates are as noted. (The first three tests on three of the columns are excluded due to assumed channelization still occurring.)

The following results are for the four columns for the *old* media. The results for the typical concentration tests for the *old* media columns are presented in Figures D.1.5 and D.1.6 for copper. Note in Figure D.1.5 that six of the tests had higher than normal effluent concentrations. Five of these were the first or second test after the channelization prevention methods. It is likely that there was still channeling occurring, so these five are excluded from the percent concentration decrease results presented in Figure D.1.6. The extreme outlier in Figure D.1.5 for the second test on one of the 50 in/hr columns, also had increased zinc concentrations in the effluent and the results are also excluded from Figure D.1.6 as it is assumed that the effluent sample was contaminated. However, all of the results are included in Figure D.1.5.

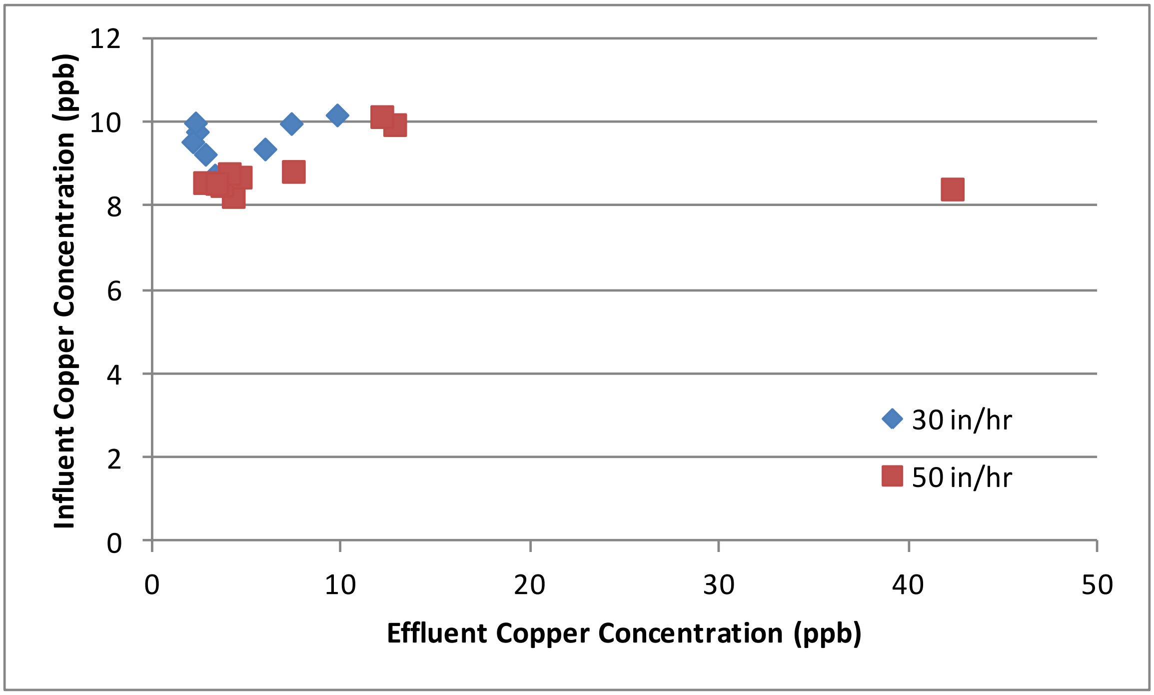

Figure D.1.5. Influent and effluent concentrations for typical performance tests of 25 year storm for copper on *old* media columns. Loading rates are as noted.

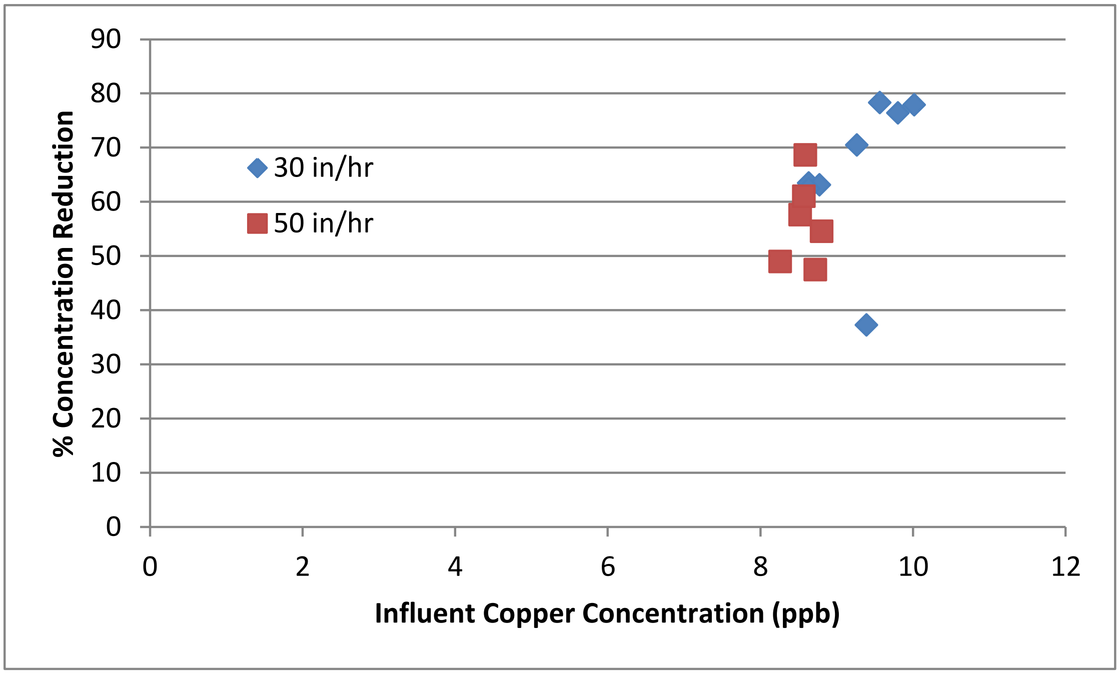

Figure D.1.6. Percent concentration reduction for typical performance tests of 25 year storm for copper on *old* media columns. Loading rates are as noted. (The outlier on one column for the 50 in/hr test is excluded due to assumed contamination, and both column first tests for 30 in/hr and 50 in/hr loading and one second test also excluded due to assumed channeling.)

The results for the typical concentration tests for the *old* media columns are presented in Figures D.1.7 and D.1.8 for zinc. Again as noted previously for copper in Figure D.1.5, six of the tests had higher than normal effluent concentrations. All six of these are also excluded from the percent concentration decrease results presented in Figure D.1.8.

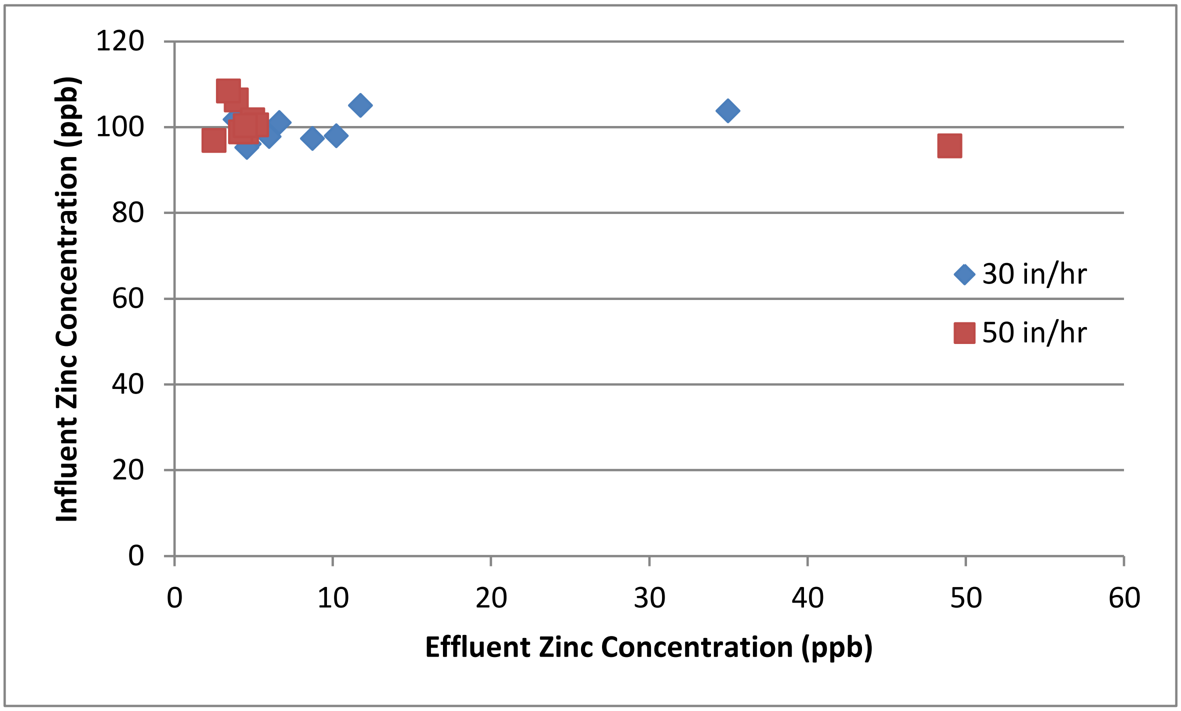

Figure D.1.7. Influent and effluent concentrations for typical performance tests of 25 year storm for zinc on *old* media columns. Loading rates are as noted.

