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Biofilter Media Performance Updates for WinSLAMM

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Introduction

This memo describes the data and calculations that will be used to update the WinSLAMM biofilter performance calculations. The literature and on-line resources describe many biofilter (with underdrains) and bioinfiltration (usually without underdrains with most of the stormwater "treatment" associated with infiltration) performance studies. This memo cannot do a complete review of these data, as it focuses on specific information needed to model the various parts of the pollutant retention processes. I great overview of the performance of biofilters (and other stormwater controls) is the International BMP Database. Unfortunately, few of these studies include detailed data concerning the partitioning of the particulates and pollutants by particle size and by total and filtered forms. In addition, rate kinetics associated with contact times, clogging by particulates, and retention capacity of the media for the wide variety of pollutants of interest, is also needed for modeling. This information is needed when modeling the expected behavior of these systems that rely on a wide range of media for stormwater quality improvements. In addition, the selection of which media (and combinations) to meet desired treatment objectives is also elusive. Clark and Pitt (2012) wrote a summary on targeting treatment technologies (such as media selection) with specific objectives. The use of a comprehensive model that addresses these many issues enable comparisons of alternative biofilter designs.

These updates are building on the existing performance calculations by applying expanded data from laboratory and field research mostly conducted by Pitt's research group at the University of Alabama, by Dr. Shirley Clark's research group at Penn State – Harrisburg, and the Wisconsin DNR/USGS. These tests were conducted to provide the details needed for modeling the performance of biofilters, specifically focusing on methods to predict treatment flow rates through the media, particulate retention by particle sizes, and retention of filterable pollutants. These tests also addressed issues not routinely described in the biofilter performance literature, such as maintenance issues associated with particulate clogging and breakthrough of pollutants, failure due to excessive salt loadings on media having large amounts of fines, problems associated with compaction of the media, and leaching of material from the media. Most of the data supporting these model enhancements are associated with several studies:

- Clark's master thesis and dissertation research using laboratory and pilot-scale field testing of different media (Clark 1996 and 2000; Clark and Pitt 1996).

- Pitt and Clark's research for the Boeing Co to develop biofilter media mixtures suitable for a wide range of pollutants at an industrial site being restored to open space use (Pitt and Clark 2010).
- Sileshi's dissertation on soil and sand media for biofilter treatment flow rates, underdrain design, and retention of particulate sizes (Sileshi 2013).

In addition, several full-scale biofilter monitoring projects also contained useful information and data for this summary. The Wisconsin DNR and USGS have been monitoring test biofilters to compare the performance of various media mixtures (Bannerman, personal communication). The Kansas City Demonstration Project of Green Infrastructure in Areas served by Combined Sewer (Pitt, *et al.* 2014) included monitoring of many biofilters throughout a large area, and examined their benefit at a large scale. During dry well performance studies, Pitt and Talebi (2012) monitored changes in stormwater pollutant concentrations as it passed through underlying soils. Pitt, *et al.* (1999) also conducted monitoring at compost-amended test sites to determine the removal benefits of these soil mixtures.

The data and processes are separated into three groups (Master Tables 1 through 3): flow rates, particulate retention by particle size, and retention of filterable pollutants. Master Table 1 includes particle size information that can be used to calculate flow rates through different mixtures of soils, sands, and amendments. Master Table 2 lists some characteristics of these materials: percent organic matter (affects infiltrate rates), CEC (may affect retention of cations), % fines (affects SAR failures with snowmelt), P content (indicates leaching of P from media), saturated water content, field capacity, and permanent wilting point (all affect ET losses from media), and the infiltration rates measured for each of these components and mixtures. Table 2 also shows the maximum accumulation of sediment before clogging, the particulate retention by particle size performance category (refers to sets of equations), equations or categories for removal of small particles (0.45 to 3 um) to supplement some of the field tests that did not have adequate data for these small particles, and the effects of solids accumulation on the flow rate reductions with time. Master Table 3 shows the category for filterable pollutant retention, category for bacteria retention, the media capacity for the filterable pollutants, and the categories for the effects of contact time on the retention of filterable pollutants.

Treatment flow rates of biofilter media affect the design and performance of these stormwater controls. High treatment flow rates allow smaller sized facilities, but also provide reduced contact time of the stormwater with the media, reducing the chemically active treatment in the media. Low treatment flow rates allow longer contact times with the media and usually better treatment, but require larger facilities. Chemically active media also has specific capacities (typically based on ion-exchange or sorption processes). Small biofilter facilities with smaller amounts of chemically active media will require more frequent replacement. In addition, low treatment flow rates may result in extended standing water above the treatment media, leading to nuisance conditions. The capture of particulate-associated pollutants is not as dependent on the treatment flow rates. Rapid treatment flow rates with small facility surface areas (especially in areas having high sediment loads and lacking pre-treatment), can lead to pre-mature failure due to clogging/silting. The media treatment flow rates can be moderated using outlet controls and underdrains.

The steps in sizing a biofilter facility (and selecting the treatment media) can be summarized as follows:

1) Characterize the stormwater to be treated (critical pollutants needing removal along with constituents that affect maintenance), along with the expected runoff volume and flow rates for the drainage area.

2) Determine the required removals of the constituents of concern (concentrations and masses).

3) Identify the chemically active media to target these constituents (including necessary contact times and other factors affecting performance, such as anaerobic conditions and degradation of the media and leaching of constituents from the media).

4) Inventory other site characteristics potentially affecting biofilter facility (maximum area available, depth to groundwater and seasonal changes to the water table, underlying natural soil characteristics, snowmelt SAR problems, etc.).

5) Prepare preliminary designs addressing these factors (size of facility, selection of media, outlet controls/underdrains, and maintenance interval).

6) Evaluate alternative designs using long-term continuous stormwater quality model and evaluate life-cycle costs and other decision support factors.

This memo describes the data sources and summarizes the statistical tests that were conducted to develop the different categories. Example uses of these data are also presented. The body of the memo presents information referenced in the large tables used to calculate the various factors, while the appendices present background information, including selected statistical analyses used to develop the table information.

Master Table 1. Particle Size Characteristics of Biofilter Media Components and Mixtures

		particle size (um) smaller than % distribution												
		100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%	median	Cu
Soil	sand	1,000	700	480	320	215	140	100	70	47	31	0	140.0	6.94
	loamy sand	1,000	630	410	290	190	120	80	48	25	9	0	120.0	21.11
	sandy loam	1,000	530	300	150	82	40	14	3	1	0	0	40.0	820.00
	loam	1,000	400	140	60	25	12	5	3	1	1	0	12.0	50.00
	silt loam	1,000	100	26	13	8	4	3	2	1	1	0	4.0	13.33
	silt	1,000	15	12	9	6	4	3	2	2	1	0	4.3	5.45
	sandy clay loam	1,000	590	310	190	100	54	26	5	1	0	0	54.0	500.00
	clay loam	1,000	340	120	41	14	6	2	1	0	0	0	5.5	140.00
	silty clay loam	1,000	28	12	6	4	2	1	1	1	0	0	2.3	40.00
	sandy clay	1,000	510	300	140	78	35	1	1	1	1	0	35.0	78.00
	silty clay	1,000	20	8	4	2	1	1	0	0	0	0	1.2	24.44
	clay	1,000	110	12	2	0	0	0	0	0	0	0	0.1	80.00
Sand	fine Rhyolite sand	1,200	680	535	490	420	390	330	310	260	225	140	390	1.87
	fine sand	4,000	410	380	330	315	290	240	220	140	110	70	290	2.86
	filter sand	3,000	1,500	1,200	1,050	890	710	590	440	340	240	180	710	3.71
	coarse sand	3,200	3,000	2,500	2,350	2,200	2,000	1,800	1,600	1,500	1,300	100	2,000	1.69
	gravel	14,000	12,000	11,000	10,250	9,250	8,350	7,750	7,000	6,150	5,250	1,000	8,350	1.76
	light media for green roofs	7,000	6,000	5,500	5,125	4,625	4,175	3,875	3,500	3,075	2,625	500	4,175	1.76

Master Table 1. Particle Size Characteristics of Biofilter Media Components and Mixtures (continued)

		particle size (um) smaller than % distribution												
		100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	0%	median	Cu
Amendments**	activated carbon	4,850	3,150	2,900	2,650	2,400	2,150	1,775	1,575	1,160	965	350	2,150	2.49
	fine zeolite	1,300	1,150	1,000	900	810	740	650	590	460	325	200	740	2.49
	coarse zeolite	4,750	4,150	3,900	3,625	3,475	3,150	2,800	2,650	2,200	1,700	650	3,150	2.04
	compost	3,200	2,300	1,800	1,200	1,000	750	580	420	280	125	25	750	8.00
	peat moss	12,000	5,750	3,600	2,000	1,075	670	445	275	185	103	35	670	10.49
	PSM (enter values directly for specific material)**													
	biochar (highly variable; enter values directly for specific material)													
Tested Mixtures	R-SMZ	Rhyolite sand and surface modified zeolite (75/25)											560	2.07
	R-SMZ-GAC	Rhyolite sand, surface modified zeolite, and granular activated carbon (33/33/33)											850	2.09
	R-SMZ-GAC-PM	Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss (30/30/30/10)											850	2.20
Biofilter Media Mixtures***	Kansas City	50,000	15,000	9,000	5,400	3,300	2,000	1,000	530	310	90	10	2,000	40.00
	Wisconsin 1	5,000	2,000	1,100	630	500	400	310	225	135	95	60	400	6.00
	Wisconsin 2	5,000	2,400	1,500	1,150	800	600	440	335	250	130	60	600	5.00
	North Carolina	5,500	2,900	1,700	1,200	900	690	510	390	180	120	40	700	6.00

* if P high in soil, 0.25 mg/L filt P effluent

**PSM amendments (phosphorus sorption materials) are not included on above list of amendments; can be added by user for specific product (Lucas' spent alum, for example)

***Kansas City	30% planting soil; 20% organic compost; 50% sand ("Seattle" mix)
Wisconsin 1	Wisconsin USGS bio mix (85-88% sand, 3-5% pine bark, 8-12% silt and clay)
Wisconsin 2	Wisconsin Neenah mix (86% sand, 11% peat moss, and 3% Imbrium)
North Carolina	85 - 88% planting soil; 8 - 12% fines (silt and clay); 3 - 5% organic matter

Master Table 1b. Percent in Size Range

	Soil												Sand					
media size range (um)	sand	loamy sand	sandy loam	loam	silt loam	silt	sandy clay loam	clay loam	silty clay loam	sandy clay	silty clay	clay	fine Rhyolite sand	fine sand	filter sand	coarse sand	gravel	light media for green roofs
<3	0	0	30	30	40	40	25	43	53	42	63	72	0	0	0	0	0	0
3 - 12	4	10	8	20	29	40	9	15	27	5	20	8	0	0	0	0	0	0
13 - 30	6	12	10	8	12	12	8	7	11	1	9	3	0	0	0	0	0	0
31 - 60	16	13	7	12	7	3	9	8	2	7	2	3	0	1	0	0	0	0
61 - 150	26	20	15	12	5	2	14	10	1	17	2	6	0	21	0	1	0	0
151 - 300	18	18	10	6	4	1	14	5	1	8	2	3	28	33	15	1	0	0
301 - 1,000	30	27	20	12	3	2	21	12	5	20	2	5	68	37	52	4	0	3
1,001 - 2,000	0	0	0	0	0	0	0	0	0	0	0	0	4	4	28	44	3	3
2,001 - 3,000	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5	40	2	12
3,001 - 4,000	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	10	2	25
4,001 - 6,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	47
6,001 - 8,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26	10
>8,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	56	0
median	140	120	40	12	4	4	54	6	2	35	1	0	390	290	710	2,000	8,350	4,175
Cu	7	21	820	50	13	5	500	140	40	78	24	80	2	3	4	2	2	2

Master Table 1b. Percent in Size Range (cont.)