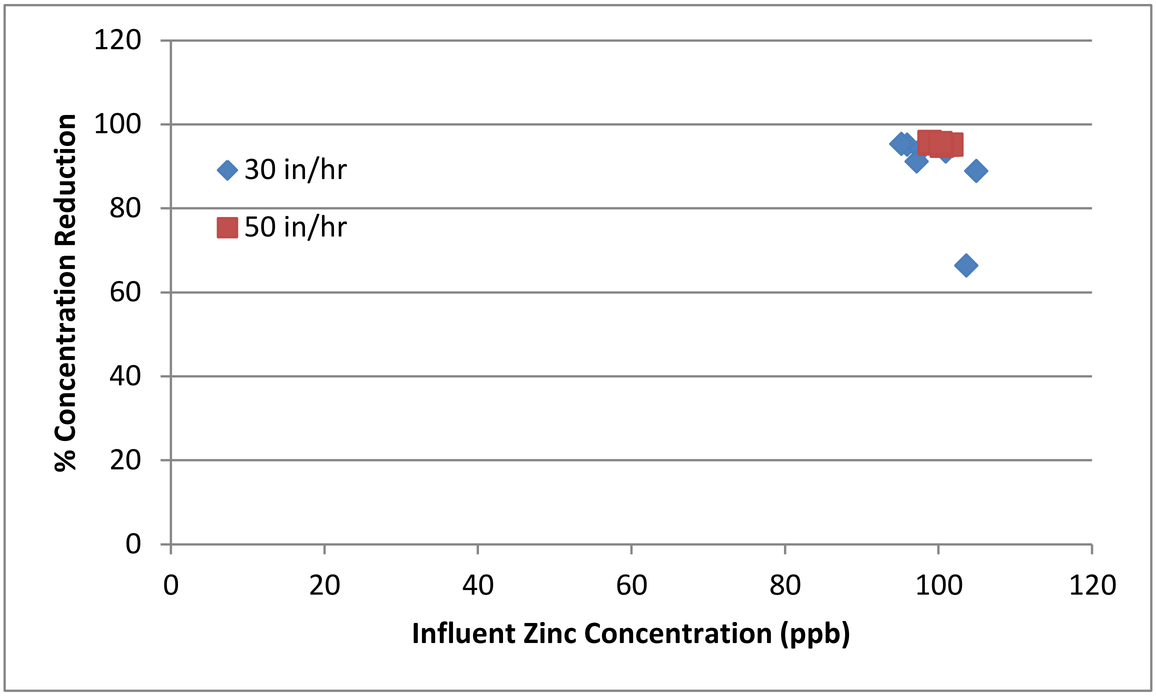

Figure D.1.8. Percent concentration reduction for typical performance tests of 25 year storm for zinc on *old* media columns. Loading rates are as noted. (The outlier on one column for the 50 in/hr test is excluded due to assumed contamination, and both column first tests for 30 in/hr and 50 in/hr loading and one second test also excluded due to assumed channeling, although all data are in Figure D.1.7.)

The other pair of testing sequences for Method #1 used high concentrations with a modified large storm event. There were eight columns tested with the *new* media and four columns tested with the *old* media. Figure D.1.9 presents the influent and effluent concentrations and Figure D.1.10 shows the concentration decrease versus influent concentration for the *new* media columns for copper in the high concentration performance tests. Similarly, Figures D.1.11 and D.1.12 present the same information on the *new* media for zinc. Note that for the 50 in/hr tests, the influent concentrations of copper were actually somewhere between the high and typical concentrations due to laboratory variability.

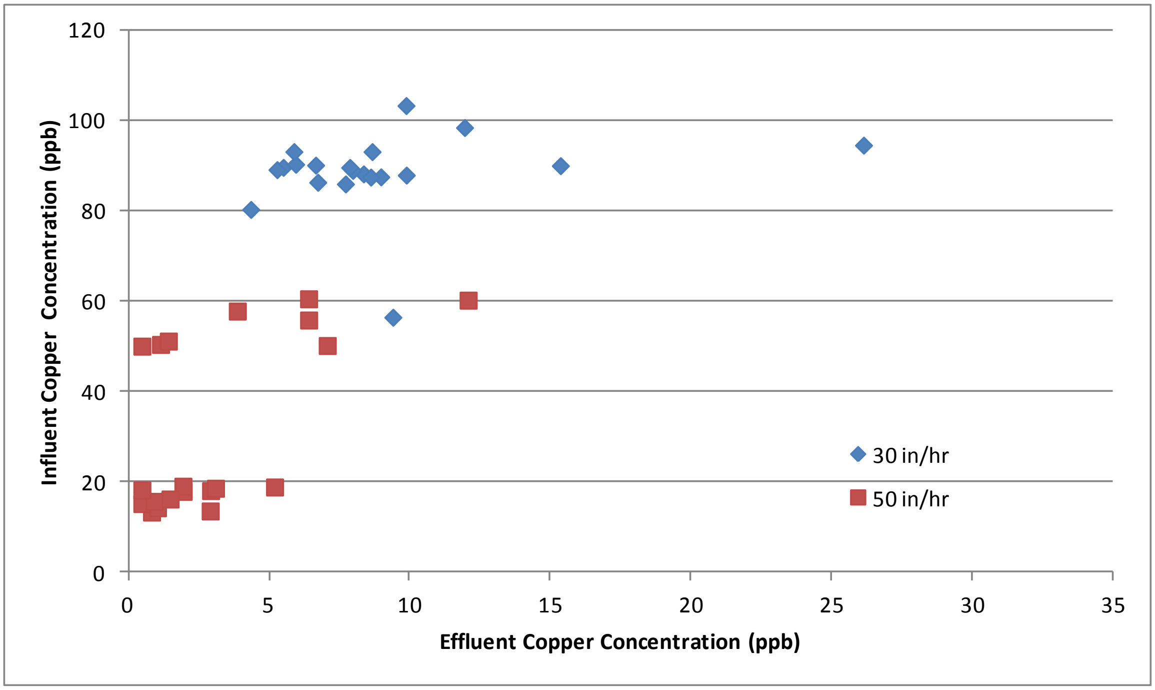

Figure D.1.9. Influent and effluent concentrations for high concentration performance tests of modified 25 year storm for copper on individual *new* media columns. Loading rates are as noted.

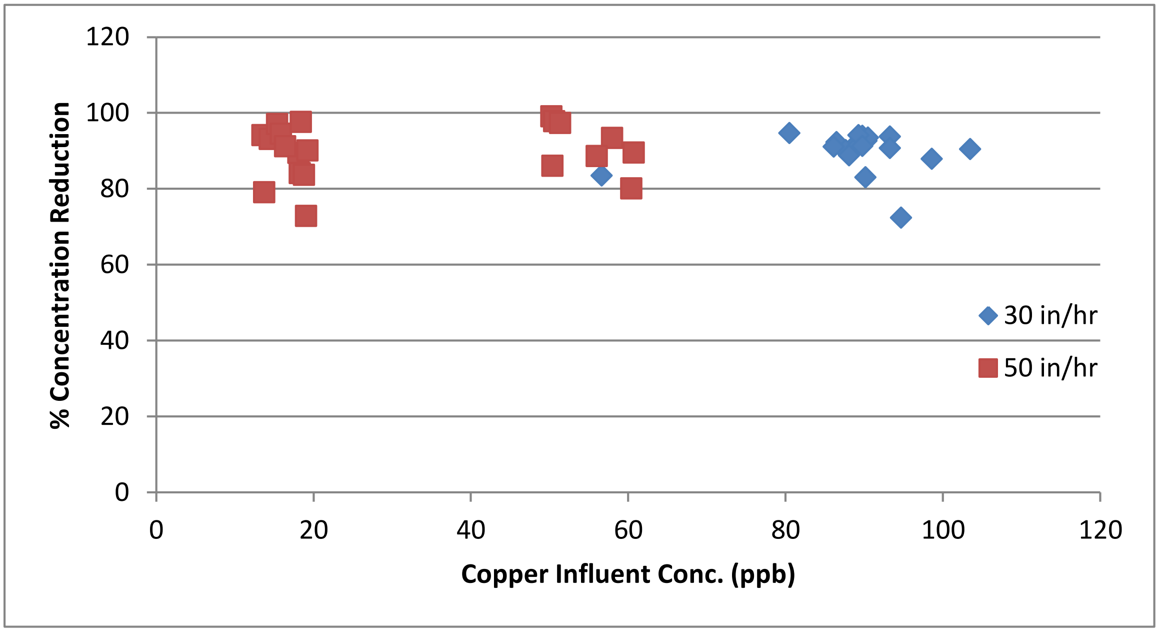

Figure D.1.10. Percent concentration reduction for high concentration performance tests of modified 25 year storm for copper on individual *new* media columns. Loading rates are as noted.

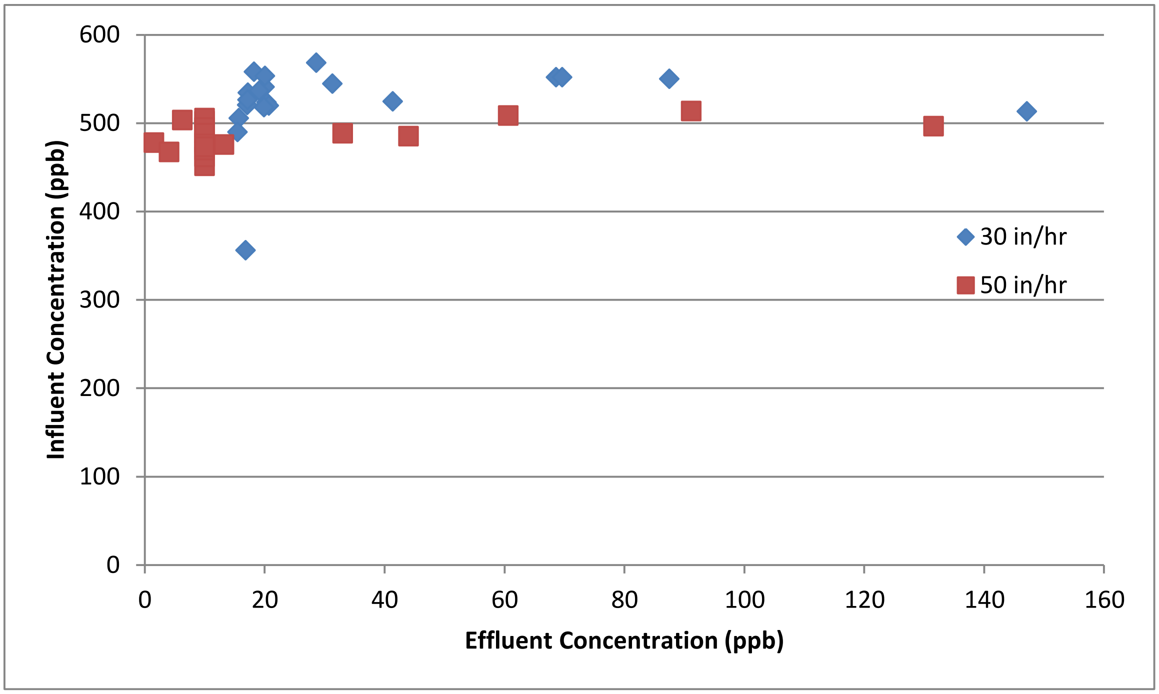

Figure D.1.11. Influent and effluent concentrations for high concentration performance tests of modified 25 year storm for zinc on individual *new* media columns. Loading rates are as noted.

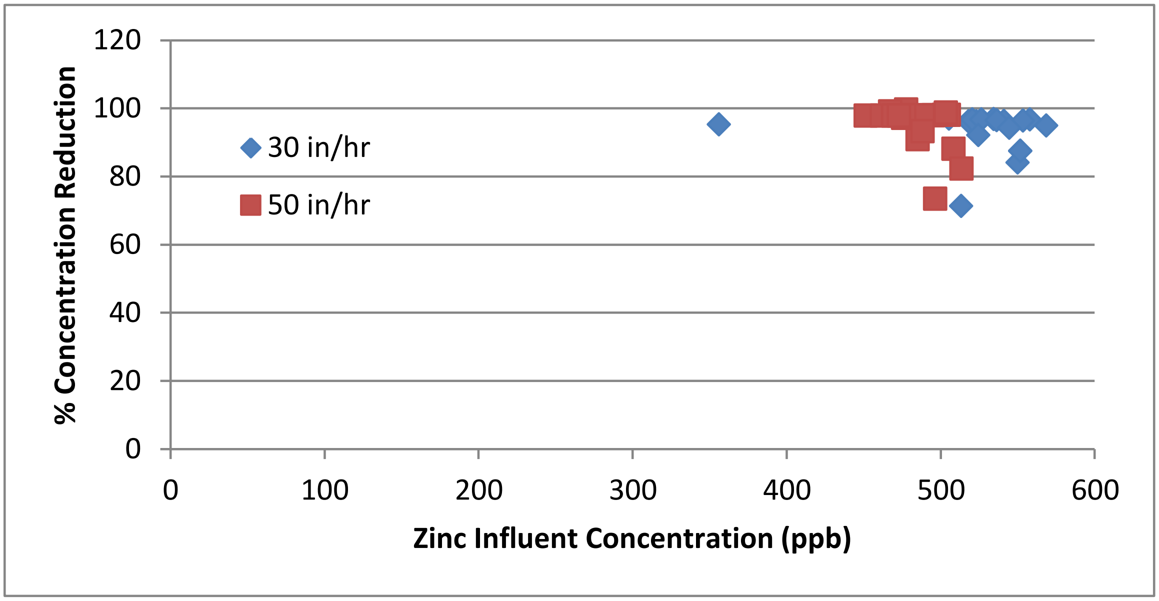

Figure D.1.12. Percent concentration reduction for high concentration performance tests of modified 25 year storm for zinc on individual *new* media columns. Loading rates are as noted.

Figure D.1.13 presents the influent and effluent concentrations and Figure D.1.14 shows the concentration decrease in the *old* media columns for copper in the high concentration performance tests. Note the high effluent concentrations for the set of 50 in/hr *old* media tests for copper. These results are not consistent with the other laboratory results. The 50 in/hr tests were performed by a different operator and it is hypothesized that this very high flow rate disturbed the media in the column allowing for development of channels. Future testing will be needed to evaluate this hypothesis. Similarly, Figures D.1.15 and D.1.16 present the same information on the *old* media for zinc. Note the extreme outliers for the first test with the 50in/hr loading rate. Channelization is assumed for these two cases and the information is excluded in all the removal efficiency figures. In addition, all the 50 in/hr tests resulted again in higher than normal effluent concentrations, consistent with the aforementioned hypothesis of channel development.

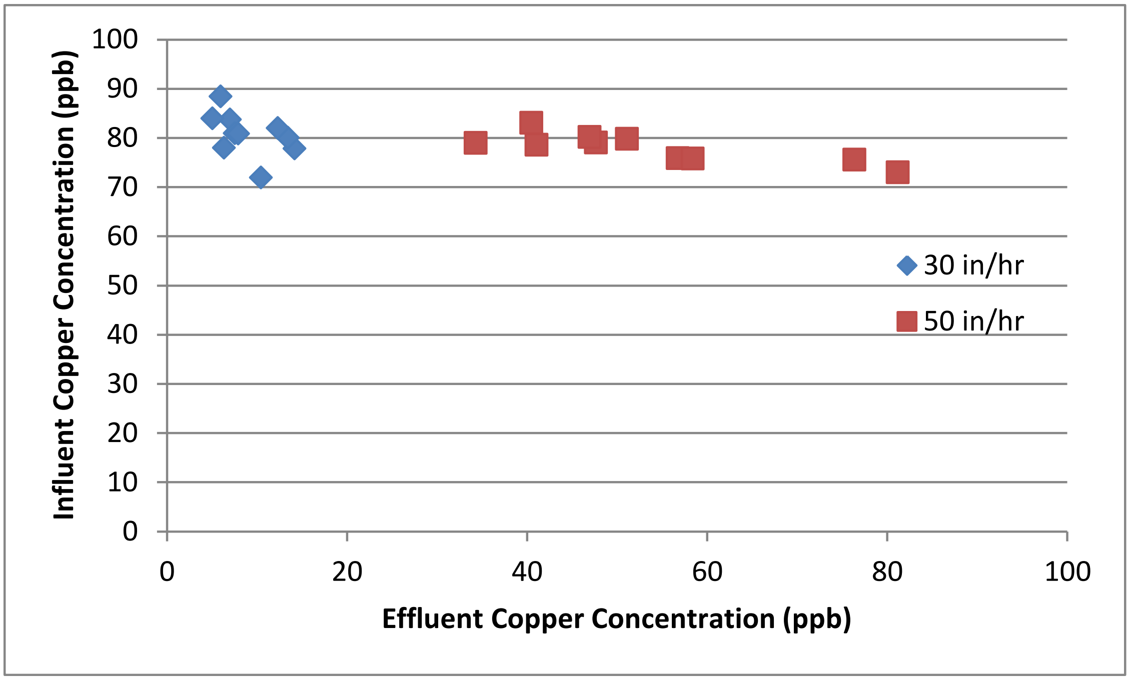

Figure D.1.13. Influent and effluent concentrations for high concentration performance tests of modified 25 year storm for copper on individual *old* media columns. Loading rates are as noted.

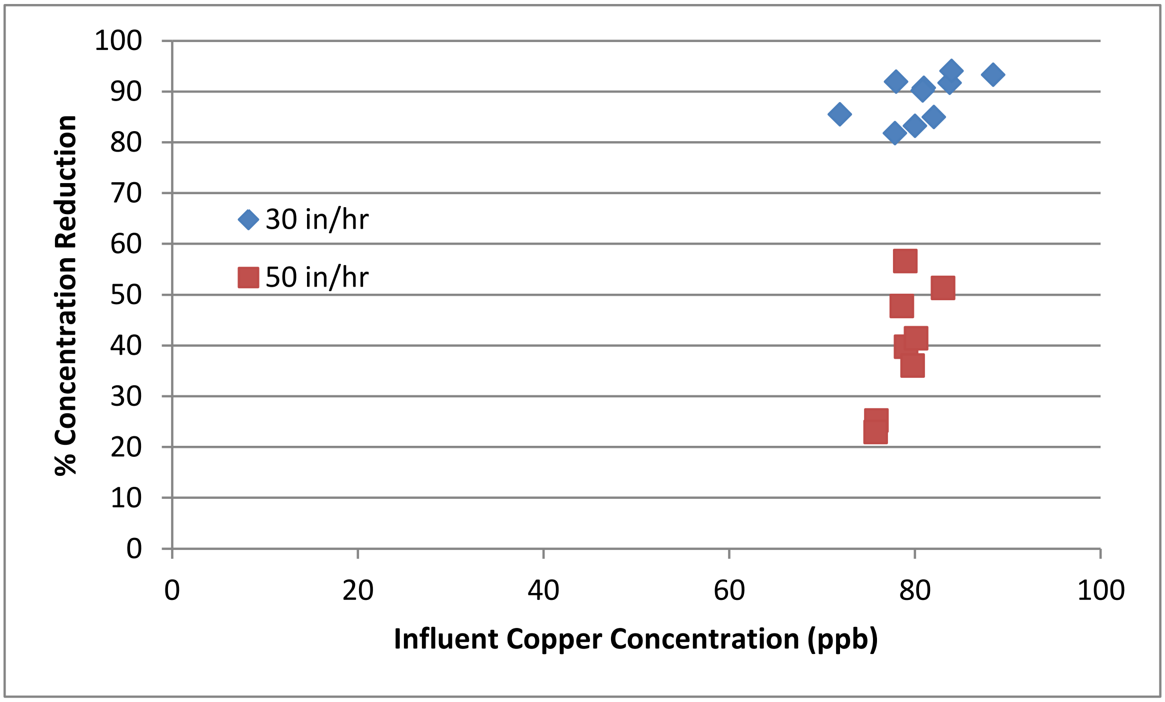

Figure D.1.14. Percent concentration reduction for high concentration performance tests of modified 25 year storm for copper on individual *old* media columns. Loading rates are as noted. (Two extreme outliers excluded due to assumed channelization)