	Amendments					Biofilter Media Mixtures			
media size range (um)	granular activated carbon	fine zeolite	coarse zeolite	compost	peat	Kansas City media	Wisconsin 1 media	Wisconsin 2 media	North Carolina media
<3	0	0	0	0	0	0	0	0	0
3 - 12	0	0	0	0	0	1	0	0	0
13 - 30	0	0	0	0	1	2	0	0	0
31 - 60	0	0	0	1	2	4	0	0	4
61 - 150	0	0	0	10	12	8	22	13	12
151 - 300	1	6	0	9	17	4	17	11	7
301 - 1,000	9	74	3	40	28	21	40	39	40
1,001 - 2,000	36	20	12	25	10	10	11	22	19
2,001 - 3,000	36	0	29	12	5	5	3	7	8
3,001 - 4,000	13	0	40	3	7	8	3	4	2
4,001 - 6,000	5	0	16	0	9	8	4	4	8
6,001 - 8,000	0	0	0	0	2	6	0	0	0
>8,000	0	0	0	0	7	23	0	0	0
median	2,150	740	3,150	750	670	2,000	400	600	700
Cu	2.5	2.5	2	8	10.5	40	6	5	6

Master Table 2: Physical Characteristics, Flow Rates, and Retention of Stormwater Particulates by Biofilter Media Components and Mixtures

		% organic matter	CEC (meq/100 g)	% fines (silt and clay)	P content*	Saturation water content % (porosity)	Field capacity (%)	Permanent Wilting Point (%)	Infiltration Rate (in/hr)	max. accum of sediment before clogging (kg/m2); average for mixtures	particulate retention by part. size (category); interpolate by median size	removal of small particles (category)	effects of solids accum. on flow rate reduc. (category)
Soil	sand	1	2.5	2.5	low	38	8	2.5	13	10	fine	y = 1.65x for 0.45 to 3 um	granular
	loamy sand	5	5	5	high	39	13.5	4.5	2.5	10	fine	y = 1.65x for 0.45 to 3 um	granular
	sandy loam	10	8	25	high	40	19.5	6.5	1	10	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	loam	15	12	17	high	43	34	14	0.15	10	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	silt loam	10	12	15	high	43	34	14	0.15	10	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	silt	10	15	5	high	42	30	12	0.3	5	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	sandy clay loam	10	15	25	high	42	26.5	10.5	0.5	5	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	clay loam	10	20	32	high	50	34.5	17	0.1	5	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	silty clay loam	10	20	33	high	50	34.5	17	0.1	5	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	sandy clay	5	25	41	low	40	34	17	0.05	5	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	silty clay	2	30	47	low	55	33.5	18	0.015	5	WI media 2	y = 1.65x for 0.45 to 3 um	granular
	clay	1	30	66	low	55	33.5	18	0.015	5	WI media 2	y = 1.65x for 0.45 to 3 um	granular
Sand	fine Rhyolite sand	0.3	2.5	0	low	38	8	2.5	13	35	Boeing Rhyolite	Boeing Rhyolite	granular
	fine sand	0	2.5	0	low	38	8	2.5	13	10	fine	y = 1.65x for 0.45 to 3 um	granular
	filter sand	0	2.5	0	low	38	8	2.5	13	20	Boeing site filter sand	Boeing site filter sand	granular
	coarse sand	0	1	0	low	32	4	0	40	35	intermediate	y = 1.65x for 0.45 to 3 um	granular
	gravel	0	1	0	low	32	4	0	40	very large (settle)	coarse	y = 1.65x for 0.45 to 3 um	granular
	light media for green roofs	0	1	0	low	50	20	5	13	very large (settle)	coarse	y = 1.65x for 0.45 to 3 um	granular

Master Table 2: Physical Characteristics, Flow Rates, and Retention of Stormwater Particulates by Biofilter Media Components and Mixtures (continued)

		% organic matter	CEC (meq/100 g)	% fines (silt and clay)	P content*	Saturation water content % (porosity)	Field capacity (%)	Permanent Wilting Point (%)	Infiltration Rate (in/hr)	max. accum of sediment before clogging (kg/m2); average for mixtures	particulate retention by part. size (category); interpolate by median size	removal of small particles (category)	effects of solids accum. on flow rate reduc. (category)
Amendments**	activated carbon	0	6	0	low	32	4	0	40	38	Boeing GAC	Boeing GAC	granular
	fine zeolite	0	7	0	low	32	4	0	40	28	Boeing SMZ	Boeing SMZ	granular
	coarse zeolite	0	7	0	low	32	4	0	40	17	Boeing site Zeolite	Boeing site Zeolite	granular
	compost	35	18	0	very high	61	55	5	3	20	intermediate	y = 1.65x for 0.45 to 3 um	compost-sand
	peat moss	35	22	0	low	78	59	5	use peat/sand equations	20	Boeing peat	Boeing peat	granular
	PSM (enter values directly for specific material)**												
	biochar (highly variable; enter values directly for specific material)												
Tested Mixtures	R-SMZ	0	5	0	low	43	4	0	25	38	Boeing R-SMZ	Boeing R-SMZ	granular
	R-SMZ-GAC	0	5	0	low	41	4	0	25	53	Boeing R-SMZ-GAC	Boeing R-SMZ-GAC	granular
	R-SMZ-GAC-PM	5	8	0	low	43	10	0.5	25	55	Boeing R-SMZ-GAC-PM	Boeing R-SMZ-GAC-PM	granular
Biofilter Media Mixtures	Kansas City	15	10	41	very high	40	12	10	0.55 (hand compaction)	15	KC biofilter	KC biofilter	granular
	Wisconsin 1	4	10	10	low	40	10	5	25.1 (hand compaction)	35	fine	y = 1.65x for 0.45 to 3 um	granular
	Wisconsin 2	11	10	0	low	40	10	5	20.5 (hand compaction)	35	WI media 2	WI media 2	granular
	North Carolina	1.5	9	10	low	40	7	5	18.7 (hand compaction)	35	intermediate	y = 1.65x for 0.45 to 3 um	granular

Master Table 3. Retention of Filterable Pollutants by Biofilter Media Components and Mixtures

		Filterable pollutant retention	Bacteria retention	media capacity	contact time effects
Soil	sand	Millburn NJ	Clark dissert sand	Clark dissert sand	Boeing R-sand
	loamy sand	Millburn NJ	Clark dissert sand	Clark dissert sand	Boeing R-sand
	sandy loam	Millburn NJ	Clark dissert sand	Clark dissert sand	Boeing R-sand
	loam	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	silt loam	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	silt	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	sandy clay loam	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	clay loam	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	silty clay loam	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	sandy clay	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	silty clay	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
	clay	Millburn NJ	Clark dissert loam	Clark dissert sand	Boeing R-sand
Sand	fine Rhyolite sand	Boeing R-sand	Clark dissert sand	Boeing R-sand	Boeing R-sand
	fine sand	Boeing site sand	Clark dissert sand	Boeing site sand	Boeing R-sand
	filter sand	Boeing site sand	Clark dissert sand	Boeing site sand	Boeing R-sand
	coarse sand	Boeing site sand	Clark dissert sand	Boeing site sand	Boeing R-sand
	gravel	no removal	no removal	no removal	no removal
	light media for green roofs	no removal	no removal	no removal	no removal

Master Table 3. Retention of Filterable Pollutants by Biofilter Media Components and Mixtures (continued)

		Filterable pollutant retention	Bacteria retention	media capacity	contact time effects
Amendments**	activated carbon	Boeing GAC	no removal	Boeing GAC	Boeing GAC
	fine zeolite	Boeing SMZ	Clark dissert zeolite-sand	Boeing SMZ	Boeing SMZ
	coarse zeolite	Boeing site zeolite	no removal	Boeing site zeolite	Boeing site zeolite
	compost	Clark dissert compost-sand and EPA compost report/BMP Database for P increases	Clark dissert compost-sand	Clark dissert compost-sand	Clark dissert compost-sand
	peat moss	Boeing PM	Clark dissert peat-sand	Boeing PM	Boeing PM
	PSM (enter values directly for specific material)**	direct entry			
	biochar (highly variable; enter values directly for specific material)	direct entry for filt P			
Tested Mixtures	R-SMZ	Boeing R-SMZ	Clark dissert sand	Boeing R-SMZ	calculate based on components
	R-SMZ-GAC	Boeing R-SMZ-GAC	Clark dissert sand	Boeing R-SMZ-GAC	calculate based on components
	R-SMZ-GAC-PM	Boeing R-SMZ-GAC-PM	Clark dissert sand	Boeing R-SMZ-GAC-PM	calculate based on components
Biofilter Media Mixtures	Kansas City	WI media 2 and 0.25 mg/L filt P effluent	Clark dissert loam	massive if suitable design	long enough
	Wisconsin 1	WI media 2 and 0.25 mg/L filt P effluent	Clark dissert sand	massive if suitable design	long enough
	Wisconsin 2	WI media 2	Clark dissert sand	massive if suitable design	long enough
	North Carolina	WI media 2 and 0.25 mg/L filt P effluent	Clark dissert loam	massive if suitable design	long enough

1) Treatment Flow Rates for Biofilter Media Components and Mixtures

Biofilter media treatment flow rate measurements were obtained from laboratory and field measurements. As part of his dissertation research, Sileshi (2013) conducted a large number of laboratory column tests examining treatment flow rates for various mixtures of stormwater biofilter media. These tests and data are described in his dissertation, available at: http://unix.eng.ua.edu/~rpitt/Publications/11_Theses_and_Dissertations/Redi_dissertation.pdf (and Sileshi, *et al.* 2014a, 2014b, 2017, and 2018. This memo summarizes these data and presents some additional statistical analyses to assist in the selection of treatment media having targeted treatment flow rates, and to evaluate monitoring data from existing biofilter facilities. Sileshi (2013) found that the biofilter media treatment flow rates were mostly affected by the median particle size (D50) and uniformity coefficient (D60/D10) of the media, and the amount of organic matter. As expected, larger particles with small uniformity coefficients had the largest treatment flow rates. Compaction had minor effects if the organic matter content was low, but had significant effects on the flow rates for high organic matter content. The master table includes the actual typical treatment flow rates, with no references to various categories for other information, except for the peat/sand equations. The following presents the equations used to calculate the treatment flow rates for mixtures of media that are not included on this table, based on their calculated median particle size (D50) and uniformity coefficient (Cu) for different amounts of organic matter and compaction.

Summary of Statistical Analyses of Treatment Flow Rates of Biofilter Media

Appendix A1 lists the characteristics of the media that were tested in the laboratory column tests by Sileshi (2013). The 22 test mixtures (including four Tuscaloosa area soils and three biofilter media mixtures from biofilter facilities) were prepared to cover the typical range of biofilter media characteristics: the median sizes ranged from 270 to 1,900 micrometers and the uniformity coefficients ranges from 1.3 to 39. The organic matter content ranged from a low of 1.5 to a high of about 50%. Each test was conducted in triplicate and the resulting saturated flows in the columns are shown, along with their coefficients of variation for three levels of compaction. About 200 column tests were conducted to obtain these data. The test methods, detailed chemical and physical analyses and other supporting information are all described by Sileshi (2013).