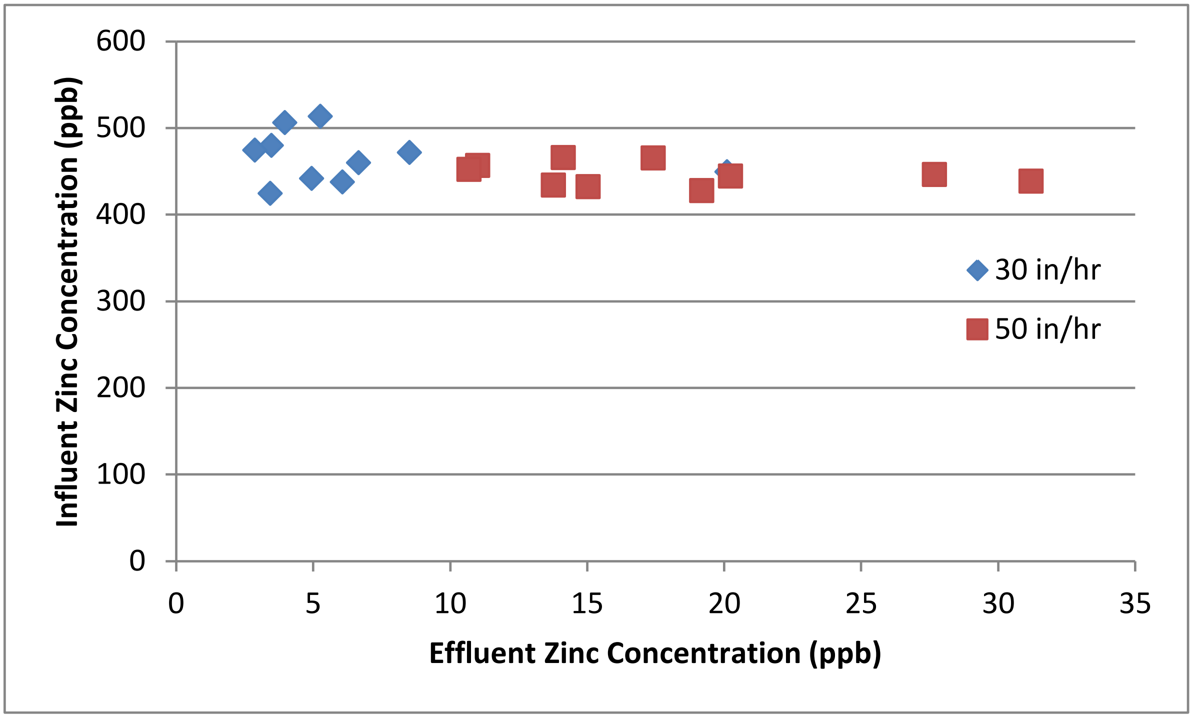

Figure D.1.15. Influent and effluent concentrations for high concentration performance tests of modified 25 year storm for zinc on individual *old* media columns. Loading rates are as noted.

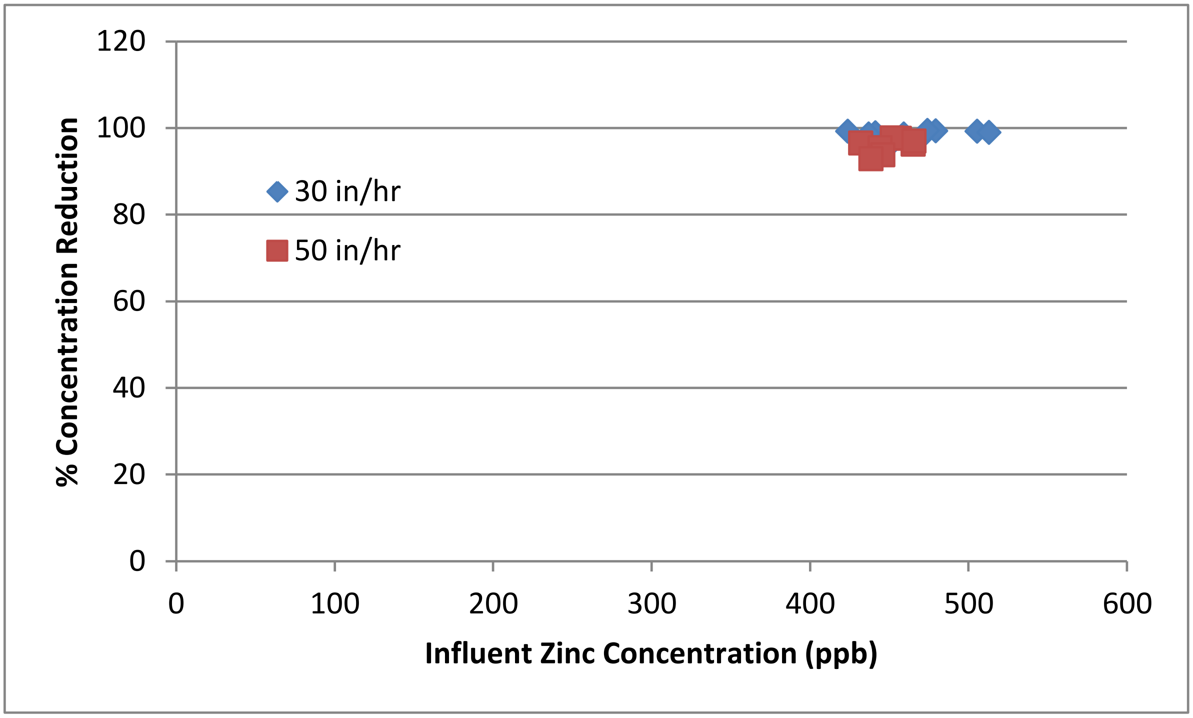

Figure D.1.16. Percent concentration reduction for high concentration performance tests of modified 25 year storm for zinc on individual *old* media columns. Loading rates are as noted. (Two extreme outliers excluded due to assumed channelization)

Figures D.1.17 and D.1.18 present the volumes of the effluent and influent for the typical and high concentration performance tests respectively. Note in Figure D.1.17 that the effluent volume for a number of the typical concentration tests were nearly the same as the influent. These were all for the *old* media tests and appear to be a laboratory accounting error of effluent beakers.

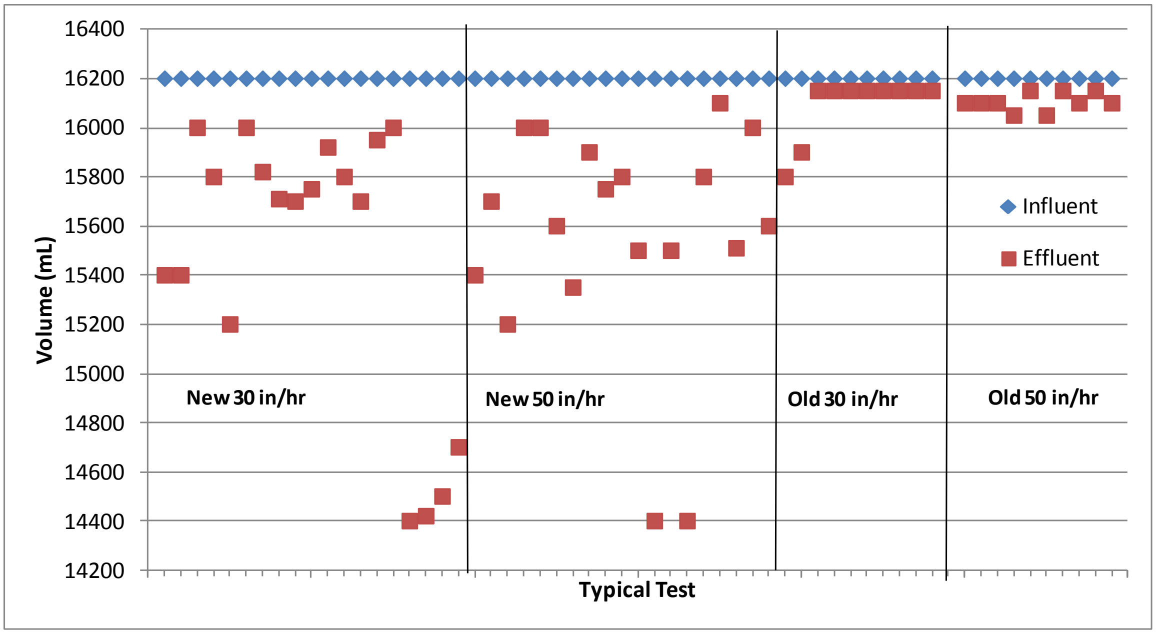

Figure D.1.17. Influent and effluent volumes for typical concentration tests. (Test 2 on *new* media columns "Hb" and "He" were excluded due to incorrect influent volumes.)

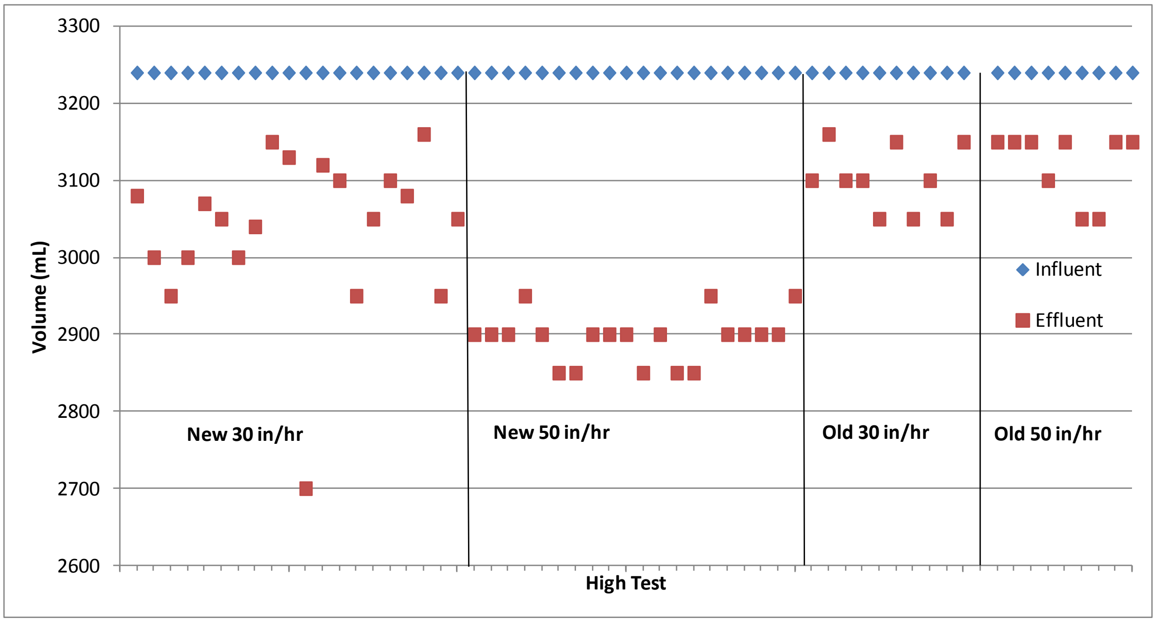

Figure D.1.18. Influent and effluent volumes for high concentration tests.

Table D.1.1 presents the results of the infiltration tests for the 16 *new* media columns and the eight *old* media columns used in Method #1. The values given are the average of the two tests after the initial wetting tests. All the infiltration tests were performed after completion of either the typical or high concentration performance tests. Column "Hi" for the *new* media was excluded from the previous figures with respect to removal efficiency due to the first test after the channelization prevention procedure completion having a greater effluent than influent concentration as previously noted. The typical concentration performance tests on Column 'Hi' had a significantly decreased volume of effluent in the final test out of the five, implying that some sort of compaction or other blocking mechanism occurred at this time.

Table D.1.1. Infiltration Test Results for Method #1

Column ID *New* Media	**Infiltration Rate (in/hr)**	**Performance Test for *New* Column**	**Column ID *Old* Media**	**Infiltration Rate (in/hr)**	**Performance Test for *Old* Column**
Ha	1369	Typical	Hq	1494	Typical
Hb	1039	Typical	Hr	1022	Typical
Hc	1432	High	Hs	1160	High
Hd	1130	High	Ht	909	High
He	1147	Typical	Hw	1872	High
Hf	1228	Typical	Hx	883	High
Hi*	56	Typical	Hy	1619	Typical
Hj	1043	Typical	Hz	1375	Typical
Hk	861	High			
Hl	1248	High			
Hm	1284	Typical			
Hn	1138	Typical			
Ho	1644	High			
Hp	1466	High			
Hu	1413	High			
Hv	1955	High			
Average	1220 ± 400* 1290 ± 270*			1290 ± 360	

*Column "Hi" was an outlier as explained in the preceding narrative and is included in the first average, but not the second.

2. Method #2 Results

Figures D.2.1 and D.2.2 presents the results for the Accelerated Aging Events applied to the *new* media columns for copper and zinc respectively. Note that Stage 1 and parts of Stage 2 (Stage 2+) represent aging events with variable influent concentrations that provide additional removal efficiency information based on influent concentrations. As previously mentioned, the first two columns that were sent to High Concentration Performance Testing did not return to the Accelerated Aging Event Sequence, thus initially the results are the average of six columns and then the average of the remaining four columns. The efficiencies of the columns have not appeared to decrease after the 112 aging events. Thus, it may be possible to present the data as removal efficiency versus concentration without the time component. This has been done for both copper and zinc in Figures D.2.3 and D.2.4, respectively as a percent concentration decrease, and for both copper and zinc in Figures D.2.5 and D.2.6, respectively as a percent metal retained in the columns on a mass basis. These figures exhibit the classical removal efficiency curves, with similar removals over wide ranges, but decreasing efficiency as the influent concentrations get very low. (For all Figures D.2.1-6, results for two of the individual columns for Events 13, 29 and 97 were omitted due to insignificant metals in the influent.)

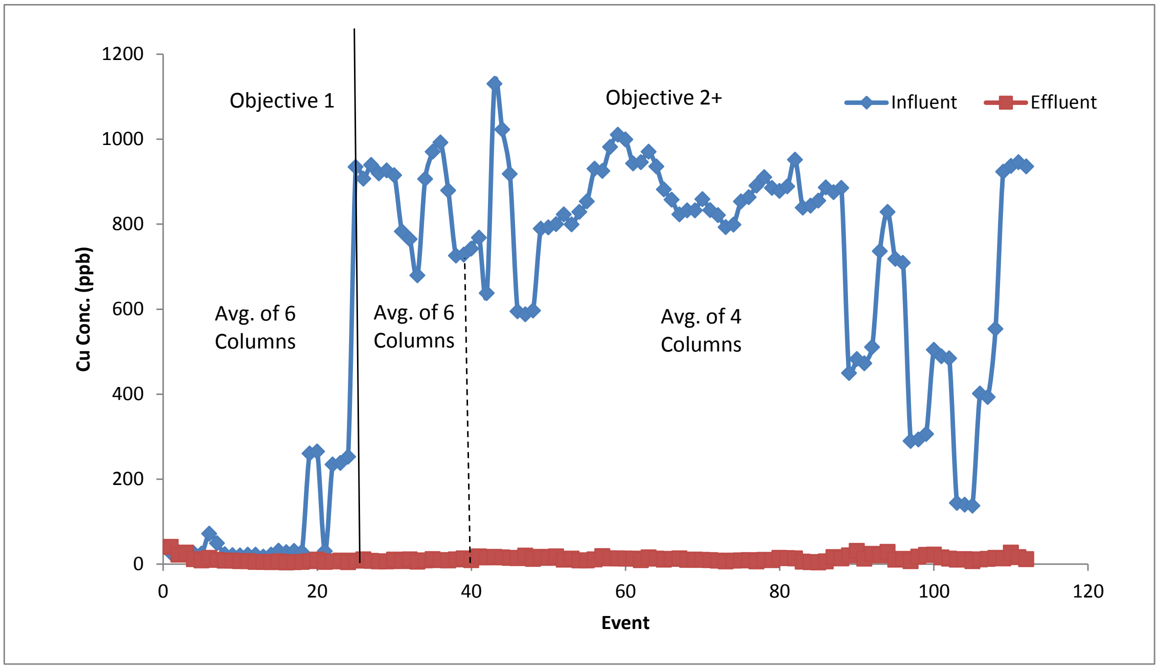

Figure D.2.1. Accelerated aging influent and effluent copper concentrations for *new* media columns averaged as noted using 0.77L of stormwater solution at a loading rate of 10 in/hr.

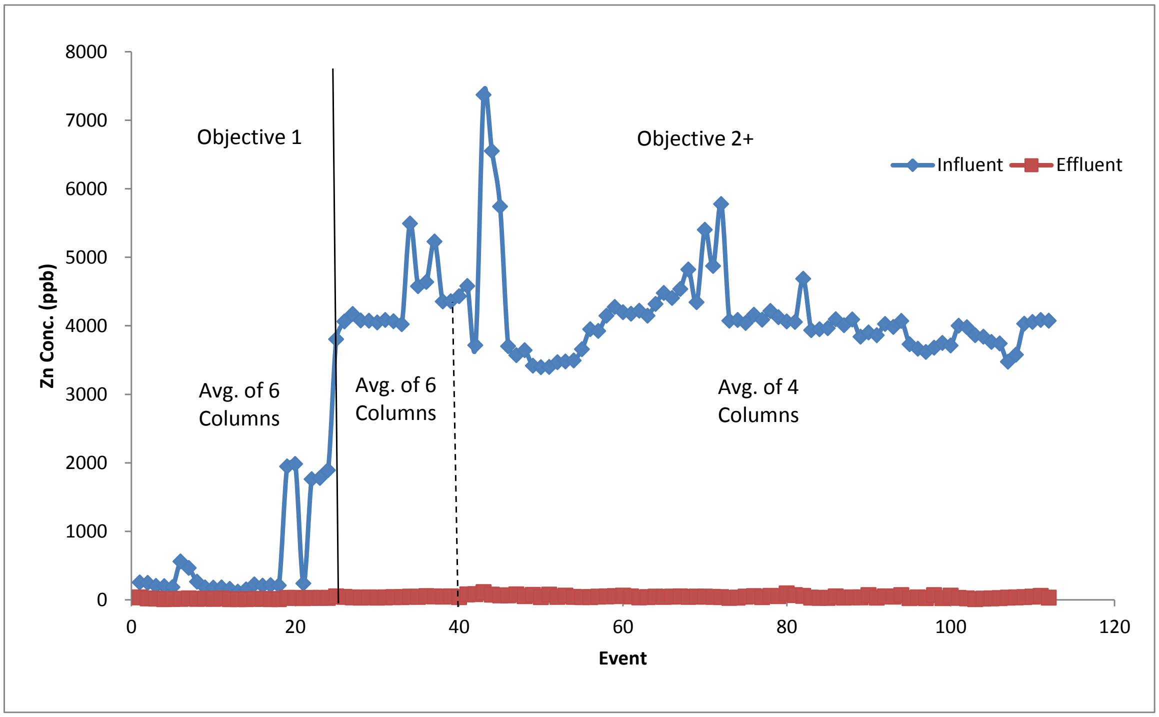

Figure D.2.2. Accelerated aging influent and effluent zinc concentrations for *new* media columns averaged as noted using 0.77L of stormwater solution at a loading rate of 10 in/hr.