Appendix A2 presents the statistical analyses of these data, building on the factorial test results and preliminary analyses presented by Sileshi (2013). The following lists the resulting significant regression equations developed to calculate the expected saturated flows (Fc, cm/hr) in log10 space, based on the D50 (micrometers) and Cu values. These equations are divided by organic matter content (low is <10% organic matter and high is >10%) and level of compaction. It is expected that the lowest level of compaction is most commonly used for biofilter facilities, but field monitoring has identified situations having high compaction levels. Compaction (listed below as hand compaction, the lowest level of compaction, proctor compaction, and modified proctor compaction, the highest level of compaction normally available) is most important for media mixtures having high organic matter content.

Low Organic Matter Content (<10% OM):

- hand $\log Fc = -1.72\text{X}10^{-6}(D50)^2 + 0.00410(Cu)^2 + 0.00469(D50) - 0.162(Cu)$
- proctor $\log Fc = -1.291\ \text{X}10^{-6}(D50)^2 + 0.00356(Cu)^2 + 0.00407(D50) - 0.175(Cu)$
- modified proctor $\log Fc = 0.00162(D50) - 0.0590(Cu)$

High Organic Matter Content (>10% OM):

- hand log Fc = 1.84 + 0.000522 (D50) - 0.0648(Cu)
- proctor log Fc = 1.31 + 0.000683(D50) - 0.0594(Cu)
- modified proctor log Fc = 1.28 + 0.000640(D50) - 0.070(Cu)

The calculated log Fc values need to be transformed to obtain the cm/sec values by raising 10 to these powers. Appendix A2 contains full regression analyses and analyses of variance indicating the significance of the equation terms. The regression behaviors are all reasonable and all coefficients and equations are significant, with the exception of the squared Cu and Cu terms in the low organic matter low compaction equation which have marginally significant p values at the 0.08 and 0.09 levels, compared to the other coefficients that have significant p values <0.05.

Flow Rates for Sand/Peat Biofilter Mixtures

Sileshi (2013) also conducted many tests examining the treatment flow rate for sand mixtures having varying amounts of peat. In all cases, the peat should not exceed 50% of the mixture to prevent compaction and subsequent failure. The following sets of equations are for peat mixed with fine to coarse sand (<2,000 µm D50), or poorly graded sand (Cu>10), and for very coarse sand (>5,000 µm D50), for three levels of compaction. In most cases, biofilters would have minimal compaction of the media. For median sand sizes between 2,000 and 5,000 µm, interpolate between the two equations for the appropriate compaction. Appendix B presents the data from Sileshi (2013) and the plots and regressions for this information.

Sand and Peat mixture equations:
x is fraction of peat (not percentage)
y is infiltration rate (Fc), in/hr

Fine and poorly graded sand plus peat mixtures (<2,000 µm median size, or Cu >10):

- minimal to normal compaction (hand compaction): $y=108x^2 - 28.9x + 7.73$
- moderate compaction (standard compaction): $y=14.4x^2 + 0.50x + 3.21$
- severe compaction (modified proctor compaction): $y=6.0x^2 +1.23x + 2.42$

Table 1. Examples:

	infiltration rate (Fc), in/hr		
amount of peat in mixture (fraction of total)	0.1	0.25	0.5
minimal to normal compaction (hand compaction)	5.9	7.3	20
moderate compaction (standard compaction)	3.4	4.2	7.1
severe compaction (modified proctor compaction)	2.6	3.1	4.5

Very coarse sand plus peat mixtures (>5,000 µm median size):

- minimal to normal compaction (hand compaction): $y=-780x^2 - 314x + 444$
- moderate compaction (standard compaction): $y=113x^2 - 933x + 488$
- severe compaction (modified proctor compaction): $y=3263x^2 -2835x + 645$

Table 2. Examples:

	infiltration rate (Fc), in/hr		
amount of peat in mixture (fraction of total)	0.1	0.25	0.5
minimal to normal compaction (hand compaction)	405	317	92.3
moderate compaction (standard compaction)	396	262	50.0
severe compaction (modified proctor compaction)	394	140	43.0

Biofilter Media Mixture Treatment Flow Rate Tests

Pitt and Clark (2010) conducted a series of tests while developing treatment media for an industrial site in Southern California. Table 3 shows the results of extensive column tests using stormwater for these components and candidate mixtures. Detailed study descriptions and results are available at: http://unix.eng.ua.edu/~rpitt/Publications/5_Stormwater_Treatment/Media_for_stormwater_treatment/media%20report%20SSFL%20May%2010%202010.pdf

Table 3. Treatment Flow Rates for Media and Mixtures for Santa Susana Field Laboratory Biofilter Media Development

Media, ranked by clogging potential	**Typical flow rate**		
	m/day	**gal/min/ft^2**	**in/hr**
Granular Activated Carbon (GAC) (50/50 with sand)	15	0.035	25
Peat moss (50/50 with sand)	15	0.035	25
Rhyolite sand	15	0.035	25
Site sand	5	0.012	8.3
Site zeolite (50/50 with sand)	15	0.035	25
Surface modified zeolite (SMZ) (50/50 with sand)	13	0.03	21. 5
Rhyolite sand and surface modified zeolite	15	0.035	25
Rhyolite sand, surface modified zeolite, and granular activated carbon	15	0.035	25
Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss	15	0.035	25

Outlet Controls and Underdrain Spacing

Sileshi (2013) also examined the use of underdrains for flow control in biofilters. Underdrains are used in biofilters to decrease the standing water duration to prevent nuisance conditions from developing, and for consistent flow control. Some regulations restrict standing water to less than 24 hrs, for example. However, if an underdrain is used (and if not needed to meet this standing water criterion), short-circuiting of the infiltration will occur with substantial decreases in runoff volume reduction performance. Therefore, underdrains should be evaluated using continuous WinSLAMM model analyses to produce production functions to help determine the need for underdrains and associated performance effects.

The depth of the drains below the ground surface determines the hydraulic head (*h*) of the water, driving flow to the drains (assuming saturated overlying soil), while the distance between the drains and the restrictive layer determine the cross-sectional area that is available for water flow. Hydraulic conductivity of the soil is an essential and invariably used parameter in all drain spacing equations (Raju, *et al.* 2012). The Hooghoudt (1940) equation can be used to determine the underdrain design attributes to meet specific ponding time criterion. Important soil properties needed to use the Hooghoudt equation include the saturated hydraulic conductivity (K_s) and the depth to a restrictive layer (d_e).

The Hooghoudt equation is expressed as (refer to Figure 1 for a schematic of the parameters):

$$s = \sqrt{\frac{4.k_s(m^2 + 2.d_e.m)}{{}^{q}/_{24}}}$$

Where:

s spacing between drains (ft)

q amount of water that the underdrain carries away (in/day),

K_s average saturated hydraulic conductivity of the facility media (in/hr),

d_e effective depth (ft) (the height of the underdrain above the biofilter bottom),

m depth of water, or head, created over the pipes (ft), in the drainage layer (to bottom of media layer) (Irrigation Association 2000).

A conversion factor of 24 is used to convert hours to days. The values for the effective depth are determined from various figures and tables. The equation above is used to compute the drain spacing.

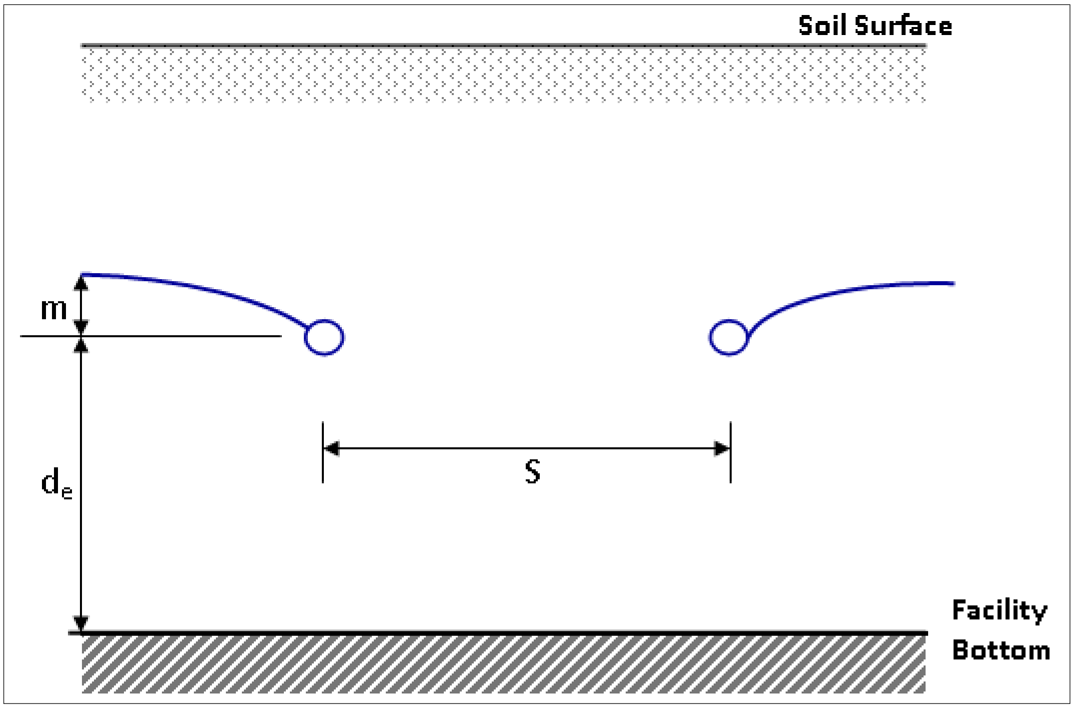


Figure 1. Scheme of Hooghoudt Equation

The value of *q* is determined by the amount of water that the underdrain must carry away in 24 hours (or whatever other time criterion is used). The water removal rate, *q* (inches per day) is commonly called the drainage coefficient. For subsurface drainage systems, drainage coefficients are usually expressed as a depth of water removed per 24 hr over the drained area (in/day or mm/day), and for surface drainage systems, as a rate of flow per unit area drained. The drainage rate of a drainage system is affected by the soil properties, water table depth, depth of the drains, and the spacing between drains.

The hydraulic conductivity (Ks) of the media depends on the grain size and the type and amount of water (including entrapped air) present in the media matrix. Sandy materials have larger pores, a lower water holding capacity and a higher hydraulic conductivity, diffusivity and infiltration rate compared to clayey-sized materials, which have smaller micropores. Saturated hydraulic conductivity, Ks, describes water movement through saturated media. It has units with dimensions of length per time (m/s, cm/s, ft/day, in/hr). Table 4 shows saturated hydraulic conductivity of sand for different grain sizes.

Table 4. Saturated Hydraulic Conductivity (in/hr) of Different Grain Size Sand (US EPA 1986)

	Degree of Sorting		
Grain size class	Poor	Moderate	Well
medium sand	33.5	40	47
medium to coarse sand	37	47	-
medium to very coarse sand	42	49-56	-
coarse sand	40	54	67
coarse sand to very coarse sand	47	67	-
very coarse sand	54	74	94

*A hyphen indicates that no data are available

For a sand to be classified as well graded, $C_u \leq 6$ and $1 < C_c < 3$, where C_u and C_c are the coefficient of uniformity and coefficient of curvature respectively and were calculated using the following equations:

$$C_u = \frac{D_{60}}{D_{10}}$$

$$C_c = \frac{{D_{30}}^2}{D_{10}D_{60}}$$

where D_{60} is the grain diameter at 60% passing, D_{10} is the grain diameter at 10% passing, and D_{30} is the grain diameter at 30% passing. Table 4 indicates that the saturated hydraulic conductivity of medium to very coarse sized sand ranges from 33 to 94 in/hr. Washed concrete sand with everything passing the #10 sieve (2 mm) and no more than 10% passing the #40 sieve (0.42 mm) is a suitable drainage layer material.

Sileshi (2013) provided design guidance to determine the number of restricted flow SmartDrains required for different biofilter areas ranging from 100 to 10,000 ft^2 and with saturated conductivities (K_s) of the drainage layer material ranging from 30 to 100 in/hr (recommend K_s ranges for filter sand used in SmartDrain™ field application). Typical K_s values for conventional underdrains range from 10 to 500 in/hr. The biofilter facility examined for these calculations has a 2 ft engineered soil layer, 1 ft medium to coarse sand drainage layer, and a maximum ponding depth of 1.5 ft, as shown in Figure 2. The porosity of the engineered media and drainage layers are 0.44 and 0.3, respectively.

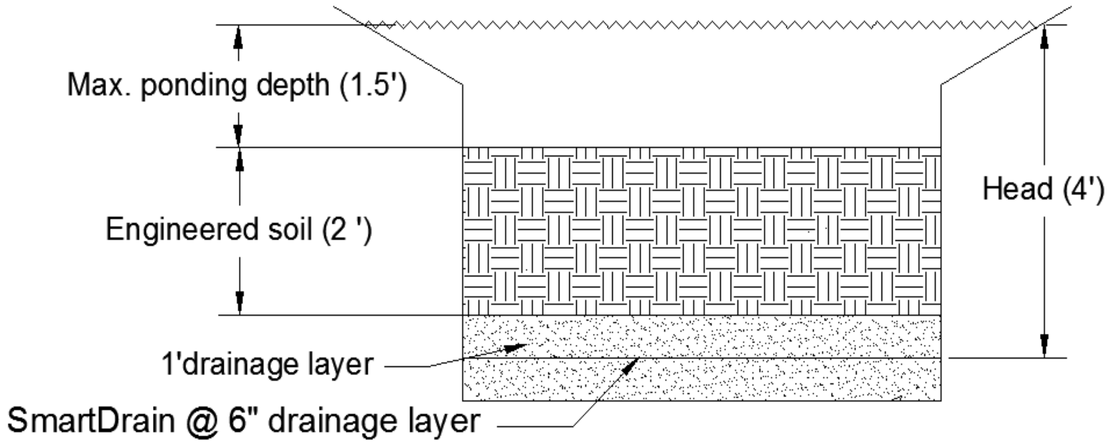
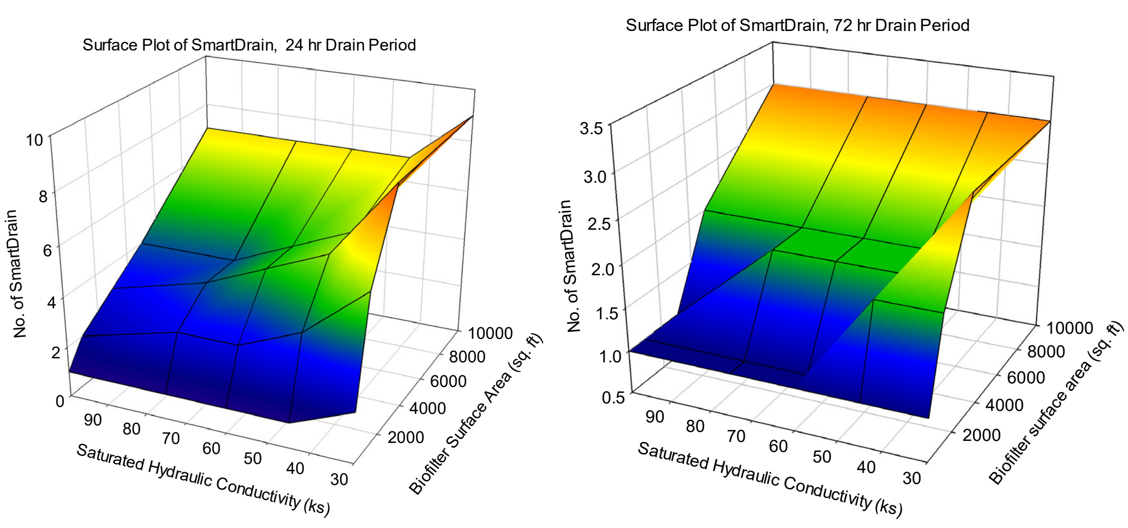


Figure 2. Cross-Section of a Typical Biofilter Facility

Figure 3 shows three dimensional plots of the required number of SmartDrains or conventional underdrains required for different biofilter sizes and saturated hydraulic conductivities. For low values of hydraulic conductivities of the media, the number of SmartDrains or conventional underdrains required in the field increases, as expected. These plots consider the number of underdrains needed for the basic infiltration rates of the devices, ensuring that the underdrains can carry away the infiltration water within the 24 or 72 hour time periods, and the spacing of the underdrains to insure that the water can reach the underdrains within the stated time, as shown in the basic equations.



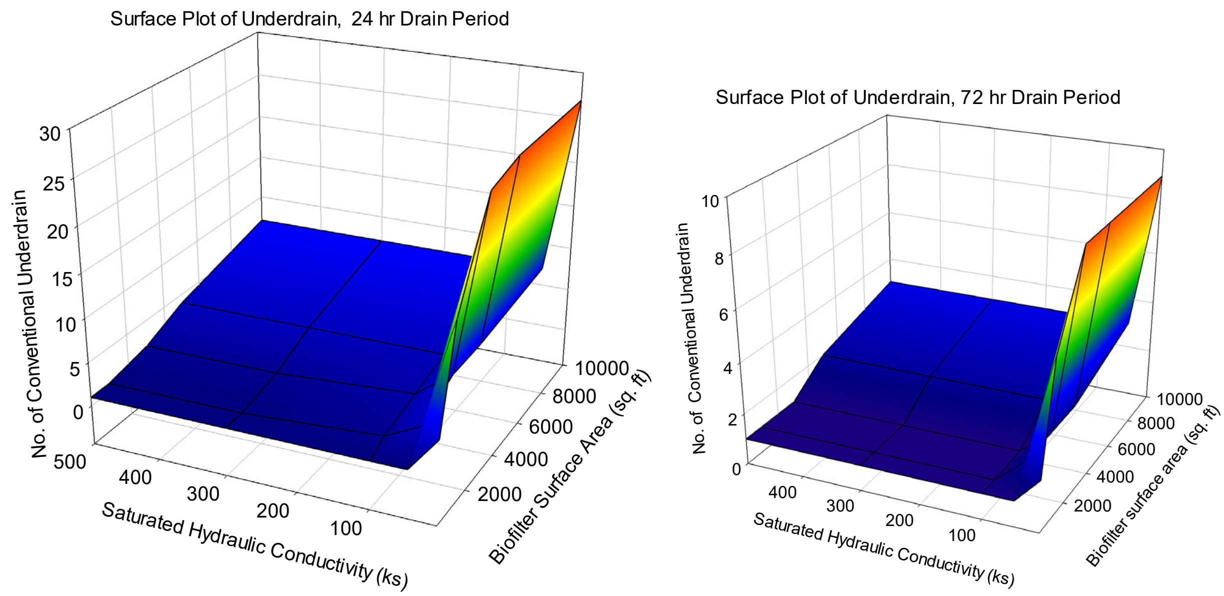


Figure 3. Three Dimensional Plots of No. of SmartDrains or Conventional Underdrains Required for Different Biofilter Area and Saturated Hydraulic Conductivities.

The following is an example calculation, from Sileshi (2013), showing biofilter dewatering calculations, as reflected on the above 3D figures.

Biofilter storage volume (ft^3) = Ponding storage (ft^3) + Engineered media storage (ft^3) + Drainage layer storage above underdrain (ft^3) = surface area*ponding depth + surface area*engineered media depth*engineered media porosity + 0.5*surface area*drainage layer*drainage layer porosity

Note: the underdrain is installed at the center of drainage layer.

The restricted flow SmartDrain flow rate (as used in this example) was determined by Sileshi (2013) to be:

$$Q = 0.0286 + 0.0015(L) + 0.0246(H)$$

Where: *Q* **=** Predicted flowrate (L/s) [28.32 L per ft^3]
L = SmartDrain length (ft)
H = SmartDrain head (in)

Table 5. Design parameters used for example calculation

Biofilter surface area (ft^2)	Ponding depth (ft)	Engineered media depth (ft)	Drainage layer (ft)	Porosity of media mix (%)	Porosity of drainage layer (%)
100	1.5	2	1	0.44	0.3

Required drainage rate = storage volume /drain time

Storage volume = 100 ft^2*1.5 ft + 100 ft^2*2 ft*0.44 +100 ft^2*0.5 ft*0.3
= 253 ft^3

Required drainage rate for 24 hr ponding period= 253 ft^3/ (24 hr*3600 s/hr) = 0.003 cfs

This drainage rate needs to be converted to *q* which has units of in/day by dividing the drainage rate by the surface area of the biofilter facility (100ft^2) and using appropriate unit conversions. Therefore:

q = [(0.003 ft^3/sec)/(100 ft^2)](86,400 sec/day)(12 in/ft) = 31 in/day

The example below rounds this down to 30 in/day. It should be noted that as the area of the biofilter facility increases, the required drainage rate increases the same (area increases are the same as volume increases), assuming the depth characteristics remain the same. Therefore, in the example below, the *q* values remains the same as the biofilter areas increase.

Assume the 100 ft^2 biofilter has a square geometry, so the SmartDrain length =$\sqrt{\text{biofilter surface area}}$ = 10 ft

SmartDrain drainage rate:

$$Q\ \left({}^{L}/_{S}\right) = 0.0286 + 0.0015(L) + 0.0246(H)$$

Given: SmartDrain length = 10 ft with a head = 48 in

Q = 0.0286 + 0.0015(10) + 0.0246(48) = 1.22 L/s

To convert to cfs:

Q = 0.0353*Q (L/s) = 0.043 cfs

Minimum number of SmartDrains = 0.003 cfs/0.043 cfs = 0.07 (use 1 as need to roundup to next largest full integer value). A single SmartDrain 10 ft long has a much greater flow capacity than this small biofilter facility.

Maximum spacing of underdrains to ensure that the infiltrating water reaches the underdrain without causing ponding. Therefore, using the Hooghoudt equation:

$$s = \sqrt{\frac{4.k_s(m^2+2.d_e.m)}{q/_{24}}}$$

Where:

s maximum spacing between drains (ft)

q amount of water that the underdrain carries away (in/day),

K_s average saturated hydraulic conductivity of the drainage layer media (in/hr),

d_e effective depth (ft) (height of underdrains above the pond bottom)`,

m depth of water, or head, created over the pipes (ft).

Design values for the Dewatering Equation

d_e (ft)	m (ft)	q (in/day)	K_s (in/hr)
0.5	0.5	30	30

The maximum spacing between tile drains using the design parameters given above:

$$S = \sqrt{\frac{4*30in/hr\ ((0.5ft)^2+2*0.5ft*0.5ft)}{30in/day/_{24}}} = 8 \text{ ft}$$

Minimum No. of SmartDrain for 100 ft^2 biofilter having a square geometry in example:

$$= \left(\frac{\text{Biofilter length}}{\text{SmartDrain spacing}}\right) * \left(\frac{\text{Biofilter width}}{\text{SmartDrain spacing}}\right)$$

$$= \left(\frac{10 \text{ ft}}{8 \text{ ft}}\right) * \left(\frac{10 \text{ ft}}{8 \text{ ft}}\right) = 2$$

Need to use the largest number of underdrains indicated by either option. Therefore, for a 100 ft^2 biofilter having a square geometry (10 ft by 10 ft), two SmartDrain strips are required.