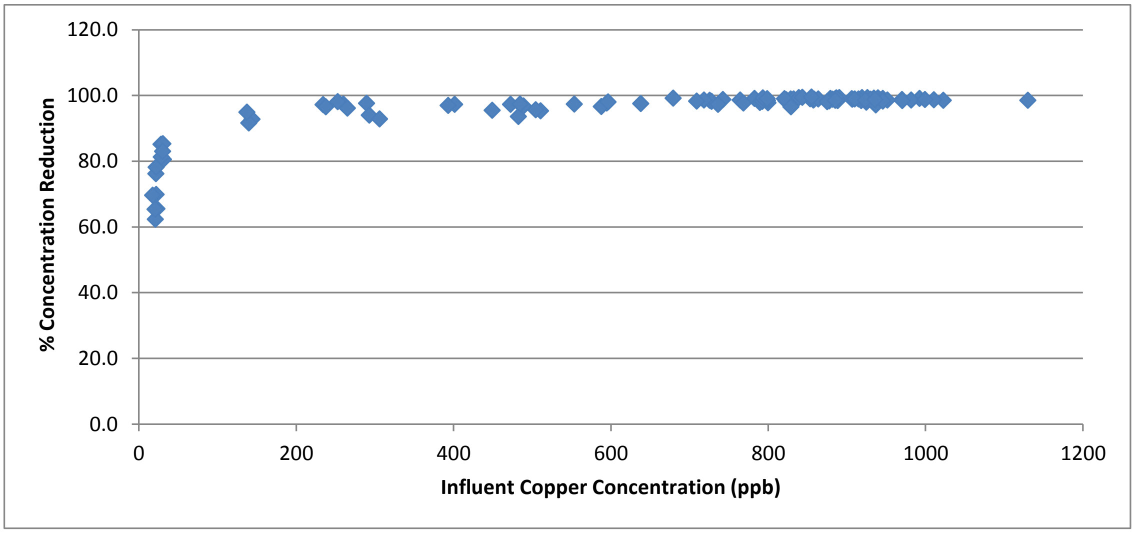

Figure D.2.3. Percent concentration reduction versus influent copper concentration averaged for the columns using 0.77L of solution and a loading rate of 10 in/hr during the aging events on *new* media columns.

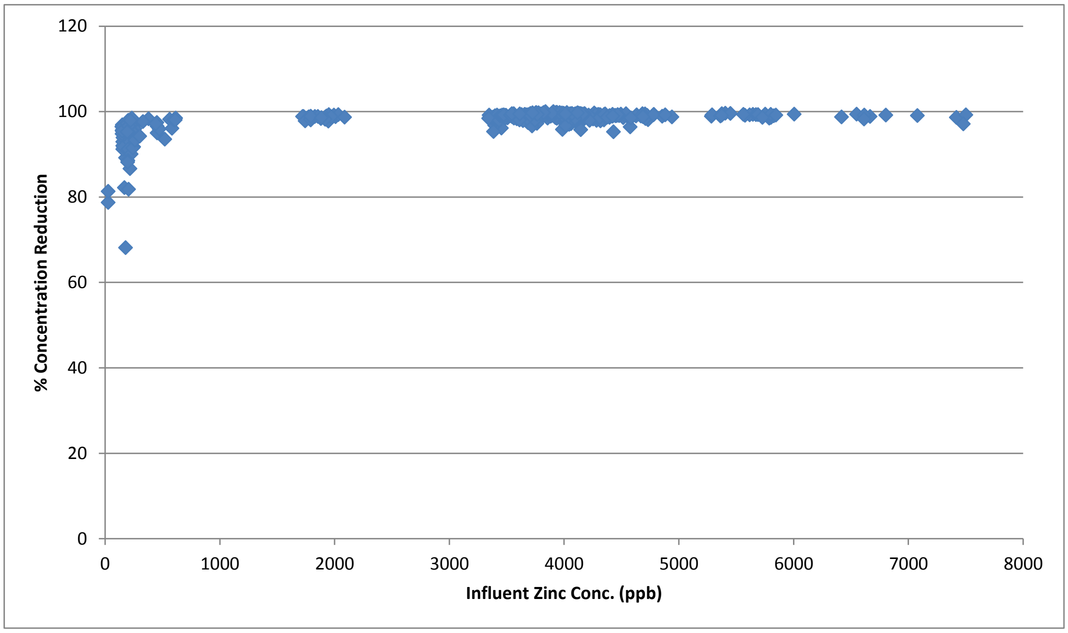

Figure D.2.4.Percent concentration reduction versus influent zinc concentration for individual columns using 0.77L of solution and a loading rate of 10 in/hr during the aging events on *new* media columns.

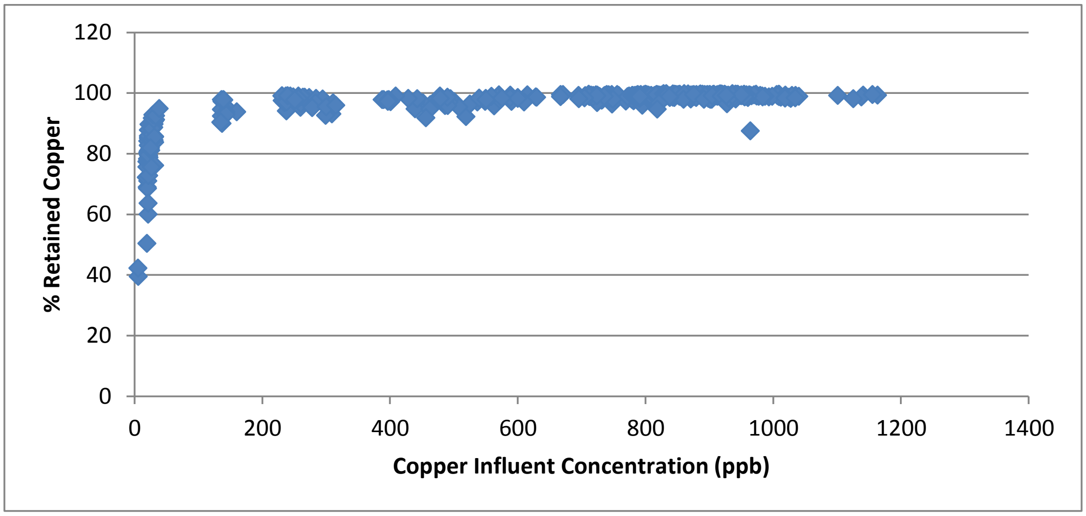

Figure D.2.5. Percent metal retained versus influent copper concentration for individual columns using 0.77L of solution and a loading rate of 10 in/hr during the aging events on *new* media columns.

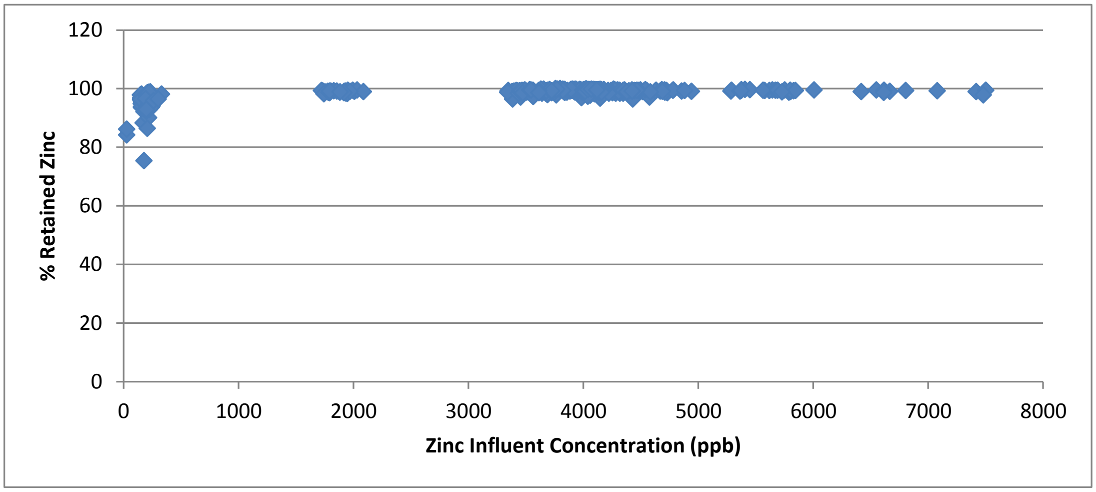

Figure D.2.6. Percent metal retained versus influent zinc concentration for individual columns using 0.77L of solution and a loading rate of 10 in/hr during the aging events on *new* media columns.

As previously mentioned, after 40, 60 and 80 aging events, pairs of columns were subjected to high concentration performance testing to evaluate the functionality of the media after the respective amount of accelerated aging. Figure D.2.7 and Figure D.2.8 presents the average results for these tests after each aging period for copper and zinc respectively. The results are presented as percent concentration decrease and exceed 89%

on average for the copper sets and 92% for zinc. Individual column results for both copper and zinc with respect to percent concentration reduction are also presented in Figure D.2.9. Percent concentration removal always exceeded 80%.