A design example for various biofilter sizes, hydraulic conductivities, and 24 hour drain periods are summarized in Table 6 through 8.

Table 6. An Example Calculation Showing a Biofilter Facility Hydraulics and Design of Dewater Using SmartDrain (SD).

surface area (ft^2)	Ponding depth (ft)	Engineered media layer (ft)	Porosity of media mix (%)	Drainage layer (ft)	Porosity of drainage layer (%)	Head above SD (ft)	Storage volume (ft^3)	Drainage time (hr)	Required drainage rate (cfs)
100	1.5	2	0.44	1	0.3	4	253	24	0.003
1000	1.5	2	0.44	1	0.3	4	2530	24	0.029
3000	1.5	2	0.44	1	0.3	4	7590	24	0.088
5000	1.5	2	0.44	1	0.3	4	12650	24	0.146
10000	1.5	2	0.44	1	0.3	4	25300	24	0.293

Table 7. Minimum No. of SmartDrain (SD) Required for a Biofilter Basin Having a Square Geometry

SD length (ft)	Q (L/s), from factorial design	Q (gpm)	Q (cfs)	Drain volume (cf)/SM = [Q*t]	Min. No. of SD	Example max. spacing (= sqrt. (A)/min No. of SD)
10	1.22	19.41	0.043	3734.32	1	10
32	1.26	19.92	0.044	3833.24	1	32
55	1.29	20.47	0.046	3939.15	2	27
71	1.32	20.85	0.046	4012.07	4	18
100	1.36	21.55	0.048	4146.06	7	14

Table 8. Biofilter Basin Dewatering and Minimum No. of SmartDrain (SD) Required for a Biofilter Basin Based On SmartDrain Spacing.

q - the amount of water that the underdrain carries away (in/day)	K_s-the average saturated hydraulic conductivity of the facility media (in/hr)	de-the difference in elevation between the tile drain and the impermeable layer (ft)	m- head, created over the tiles (ft)	S-the max. spacing between tile drains (ft)	Min. number of SD for square geometry
30	30	0.5	0.5	8	2
30	45	0.5	0.5	10	1
30	60	0.5	0.5	12	1
30	75	0.5	0.5	13	1
30	100	0.5	0.5	15	1

Note: The largest number of SmartDrain was selected for the final model.

The accompanying spreadsheet (CEC SAR loading and underdrains Pitt Sept 28 2017.xlsx) performs many of these calculations to assist in the initial sizing of a biofilter facility based on the media flow rates and other features. Pitt, *et al.* (2008) describes how some of these relationships were developed. Continuous modeling with WinSLAMM is needed to produce production functions that consider flow routing through the device and infiltration and performance expectations for a wide range of events.

2) Retention of Stormwater Particulates by Biofilter Media

Sileshi (2013), as part of the comprehensive investigation of biofilter media, also examined the retention of stormwater particulates of different particle sizes. This information is also available from a number of other research projects, as summarized below.

Loading Capacity before Media Clogging

The values in Table 9 are from the detailed media tests

Table 9. Clogging Conditions Observed during Long-Term Full-Depth Column Tests (Pitt and Clark 2010)

Media, ranked by clogging potential	Cumulative load to initial maintenance, at 5 m/d (kg/m^2)*	Cumulative load to clogging, if no maintenance at 1 m/d (kg/m^2)*
Granular Activated Carbon (GAC)	7 (35)	7.5 (38)
Peat moss	3.3 (17)	4 (20)
Rhyolite sand	6.5 33)	7 (35)
Site sand	0.3 (1.5)	2 (10)
Site zeolite	3.1 (15)	3.5 (17)
Surface modified zeolite (SMZ)	4.8 (24)	5.5 (28)
Rhyolite sand and surface modified zeolite	7.5 (38)	7.5 (38)
Rhyolite sand, surface modified zeolite, and granular activated carbon	9.7 (49)	10.5 (53)
Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss	10.5 (53)	11 (55)
*Column study results and estimated full-scale results, with 5X factor in parentheses		

The Master Table shows the recommended maximum retention for each of the media and mixtures.

Particulate Retention Equations

Four main data sources and groups of information are presented as 13 different categories for the particulate retention calculations:

Sileshi (2013) column tests:

- Fine textured mixtures
- Intermediate textured mixtures
- Coarse textured mixtures

Boeing media tests (Pitt and Clark 2010):

- Boeing GAC (granular activated carbon)
- Boeing peat
- Boeing site filter sand (a coarse textured sand)
- Boeing Rhyolite sand (a fine textured sand)
- Boeing site Zeolite
- Boeing R-SMZ (mixture of Rhyolite sand and surface modified zeolite (75/25))
- Boeing R-SMZ-GAC (mixture of Rhyolite sand, surface modified zeolite, and granular activated carbon (33/33/33))
- Boeing R-SMZ-GAC-PM (mixture of Rhyolite sand, surface modified zeolite, granular activated carbon, and peat moss (30/30/30/10))

Kansas City EPA Demonstration Project biofilters (Pitt, *et al.* 2014):

- Biofilter media (30% planting soil; 20% organic compost; 50% sand ("Seattle" mix))

Wisconsin DNR/USGS biofilter media tests (Bannerman, personal communication):

- Neenah WI mix 2 (86% sand, 11% peat moss, and 3% Imbrium)

The following tables present these data, while Appendix C1 includes some of the basic information and statistical analyses.

Detailed Column Tests of Media Retention of Stormwater Particulates by Size

The following tables summarize the Sileshi (2013) laboratory column test results (fine, intermediate, and coarse categories). There were no large particle sizes found in the effluent from these columns for stormwater particles larger than about 300 µm. Most of the other size categories have consistent effluent concentrations that did not change as the influent concentrations changed (the same concentrations for all influent concentrations). However, the COV values are moderate to high, as typical for most stormwater, and should be used to statistically vary the effluent concentrations using Monte Carlo options. For the very coarse biofilter media material, the silts will be retained in the voids of the media.

Table 10. Low to High Concentrations (100 to 800 SSC mg/L), fine media (about 300 um) (data from Sileshi 2013)

>1000 um		300 to 1000 um		100 to 300 um		30 to 100 um		10 to 30 um		3 to 10 um		1 to 3 um		total	
inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl
no sign regression		no sign regression		no sign regression		intercept sign		intercept sign		intercept sign		no likely removal		intercept sign	
mean	efl = 0	mean	efl = 0	mean	efl = 0.06	mean	efl = 0.30	mean	efl = 1.55	mean	efl = 2.43			mean	efl = 4.5
COV	n/a	COV	n/a	COV	1.33	COV	0.5	COV	0.66	COV	0.3			COV	0.39

Effluent particle size data are not available for the intermediate and very coarse media. Therefore, the particle size distributions for the effluent for the fine media were used to distribute the total SSC concentration for these coarser textured media. For this reason, these data are only used in the absence of other information for the other media components and mixtures.

Table 11. Low to High Concentrations (50 to 500 SSC mg/L), intermediate media (about 1000 to 2000 um) (data from Sileshi 2013)

>1000 um		300 to 1000 um		100 to 300 um		30 to 100 um		10 to 30 um		3 to 10 um		1 to 3 um		total	
inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl
												no likely removal		no sign regression	
mean	efl = 0	mean	efl = 0	mean	efl = 0.70	mean	efl = 3.33	mean	efl = 17.1	mean	efl = 26.8			mean	49.6
														COV	0.63

Table 12. Low to High Concentrations (50 to 500 SSC mg/L) Very Coarse Media (pea gravel and coarse gravel; >5,000 um D50) (data from Sileshi 2013)

>1000 um		300 to 1000 um		100 to 300 um		30 to 100 um		10 to 30 um		3 to 10 um		1 to 3 um		total	
inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl
												no likely removal		no sign intercept	
														y = 1.69 x	
mean	efl = 0	mean	efl = 0	mean	efl = 6.17	mean	efl = 29.4	mean	efl = 150	mean	efl = 237			mean	438
														COV	0.75

Tests of Media Components and Mixtures for Boeing

An extensive series of laboratory and pilot-scale tests were conducted by Pitt and Clark (2010) as part of a research project to test and develop a high-performance biofilter media mixture to treat a wide range of stormwater pollutants at an aerospace test facility for the Boeing Co. that is being restored. The research report describes the series of different tests conducted with these media, including the long-term column tests reported here. Stormwater particulate retention for different particle sizes were an important part of these tests. The following tables show the resulting regression equations that were developed and recommended for use in the WinSLAMM biofilter calculations, as noted on the master table. Clark and Pitt (2009a) also describe a power equation for particulate retention in the media, while Clark, *et al.* (2006) summarizes some of the earlier test results.

Table 13. Removals for Granular Activated Carbon for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.5	Y = X	199 (80 to 250)	202	0
0.45 to 3 um particles, mg/L	0.014	Y = 3.3 (0.62)	9.9 (3 to 22)	3.3	67
3 to 12 um particles, mg/L	0.009	Y = 1.2 (0.69)	50.6 (22 to 90)	1.2	98
12 to 30 um particles, mg/L	0.009	Y = 0.71 (0.53)	54.5 (18 to 90)	0.62	99
30 to 60 um particles, mg/L	0.009	Y = 2.0 (0.73)	37.4 (3 to 80)	1.1	97
60 to 120 um particles, mg/L	0.009	Y = 0.96 (0.86)	20.0 (2 to 58)	0.62	97
120 to 250 um particles, mg/L	0.009	Y = 0.44 (1.3)	5.1 (0 to 17)	0.3	94
250 to 1180 um particles, mg/L (no particles found >1180)	0.021	Y = 2.6 (0.56)	13.9 (3 to 45)	2.5	82
SSC, mg/L	0.009	Y = 10.2 (0.27)	191 (50 to 400)	9.7	95
TSS (0.45 to 75 µm), mg/L	0.009	Y = 6.3 (0.22)	161 (50 to 310)	6.5	96

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed

** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent concentration (except for pH, and when significant increases are noted in the % removal column)

*** <LOD substituted with half of the detection limits for these calculations

Table 14. Removals for Peat Moss for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.12	Y = X	199 (80 to 250)	216	0*
0.45 to 3 um particles, mg/L	0.31	Y = X	10.6 (3 to 22)	4.7	0*
3 to 12 um particles, mg/L	0.064	Y = 0.50 (0.7)	54.9 (22 to 90)	0.5	99
12 to 30 um particles, mg/L	0.009	Y = 1.3 (1.7)	54.5 (18 to 90)	1.3	98
30 to 60 um particles, mg/L	0.009	Y = 1.6 (0.9)	37.4 (3 to 80)	1.6	96
60 to 120 um particles, mg/L	0.021	Y = 1.8 (1.4)	20.0 (2 to 58)	1	95
120 to 250 um particles, mg/L	0.014	Y = 0.27 (1.0)	5.1 (0 to 17)	0.27	95
250 to 1180 um particles, mg/L (no particles found >1180)	0.088	Y = 4.7 (0.92)	13.9 (3 to 45)	3.5	75
SSC, mg/L	0.045	Y =7.0 (0.3)	206 (50 to 400)	9.9	94
TSS (0.45 to 75 µm), mg/L	0.045	Y = 7.1 (0.5)	171 (50 to 310)	7.1	96

Table 15. Removals for Rhyolite Sand for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.2	Y = X	199 (80 to 250)	228	0*
0.45 to 3 um particles, mg/L	0.25	Y = X	10.6 (3 to 22)	6.1	0*
3 to 12 um particles, mg/L	0.009	Y = 1.7 (0.7)	54.9 (22 to 90)	1.7	97
12 to 30 um particles, mg/L	0.009	Y = 1.21 (1.2)	54.5 (18 to 90)	1.2	98
30 to 60 um particles, mg/L	0.009	Y = 4.1 (1.2)	37.4 (3 to 80)	2.4	94
60 to 120 um particles, mg/L	0.021	Y = 1.94 (1.5)	20.0 (2 to 58)	1.07	95
120 to 250 um particles, mg/L	0.009	Y = 0.44 (1.3)	5.1 (0 to 17)	0.31	94
250 to 1180 um particles, mg/L (no particles found >1180)	0.045	Y = 5.3 (0.90)	13.9 (3 to 45)	3.8	73
SSC, mg/L	0.014	Y = 7.30 (0.5)	206 (50 to 400)	13.4	93
TSS (0.45 to 75 µm), mg/L	0.009	Y = 3.52 (0.6)	171 (50 to 310)	10.2	94

Table 16. Removals for Site Sand for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.25	Y = X	199 (80 to 250)	202	0*
0.45 to 3 um particles, mg/L	0.04	Y = 3.2 (1.0)	9.9 (3 to 22)	3.2	68
3 to 12 um particles, mg/L	0.022	Y = 1.7 (0.26)	50.6 (22 to 90)	2.4	95
12 to 30 um particles, mg/L	0.022	Y = 1.6 (1.2)	54.5 (18 to 90)	1.6	97
30 to 60 um particles, mg/L	0.022	Y = 1.8 (1.1)	37.4 (3 to 80)	1.8	95
60 to 120 um particles, mg/L	0.022	Y = 0.067X	20.0 (2 to 58)	1.3	94
120 to 250 um particles, mg/L	0.022	Y = 0.002X	5.1 (0 to 17)	0.3	94
250 to 1180 um particles, mg/L (no particles found >1180)	0.11	Y = 2.63 (0.53)	14.4 (3 to 45)	2.6	82
SSC, mg/L	0.022	Y =13.3 (0.49)	191 (50 to 400)	13.3	93
TSS (0.45 to 75 µm), mg/L	0.022	Y = 9.5 (0.60)	161 (50 to 310)	9.5	94

Table 17. Removals for Site Zeolite for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.43	Y = X	198 (80 to 250)	183	0*
0.45 to 3 um particles, mg/L	0.031	Y = 2.5 (1.1)	9.9 (3 to 22)	2.5	75
3 to 12 um particles, mg/L	0.009	Y = 1.6 (0.81)	50.6 (22 to 90)	1.6	97
12 to 30 um particles, mg/L	0.009	Y = 0.78 (1.1)	54.5 (18 to 90)	0.78	99
30 to 60 um particles, mg/L	0.009	Y = 2.0 (1.3)	37.4 (3 to 80)	1	97
60 to 120 um particles, mg/L	0.014	Y = 1.3 (1.5)	20.0 (2 to 58)	0.73	96
120 to 250 um particles, mg/L	0.014	Y = 0.31 (1.5)	5.1 (0 to 17)	0.2	96
250 to 1180 um particles, mg/L (no particles found >1180)	0.064	Y = 4.0 (0.61)	13.9 (3 to 45)	2.9	79
SSC, mg/L	0.009	Y =12 (0.52)	191 (50 to 400)	9.7	95
TSS (0.45 to 75 µm), mg/L	0.009	Y = 6.1 (0.53)	161 (50 to 310)	6.3	96

Table 18. Removals for Surface Modified Zeolite for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	n/a	Y = X (by observation)	199 (80 to 250)	232	0*
0.45 to 3 um particles, mg/L	0.014	Y = 0.40X	9.9 (3 to 22)	3.8	62
3 to 12 um particles, mg/L	0.009	Y = 1.6 (0.56)	50.6 (22 to 90)	1.6	97
12 to 30 um particles, mg/L	0.009	Y = 0.71 (0.40)	54.5 (18 to 90)	0.74	99
30 to 60 um particles, mg/L	0.009	Y = 1.9 (0.90)	37.4 (3 to 80)	1.3	97
60 to 120 um particles, mg/L	0.009	Y = 0.97 (1.1)	20.0 (2 to 58)	0.97	95
120 to 250 um particles, mg/L	0.009	Y = 0.19 (1.4)	5.1 (0 to 17)	0.19	96
250 to 1180 um particles, mg/L (no particles found >1180)	0.045	Y = 3.5 (0.52)	13.9 (3 to 45)	3.1	78
SSC, mg/L	0.009	Y = 7.7 (0.35)	191 (50 to 400)	11.7	94
TSS (0.45 to 75 µm), mg/L	0.009	Y = 0.047X	161 (50 to 310)	8	95

Table 19. Removals for Rhyolite Sand - Surface Modified Zeolite (R-SMZ) Mixture for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.25	Y = X	199 (80 to 250)	202	0*
0.45 to 3 um particles, mg/L	0.04	Y = 3.2 (1.0)	9.9 (3 to 22)	3.2	68
3 to 12 um particles, mg/L	0.022	Y = 1.7 (0.26)	50.6 (22 to 90)	2.4	95
12 to 30 um particles, mg/L	0.022	Y = 1.6 (1.2)	54.5 (18 to 90)	1.6	97
30 to 60 um particles, mg/L	0.022	Y = 1.8 (1.1)	37.4 (3 to 80)	1.8	95
60 to 120 um particles, mg/L	0.022	Y = 0.067X	20.0 (2 to 58)	1.3	94
120 to 250 um particles, mg/L	0.022	Y = 0.002X	5.1 (0 to 17)	0.3	94
250 to 1180 um particles, mg/L (no particles found >1180)	0.11	Y = 2.63 (0.53)	14.4 (3 to 45)	2.6	82
SSC, mg/L	0.022	Y =13.3 (0.49)	191 (50 to 400)	13.3	93
TSS (0.45 to 75 µm), mg/L	0.022	Y = 9.5 (0.60)	161 (50 to 310)	9.5	94

Table 20. Removals for Rhyolite Sand - Surface Modified Zeolite - Granular Activated Carbon Mixture (R-SMZ-GAC) for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.25	Y = X	199 (80 to 250)	225	0*
0.45 to 3 um particles, mg/L	0.16	Y = X	9.9 (3 to 22)	7.2	0*
3 to 12 um particles, mg/L	0.009	Y = 4.0 (0.5)	54.9 (22 to 90)	2.9	95
12 to 30 um particles, mg/L	0.009	Y = 0.68 (0.76)	54.5 (18 to 90)	0.67	99
30 to 60 um particles, mg/L	0.009	Y = 1.1 (0.70)	37.4 (3 to 80)	1	97
60 to 120 um particles, mg/L	0.009	Y = 0.85 (0.77)	20.0 (2 to 58)	0.76	96
120 to 250 um particles, mg/L	0.009	Y = 0.08 (1.4)	5.1 (0 to 17)	0.08	98
250 to 1180 um particles, mg/L (no particles found >1180)	0.075	Y = 5.0 (0.66)	13.9 (3 to 45)	4.1	71
SSC, mg/L	0.009	Y = 10.2 (0.24)	206 (50 to 400)	13.6	93
TSS (0.45 to 75 µm), mg/L	0.009	Y = 10.2 (0.37)	171 (50 to 310)	10.2	94

Table 21. Removals for Rhyolite Sand - Surface Modified Zeolite - Granular Activated Carbon - Peat Moss (R-SMZ-GAC-PM) for Full-Depth Column Tests (Pitt and Clark 2010)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***	Mean Effluent Concentration***	Reduction (%)***
< 0.45 um particles, mg/L	0.2	Y = X	199 (80 to 250)	205	0*
0.45 to 3 um particles, mg/L	0.031	Y = 4.8 (0.70)	9.9 (3 to 22)	4.8	52
3 to 12 um particles, mg/L	0.009	Y = 4.1 (0.86)	50.6 (22 to 90)	2.6	95
12 to 30 um particles, mg/L	0.009	Y = 0.48 (0.57)	54.5 (18 to 90)	0.48	99
30 to 60 um particles, mg/L	0.009	Y = 1.3 (0.79)	37.4 (3 to 80)	0.97	97
60 to 120 um particles, mg/L	0.009	Y = 1.0 (0.71)	20.0 (2 to 58)	0.78	96
120 to 250 um particles, mg/L	0.009	Y = 0.15 (0.88)	5.1 (0 to 17)	0.15	97
250 to 1180 um particles, mg/L (no particles found >1180)	0.009	Y = 2.4 (0.33)	13.9 (3 to 45)	2.8	80
SSC, mg/L	0.009	Y =9.2 (0.48)	191 (50 to 400)	12.6	93
TSS (0.45 to 75 µm), mg/L	0.009	Y = 14.5 (0.82)	161 (50 to 310)	14.5	91

Full-Scale Tests of Biofilter Retention of Stormwater Particles

The Kansas City project was an EPA-funded demonstration project to show how green infrastructure can be integrated into areas having combined sewers (Pitt, *et al.* 2013, and summarized by Pitt and Talebi 2013). This was an extensive project and included the construction of several hundred controls in the test area. An adjacent area with no stormwater controls was used for comparison. The monitoring program lasted for about 2 years and included more than 50 storms. However, the monitored biofilters worked very well and only six events produced underdrain flows that could be sampled and analyzed. The media was comprised of 30% planting soil, 20% organic compost, and 50% sand ("Seattle" mix). The performance data for these biofilters are summarized below and the details are shown in Appendix C4.

The Wisconsin full-scale biofilter tests were conducted in Neenah, WI (Bannerman, personal communication). These were especially constructed biofilters to compare different test mixtures and biofilter designs. The data shown below are for the mix-2, which was comprised of 86% sand, 11% peat moss, and 3% Imbrium phosphorus removal material. The biofilters were sealed and all of the treated effluent was collected by underdrains and analyzed, resulting in 44 sets of data. The performance data for these tests are shown below, and details are shown in Appendix C5.

The summary performance data shown below indicate the range of influent concentrations for each particle size category, along with the regression equations and significance of the overall equations and coefficients. In some cases, only the intercepts are significant for significant regression equations. In this case, the effluent is not related to influent concentrations and is a constant value (the COV values should be applied with a Monte Carlo procedure to account for the remaining variation). Depending on the plots, if the overall regression was not significant, the recommended effluent value is also shown as a constant (the average and COV of the monitored effluent concentrations). The larger amount of data from the Wisconsin tests indicated that most of the data were not normally distributed, so log10 transformations were used to develop those equations. The few Kansas City data did not indicate non-normal conditions, so those data were not transformed. Sime of the equations are shown to be highly significant. However, there is still a lot of variation when the predicted effluent concentration is compared to the observed effluent concentration. Therefore, the observed effluent COV values should also be applied to these calculated effluent values using a Monte Carlo process.