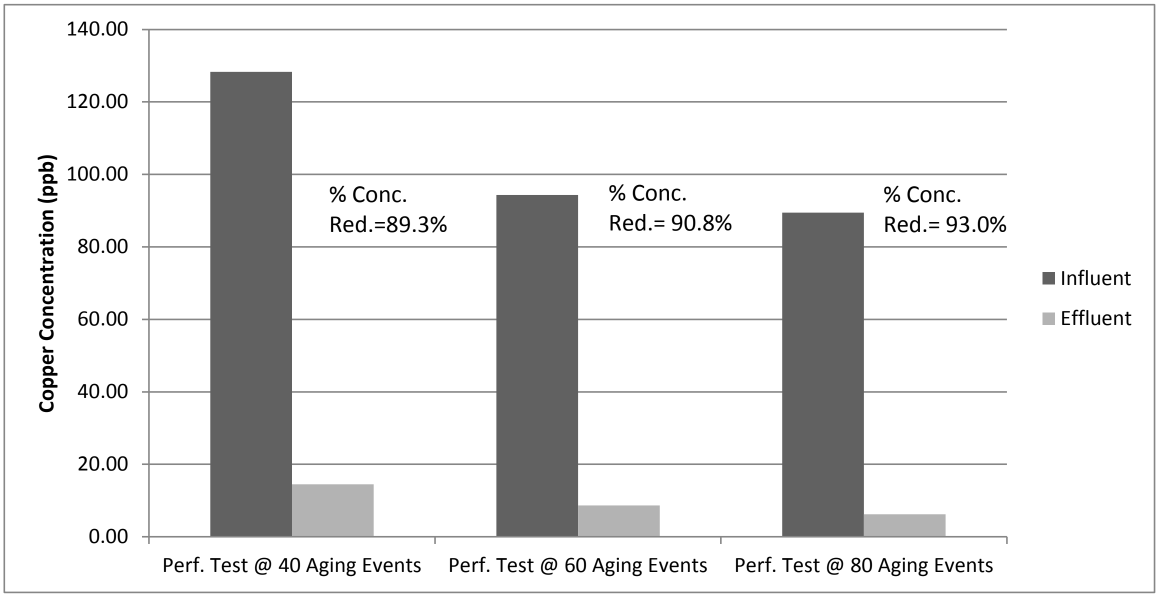

Figure D.2.7. Average high concentration performance test influent and effluent copper concentrations for two *new* media columns after the number of aging events as noted using 3.24L of stormwater solution and a loading rate of 30 in/hr.

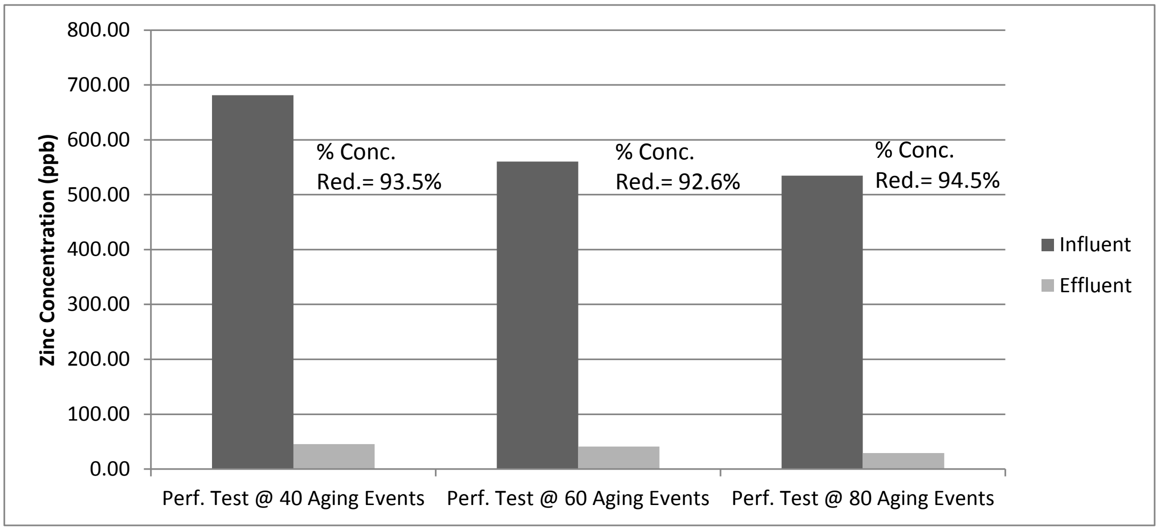

Figure D.2.8. Average high concentration performance test influent and effluent zinc concentrations for two *new* media columns after the number of aging events as noted using 3.24L of stormwater solution and a loading rate of 30 in/hr.

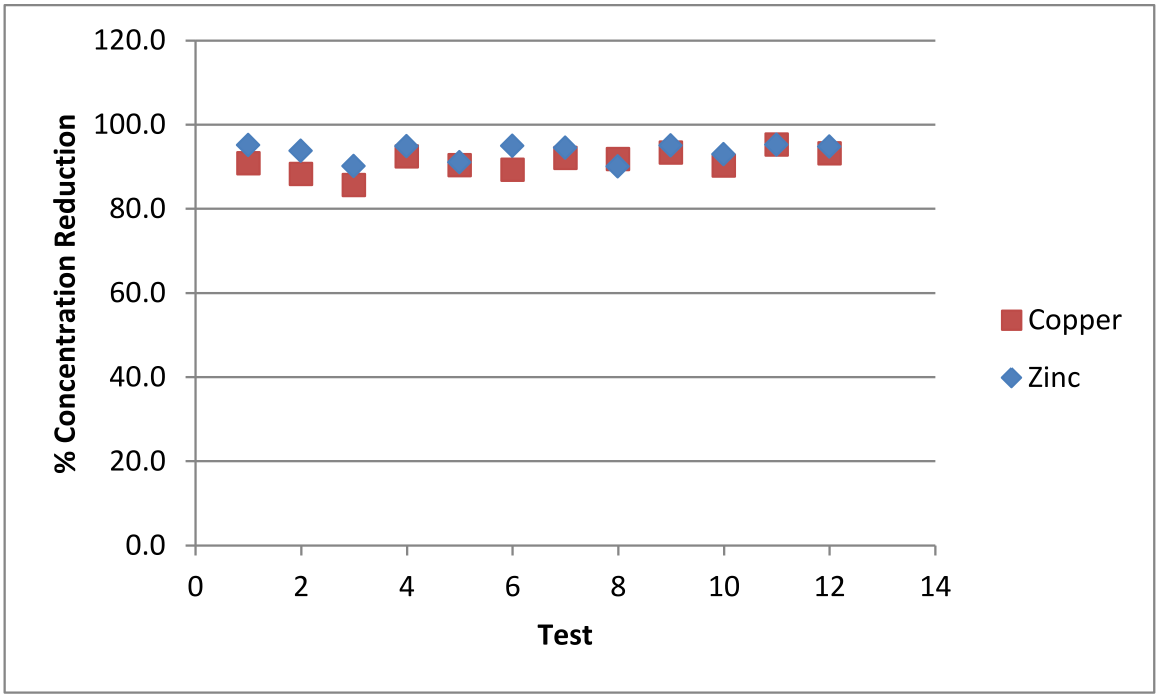

Figure D.2.9.High concentration performance percent concentration reduction for individual *new* media columns using 3.24L of solution and a loading rate of 30 in/hr. The high concentration performance tests can be grouped as 1-4 for columns after 40 aging events, 5-8 after 60 aging events and 9-12 after 80 aging events.

The influent and effluent volumes are used for calculating mass retained and also useful in understanding how much water might be retained in a MFD and subsequently removed by evaporation or very slowly drained. Figures D.2.10 and D.2.11 present the influent and effluent volumes for the accelerated aging events and the high concentration performance tests respectively. Note that in Figure D.2.10 the volumes are not provided for the first few aging events as effluent volumes were not recorded for them, and averages from subsequent events used for mass balance calculations. Approximately 180 to 280 mL were retained during each event or test. Variability was due to retained moisture from preceding events or tests, and the high concentration performance tests, with the much larger volumes of stormwater applied appeared to retain more, perhaps due to additional time for water absorption in the media (14 versus 10 minutes).

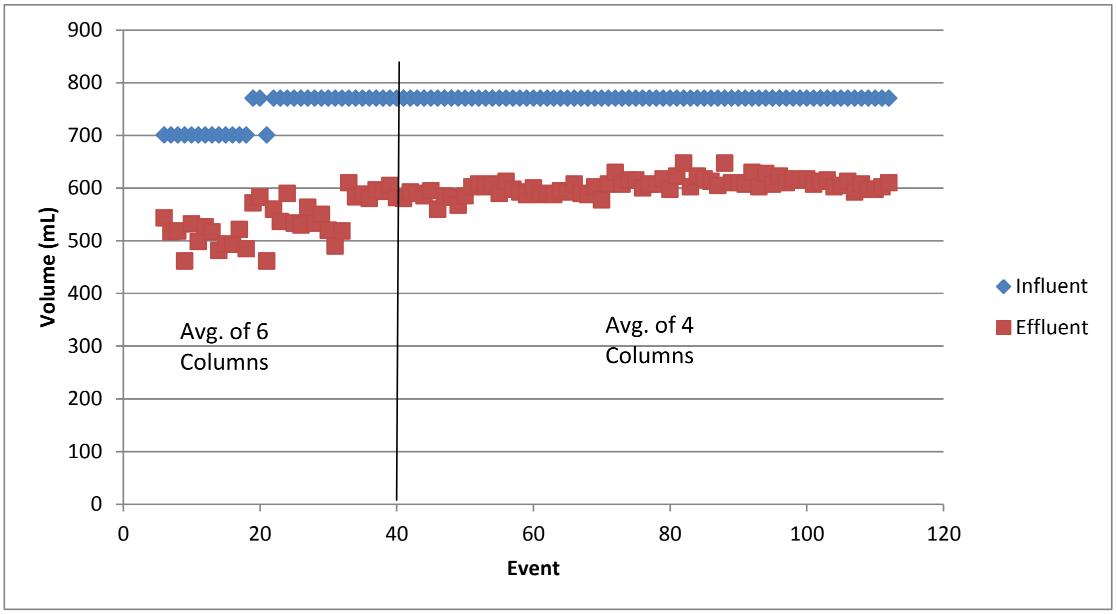

Figure D.2.10. Influent and effluent volumes averaged over columns as noted using a loading rate of 10 in/hr for accelerated aging events on the *new* media.