Table 22. Kansas City Biofilter Tests ("Seattle" biofilter mix) (Pitt, *et al.* 2014)

	min influent conc, mg/L	max influent conc, mg/L	median reduction (%)	count	influent COV	effluent COV	p of regression equation	p of intercept	p of slope term	final equation
0.45 to 3	0.51	2.86	-56.2	6	0.45	0.31	0.012	n/a	0.007	y = 1.089x
3 to 12	18.8	94.04	55.5	6	0.66	0.5	0.086	n/a	0.072	y = 0.234x
12 to 30	12.1	202.9	62.6	6	1.12	0.8	0.0068	n/a	0.0036	y = 0.211x
30 to 60	9.44	175.3	65.3	6	1.44	0.86	0.0042	n/a	0.002	y = 0.195x
60 to 120	5.6	104.7	73.7	6	1.38	0.67	0.18	n/a	0.17	y = 4.9 mg/L (COV = 0.66)
120 to 250	0	21.9	81.3	6	1.14	1.06	0.0062	n/a	0.0033	y = 0.20x
250 to 1180	13.7	112.9	72.3	6	0.69	0.56	0.098	n/a	0.085	y = 12.6 mg/L (COV = 0.56)
>1180	0	0	n/a	6						y = 0
Total SSC	61	595	62.4	6	0.81	0.51	0.011	n/a	0.0067	y = 0.215x

Table 23. Wisconsin Media 2 Neenah biofilter tests (mix 2 only available) (Bannerman, personal communication)

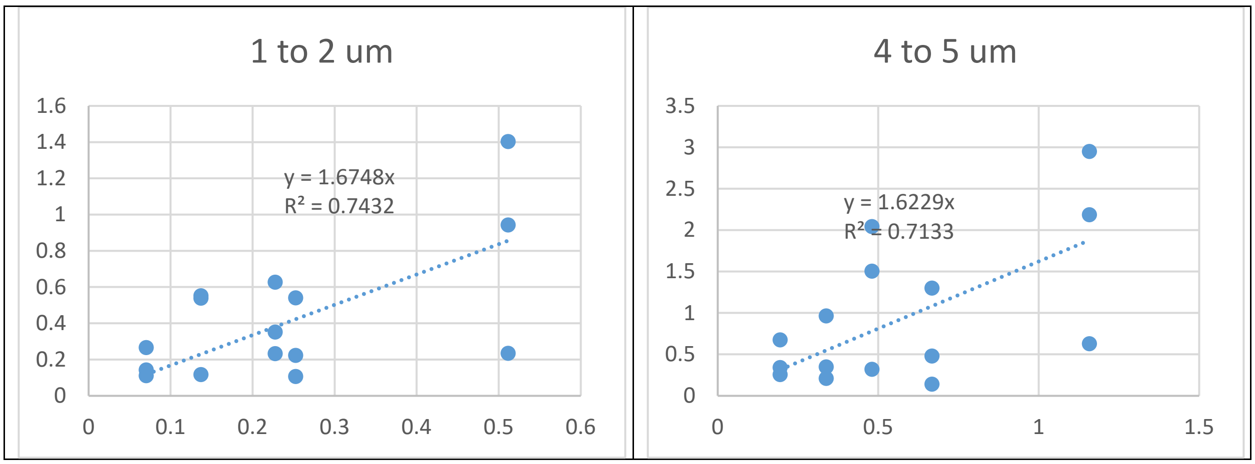
	min influent conc	max influent conc	median reduction (%)	count	influent COV	effluent COV	p of regression equation	p of intercept	p of slope term	final equation
0.45 to 2	0.56	60	56	44	1.3	0.72	2.10E-05	n/a	2.00E-05	log effluent = 0.346 (log influent)
2 to 4	0.07	86	86	44	2.4	0.81	0.017	2.20E-11	0.017	log effluent = -0.743 + 0.320 (log influent)
4 to 8	0.03	36	89	44	1.8	0.88	0.0086	1.30E-17	0.0086	log effluent = -1.037 + 0.319 (log influent)
8 to 16	0.04	29	90	44	1.5	0.91	0.011	5.40E-15	0.011	log effluent = -0.99 + 0.329 (log influent)
16 to 31	0.08	23	93	44	1.3	0.85	0.046	1.70E-12	0.046	log effluent = -0.969 + 0.331 (log influent)
31 to 63	0.96	52	88	44	1.2	1.2	0.00014	n/a	0.00014	effluent = 0.48 mg/L; COV = 1.2
63 to 125	0.8	52	90	44	1	0.92	0.0027	n/a	0.0027	effluent =0.65 mg/L; COV = 0.92
125 to 250	0.27	41	88	44	0.95	1.2	0.6	0.00081	0.6	effluent = 0.40 mg/L; COV = 1.15
250 to 500	0.02	33	87	40	1.8	1.4	0.31	2.30E-07	0.31	effluent= 0.34 mg/L; 1.4
>500	0.14	54	86	43	1.8	1.2	0.76	0.00027	0.76	effluent = 0.32mg/L; COV = 1.2
SSC	4	262	82	44	1	0.65	0.13	0.0011	0.13	effluent = 6 mg/L; COV = 0.65

Table 24. Comments on the use of the WI Neenah biofilter equations

SSC	constant effluent conc (but not larger than influent conc)
>500	constant effluent conc (but not larger than influent conc)
250 to 500	constant effluent conc (but not larger than influent conc)
125 to 250	constant effluent conc (but not larger than influent conc)
63 to 125	very small apparent slope term (but not larger than influent conc)
31 to 63	very small apparent slope term (but not larger than influent conc)
16 to 31	apply effluent COV to equation coefficients
8 to 16	apply effluent COV to equation coefficients
4 to 8	apply effluent COV to equation coefficients
2 to 4	apply effluent COV to equation coefficients
0.45 to 2	apply effluent COV to equation coefficients

Removal of Small Stormwater Particulates

Most of the laboratory and field monitoring tests of biofilter media have limited information for the removal of fine particulates, beyond the indication that removal is not expected, or that some media washout was observed (as indicated in Sileshi's 2013 results). During tests using pre-settled stormwater, Clark and Pitt (1999) obtained removal data for the smaller particles during long-duration pilot-scale tests in the field. The resulting plots for the 1 to 2 µm and 4 to 5 µm particle size removals are shown below:



These plots and analyses were prepared by combining the granular media (not found to vary significantly). The equations were highly significant based on ANOVA results. These plots were also similar and indicated a moderate flushing of these fines during these long tests. The following equation was therefore shown on the summary table for most media (that did not have specific small particle size removal data):

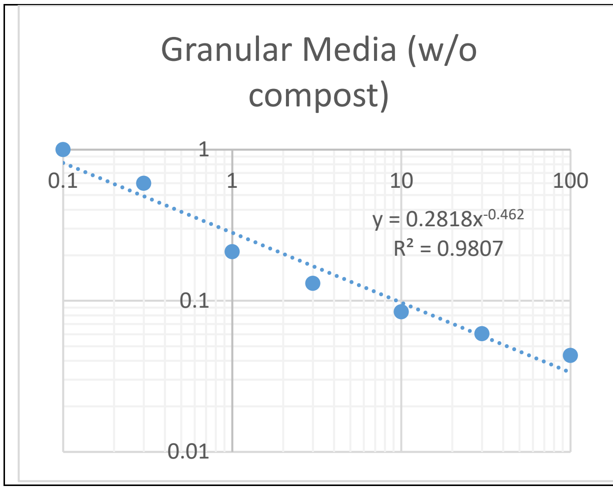
$$y = 1.65X$$

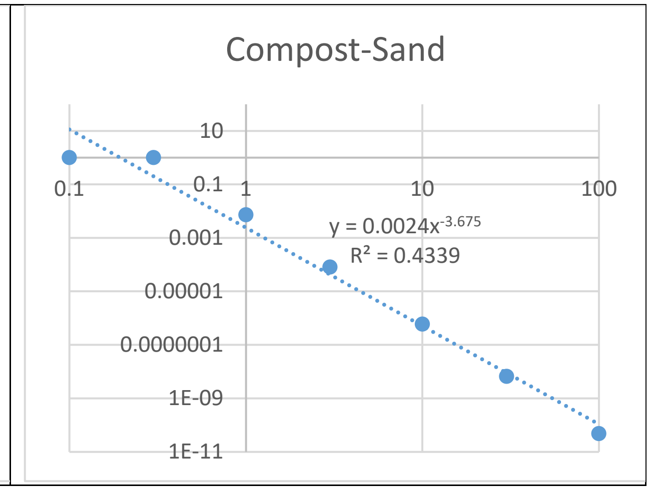
This equation is used for 0.45 to 3 um size for all bioretention media, indicating about 65% increase in concentrations for these small particles. Again, even though this equation is highly significant, there is still substantial variation in the results. A COV of about 0.85 and a Monte Carlo calculation is recommended to incorporate this uncertainty in the calculated effluent quality. Appendix C2 shows the basic data for these plots.

Effects of Solids Accumulation on Flow Rate Reductions

As solid material accumulates in the biofilter media, the treatment flow rate decreases. Clark (2000) developed clogging equations associated with accumulated loading. The following are plots of here resulting equations for two groups of data: all granular media combined and a separate plot for compost-sand mixtures. These plots show treatment flow rates (m/day) vs. sediment accumulation (kg/m^2). The granular media is seen to lose an order of magnitude of flow capacity after about 8 kg/m^2

acculturation and about 2 orders of flow capacity after about 30 kg/m^2. The compost-sand flow rate losses are much faster, with 1 order of magnitude of flow capacity lost after about 0.5 kg/m^2 of sediment accumulation and 2 orders of magnitude after about 2 kg/m^2, but the initial treatment flow rates for the compost-sand mixtures are much larger. Recommend to use the above normalized reduction factors in the biofilter calculations and the previously calculated initial flow rates.





The Role of Vegetation in Biofilters and Effects on Infiltration Rates

Vegetation in biofilters 1) involve evapotranspiration (ET) to remove runoff volume, 2) pollutant uptake in the plant systems, and 3) enhance infiltration by reducing compaction and allowing particulates to accumulate at deeper depths in the media along their root systems. Evapotranspiration can be calculated in WinSLAMM based on the density and types of plants in the biofilter. However, the runoff losses due to ET have been found to be minimal during monitoring due to the typically large amounts of runoff entering biofilters and the relatively small area for plants. ET is much more important for green roofs where the whole roof is planted and the only water entering the system is rainfall. Plant uptake of pollutants is also likely minimal for the same reasons (relatively small amounts of plants and large amounts of water). Plant uptake is much more important in wetland systems, but plant harvesting must also be considered to remove the captured pollutants from the system.

Plants, however, can extend the life of biofilters by reducing siltation by allowing sediment to accumulate through a large depth of the media, instead of forming a clogging layer on the media surface. This is most important when the critical sediment load that would cause clogging of the biofilter occurs over about 10 years, or longer. WinSLAMM checks this my examining the total accumulation after one year. If that accumulation is <1/10th of the total critical load (as indicated by calculated infiltration decrease), and if the biofilter has well established vegetation, the infiltration rate is then held constant with no additional decreases in the infiltration rate. In all other conditions (if unvegetated or if the annual accumulation rate is >1/10th of the critical load), then WinSLAMM continues to decrease the infiltration rate until clogging occurs. The following table illustrates these four conditions:

After one year, check annual rate of accumulation:

	Vegetated	Not Vegetated
<1/10 max load in first year	hold infiltration rate constant after the first year and do not decrease further	continue to decrease infiltration rate after each event and shut down when the maximum load is reached
>1/10 max load in first year	continue to decrease infiltration rate after each event and shut down when the maximum load is reached	continue to decrease infiltration rate after each event and shut down when the maximum load is reached

3) Retention of Filtered Pollutants by Biofilter Media Components and Mixtures

The final part of the biofilter calculations is to determine the retention of filtered pollutants in the media. In most cases, the retention of particulate-bound pollutants will be responsible for most of the total pollutant reductions in biofilters, but chemically-active media has also been found to reduce some of the filterable pollutant forms. If the biofilter also has significant infiltration (such as in rain gardens or bioretention facilities with no underdrains, or with high native soil infiltration capacities even with underdrains), it is likely that most of the filtered pollutant mass reductions would be associated with infiltration. The following present data associated with three aspects of filtered pollutant retention: observed concentration reductions as a function of influent concentrations (with some additional information for bacteria retention and for phosphorus leaching from compost media), media capacity, and the effects of contact time on filtered pollutant retention.