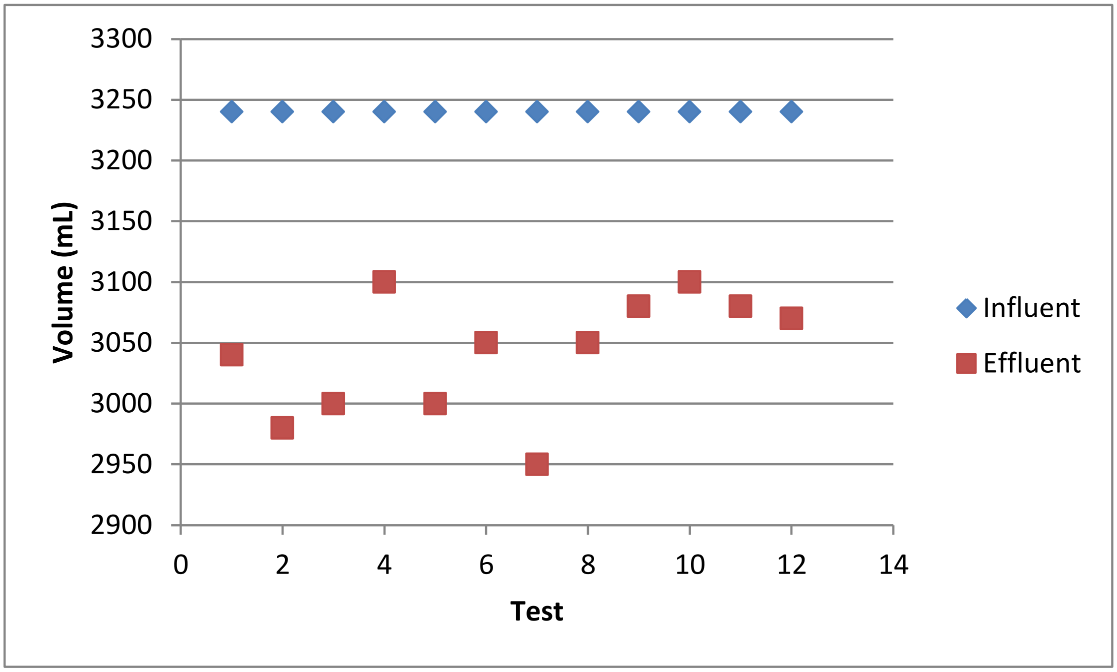

Figure D.2.11. High concentration performance test influent and effluent volumes for individual *new* media columns using a loading rate of 30 in/hr. The high concentration performance tests can be grouped as 1-4 for columns after 40 aging events, 5-8 after 60 aging events and 9-12 after 80 aging events.

6. Ancillary Test Results

This section summarizes results from ancillary tests. The pH of various influent and effluent samples was measured periodically throughout the research program. The pH values are presented in the following tables for all the methods. The pH measurements for the typical and high performance tests of Method #1 are in Tables D.6.1. The pH measurements for the accelerated aging events of Method #2 are in Table D.6.2. Finally the pH measurements for the high concentration performance tests for Method #2 are in Table D.6.3. Note that the average pH is based on the average hydrogen ion concentration.

Table D.6.1. pH Measurements on Select Influent and Effluent Samples for Various Performance Tests for Method #1

Method	Date	Media	Loading Rate	Metal Conc.	Sequence	Influent pH	Effluent pH
1	05/06/13	*New*	30 in/hr	Typical (low)	1	6.38	7.47
1	05/12/13	*New*	30 in/hr	Typical (low)	5	5.99	6.74
1	05/28/13	*New*	30 in/hr	High	1	6.91	6.09
1	06/03/13	*New*	30 in/hr	High	4	7.70	6.44
1	06/26/13	*New*	50 in/hr	Typical (low)	3	6.97	8.87
1	07/10/13	*New*	50 in/hr	High	1	5.45	7.85
1	07/17/13	*New*	50 in/hr	High	4	4.12	7.18
1	09/11/13	*Old*	30 in/hr	High	4	6.42	7.47
1	09/11/13	*Old*	50 in/hr	High	4	7.64	7.85
1	09/11/13	*Old*	30 in/hr	Typical (low)	4	7.15	6.74
1	09/11/13	*Old*	50 in/hr	Typical (low)	4	7.17	6.69

Table D.6.2. Select pH Measurements for Accelerated Aging Tests for Method#2

Method	Date	Event #	# of Columns	pH influent	pH effluent
2	11/15/12	6	6	-	6.84
2	11/26/12	10	6	-	6.87
2	12/12/12	17	6	-	6.94
2	12/18/12	19	6	5.28	6.70
2	01/04/13	24	6	4.65	6.75
2	01/09/13	26	6	-	6.94
2	01/16/13	29	6	-	6.57
2	01/23/13	32	6	-	6.83
2	01/30/13	35	6	-	6.73
2	02/04/13	37	6	5.48	6.35
2	02/11/13	40	6	5.86	6.95
2	02/18/13	43	4	5.63	6.94
2	02/25/13	46	4	5.72	6.88
2	03/04/13	49	4	5.84	6.97
2	03/13/13	53	4	5.45	6.92
2	03/18/13	55	4	5.26	7.00
2	03/25/13	58	4	5.71	7.03
2	04/08/13	62	2	5.55	6.81
2	04/08/13	64	2	5.83	6.88
2	04/15/13	65	2	5.75	6.94
2	04/15/13	67	2	6.01	6.98
2	04/22/13	68	2	5.72	6.82
2	04/22/13	70	2	5.68	6.94
2	04/29/13	71	2	5.83	7.07
2	04/29/13	73	2	5.84	7.13
2	05/06/13	74	2	5.88	7.03
2	05/06/13	76	2	5.82	6.88
2	05/12/13	77	2	5.57	7.08
2	05/12/13	79	2	5.38	6.94
2	05/20/13	80	2	6.64	6.28
2	05/28/13	83	4	7.93	6.71
2	06/03/13	86	4	7.27	6.43
2	06/12/13	90	4	7.55	6.09
2	06/19/13	93	4	7.30	7.04
2	06/26/13	96	4	6.36	7.70
2	07/03/13	99	4	6.19	7.53
2	07/10/13	102	4	6.55	7.58
2	07/17/13	105	4	6.17	7.58
2	07/31/13	111	4	6.39	7.37

Table D.6.3. pH Measurements on Select Influent and Effluent Samples for High Concentration Performance Tests for Method #2

Method	Sequence /Test/Site	Date	pH Influent	pH Effluent
2	2/1	04/01/13	3.93	6.44
2	3/2	05/20/13	6.86	6.29

E: CONCLUSIONS

1. ***New*** **Media Lifespan**

The accelerated aging experiments on the *new* media columns, combined with the intermittent high concentration performance tests, indicate that the *new* media may have expected lifespans of well beyond 15 years. (Note that the accelerated loading represents an annual precipitation of 40 in/yr with runon from 10 times the MFD area. In different regions, these ages could be adjusted with different annual rainfall and catchment area appropriately.) Field lifespans might also vary with the amount of pretreatment and pollutant sources for a particular application. Additional testing is required to more accurately determine the lifespans beyond the years already simulated.

2. ***New*** **Versus** ***Old*** **Media**

The results from Method #1 for both the *new* and the *old* media for the simulated large storm events with both typical and high influent concentrations of copper and zinc are mixed. However, both appear very effective at removal of these metals even under the high loading rates. Table E.4.1 provides a statistical summary of the results. Also included in Table E.4.1 are the results for the high concentration performance tests from Method #2 on the *new* media. Nearly identical high removal rates are experienced even after several years of simulated accelerated aging.

Table E.4.1. Mean Concentration Reduction Rates with Standard Deviations for all Performance Tests on *New* and *Old* Media Columns (Methods #1 and 2)

Method	Media	Conc.	Loading Rate (in/hr)	Aging (yrs)	Cu Avg. % Conc. Red.	Zn Avg. % Conc. Red.
1	*New*	Typical	30	0	62 ± 17	78 ± 17
1	*Old*	Typical	30	0	66 ± 13	90 ± 10
1	*New*	Typical	50	0	64 ± 8	84 ± 4
1	*Old*	Typical	50	0	56 ± 8	95 ± 0
1	*New*	High	30	0	90 ± 5	93 ± 6
1	*Old*	High	30	0	89 ± 4	99 ± 4
1	*New*	High	50	0	90 ± 7	95 ± 7
1	*Old*	High	50	0	40 ± 12*	96 ± 2
2	*New*	High	30	~3.4	89 ± 3	93 ± 2
2	*New*	High	30	~6.8	91 ± 1	93 ± 2
2	*New*	High	30	~10.5	93 ± 2	94 ± 1

*Experimental error is suspected in this, loading rate may have been higher than 50 in/hr on these tests.

F: RECOMMENDATIONS/APPLICATIONS/IMPLEMENTATION

Based on the results of this research, we recommend that WSDOT use either the *old* or the *new* media mix for MFDs depending on availability and favorable cost. After completion of this project, we propose that research continue.

For the Phase II project, it would be beneficial to continue the accelerated aging event sequences on the *new* media from Methods #2. We have retained several cylinders from this method, and it would be useful to continue these methodologies until significant breakthrough to understand the sorptive capacities of the *new* media. The *new* columns might also be split into two groups, one continuing the methods, and one with a variation between the zinc and copper split to compare for competition effects. After the media starts to lose its effectiveness, this Phase II project might also include further evaluation of a simple rehabilitation techniques. In addition, the Method #1 fast infiltration technique (50 in/hr) should be further refined to decrease variability, such as with an energy dissipater setup prior to infiltrating into a column for further evaluations at these levels.

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