The filtered pollutant retention categories are associated with six main projects as shown below. In addition, the Boeing tests are sub-divided into nine subcategories:

Boeing granular activated carbon (GAC)
Boeing peat moss (PM)
Boeing Rhyolite sand (R-sand)
Boeing site sand
Boeing surface modified zeolite (SMZ)
Boeing site zeolite
Boeing R-SMZ
Boeing R-SMZ-GAC
Boeing R-SMZ-GAC-PM

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EPA compost amended soils report

Millburn NJ

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Some additional information is also provided from the International BMP Database and from an EPA-sponsored research project on compost-amended soils associated with effluent phosphorus concentrations from biofilters having compost additions.

The bacteria retention categories are from Clark's (2000) dissertation and include six subcategories (carbon-sand, compost-sand, loam, peat-sand, sand, and zeolite-sand).

The media capacity (limits for retention of the filtered pollutants) are from the Boeing project (same nine subcategories as listed above) and two subcategories (compost-sand and sand) from Clark's (2000) dissertation.

The effects of contact time on retention of filtered pollutants are from the Boeing study (GAC, PM, Rhyolite sand, site zeolite, and surface modified zeolite) and from Clark's dissertation (compost-sand).

The information associated with these topics for each category are described in the following discussions, with additional background and statistical analyses information in the appendices. As for the treatment flow calculations, the Master Tables include information for many individual components along with some mixtures. Mass-weighted values for the components are used to calculate these factors for other mixtures, with some restrictions (such as maximum amounts of peat allowed in the mixtures at 50%). Only statistically significant removals are summarized in this memo. If a constituent is not listed for one of the categories, it is assumed that no retention of filtered pollutants occur (effluent = influent).

Filterable Pollutant Retention by Media Components and Mixtures

Boeing Media Tests (Pitt and Clark 2010)

The Boeing long-term column tests (Pitt and Clark 2010) also included detailed analyses of many pollutants in both total and filtered forms. That report statistically analyzed their retention, which are listed below for different media components and mixtures. Data are shown for conditions generally having p of about 0.05 or less (some at 0.06). Gross alpha and gross beta removals for the mixtures are shown with p values of about 0.13 due to the small number of tests available. Relationships not shown are for larger p values and in those cases, it is assumed that no statistically significant removal occurs (based on the number of samples available).

Table 25. Removals for Granular Activated Carbon for Full-Depth Column Tests (50/50 mix with filter sand)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
pH	0.063	Y = X + 0.7	7.7 (7.3 to 8.2)
Ammonia, as N	0.008	Y = 0.27 (2.1)	2.7 (0.3 to 3.9)
Nitrite + nitrate as N	0.008	Y = 0.56 (0.50)	6.0 (4.9 to 7.1)
Arsenic, filtered, µg/L	0.016	Y = 17 (0.31)	33 (<LOD to 109)
Aluminum, filtered, µg/L	0.008	Y = 38.7 (0.30)	73 (<LOD to 121)
Boron, filtered, µg/L	0.031	all effluents <LOD	177 (<LOD to 472)
Cadmium, filtered, µg/L	0.008	n/a (most effluents <LOD)	28 (1 to 54)
Copper, filtered, µg/L	0.004	Y = 6.8 (0.64)	42 (23 to 69)
Iron, filtered, µg/L	0.004	Y = 14 (0.84)	63 (44 to 109)

Magnesium, filtered, µg/L	0.004	Y = 3820 (0.35)	2480 (2140 to 3520)
Manganese, filtered, µg/L	0.063	Y = 0.56 (0.31)	3.4 (<LOD to 13)
Nickel, filtered, µg/L	0.004	Y=3.9 (0.32)	27 (7 to 68)
Potassium, filtered, µg/L	0.004	Y = 10,300 (1.52)	2410 (1960 to 3250)
Chromium, filtered, µg/L	0.004	Y = 1.5 (0.38)	14 (7 to 19)
Thallium, filtered, µg/L	0.004	n/a (most effluents <LOD)	64 (27 to 94)
Antimony, filtered, µg/L	0.004	Y = 29.7 (0.27)	56 (39 to 86)
Nitrate, mg/L	0.008	Y = 46 (0.63)	6.0 (4.9 to 7.1)
Phosphorus, mg/L	0.063	Y = 1.2 (0.54)	0.65 (0.42 to 1.28)
Phosphate, as P, mg/L	0.008	Y = 3.7 (0.62)	0.90 (0.45 to 1.43)

* calculated using the sign test, ties ignored in the count; "no data" is when no samples were analyzed
** <LOD substituted with half of the detection limits for these calculations; if predicted effluent is > influent, then use influent conc (except for pH, and when significant increases are noted in the % removal column)
*** <LOD substituted with half of the detection limits for these calculations

Table 26. Removals for Peat Moss for Full-Depth Column Tests (50/50 mix with filter sand)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
pH	0.008	Y = X - 3.0	7.7 (7.3 to 8.2)
Chloride	0.008	Y = 33 (0.15)	18 (1 to 34)
Fluoride	0.008	Y = 0.67X	2.6 (1.7 to 3.1)
Aluminum, filtered, µg/L	0.004	Y = 778 (0.48)	73 (<LOD to 121)
Calcium, filtered, µg/L	0.004	Y = 0.40 X	30,400 (22,150 to 42,400)
Cadmium, filtered, µg/L	0.008	almost all effluent <LOD	28 (1 to 54)
Copper, filtered, µg/L	0.004	Y = 12.3 (0.26)	42 (23 to 69)
Manganese, filtered, µg/L	0.004	Y = 230 (0.64)	3.4 (<LOD to 13)
Nickel, filtered, µg/L	0.035	Y = 4.8 (0.62)	27 (7 to 68)
Chromium, filtered, µg/L	0.063	Y = 3.8 (0.9)	14 (7 to 19)
Thallium, filtered, µg/L	0.004	Y = 13 (0.63)	64 (27 to 94)
Antimony, filtered, µg/L	0.004	Y = 8.1 (1.7)	56 (39 to 86)

Table 27. Removals for Rhyolite Sand for Full-Depth Column Tests

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
Ammonia, as N	0.008	Y = 0.38 (1.1)	2.7 (0.3 to 3.9)
Arsenic, filtered, µg/L	0.063	Y = 0.258 X + 9.58	33 (<LOD to 109)
Cadmium, filtered, µg/L	0.008	almost all effluent < LOD	28 (1 to 54)
Nickel, filtered, µg/L	0.035	Y = 6 (0.43)	27 (7 to 68)
Potassium, filtered, µg/L	0.004	Y = 5420 (0.23)	2410 (1960 to 3250)
Sodium, filtered, µg/L	0.035	Y = 24,500 (0.13)	17,200 (14,200 to 27,300)
Thallium, filtered, µg/L	0.004	almost all effluent < LOD	64 (27 to 94)
Phosphorus, mg/L	0.008	Y =0.24 (0.19)	0.65 (0.42 to 1.28)

Table 28. Removals for Site Sand for Full-Depth Column Tests

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
Ammonia, as N	0.063	Y = 0.54X	2.7 (0.3 to 3.9)
Cadmium, filtered, µg/L	0.031	almost all effluent <LOD	28 (1 to 54)
Iron, filtered, µg/L	0.031	Y = 41 (0.32)	63 (44 to 109)
Magnesium, filtered, µg/L	0.031	Y = 3590 (0.20)	2480 (2140 to 3520)
Thallium, filtered, µg/L	0.031	Y = 15 (1.0)	64 (27 to 94)
Phosphorus, mg/L	0.063	Y = 0.24X	0.65 (0.42 to 1.28)
Phosphate, as P, mg/L	0.063	Y = 0.48X	0.90 (0.45 to 1.43)

Table 29. Removals for Site Zeolite for Full-Depth Column Tests (50/50 mix with filter sand)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
Chloride	0.008	Y = 36 (0.10)	18 (1 to 34)
Ammonia, as N	0.008	Y = 0.18 (1.0)	2.7 (0.3 to 3.9)
nitrite as N	0.016	Y = 0.65X	0.03 (0.015 to 0.046)
Arsenic, filtered, µg/L	0.016	Y = 19 (0.43)	33 (<LOD to 109)
Cadmium, filtered, µg/L	0.008	Almost all effluent <LOD	28 (1 to 54)
Copper, filtered, µg/L	0.035	Y = 25 (0.26)	42 (23 to 69)
Iron, filtered, µg/L	0.035	Y = 0.76 X	63 (44 to 109)
Magnesium, filtered, µg/L	0.004	Y = 1400 (0.41)	2480 (2140 to 3520)
Potassium, filtered, µg/L	0.004	Y = 3900 (0.23)	2410 (1960 to 3250)
Sodium, filtered, µg/L	0.004	Y = 24,800 (0.23)	17,200 (14,200 to 27,300)
Chromium, filtered, µg/L	0.004	Y = 0.86 X	14 (7 to 19)
Thallium, filtered, µg/L	0.004	Y = 7.5 (0.77)	64 (27 to 94)
Antimony, filtered, µg/L	0.035	Y = 0.72 X	56 (39 to 86)
Phosphorus, mg/L	0.008	Y = 0.19 (0.55)	0.65 (0.42 to 1.28)
Phosphate, as P, mg/L	0.016	Y = 0.32 (0.60)	0.90 (0.45 to 1.43)

Table 30. Removals for Surface Modified Zeolite for Full-Depth Column Tests (50/50 mix with filter sand)

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
pH	0.063	Y = X + 0.1	7.7 (7.3 to 8.2)
Chloride	0.063	Y = 26 (0.41)	18 (1 to 34)
Sulfate, as SO_4	0.063	Y = 45 (0.11)	45 (39 to 51)
Aluminum, filtered, µg/L	0.008	Y = 0.65 X	73 (<LOD to 121)
Cadmium, filtered, µg/L	0.008	almost all effluent < LOD	28 (1 to 54)
Iron, filtered, µg/L	0.004	Y = 23 (0.30)	63 (44 to 109)
Magnesium, filtered, µg/L	0.035	Y = 3600 (0.39)	2480 (2140 to 3520)
Nickel, filtered, µg/L	0.035	Y = 4.8 (0.37)	27 (7 to 68)

Potassium, filtered, µg/L	0.035	Y = 4400 (0.32)	2410 (1960 to 3250)
Chromium, filtered, µg/L	0.035	Y = 12 (0.87)	14 (7 to 19)
Thallium, filtered, µg/L	0.004	almost all effluent < LOD	64 (27 to 94)
Antimony, filtered, µg/L	0.063	Y = 39 (0.42)	56 (39 to 86)
Phosphate, as P, mg/L	0.063	Y = 0.68 (0.46)	0.90 (0.45 to 1.43)

Table 31. Removals for Rhyolite Sand - Surface Modified Zeolite (R-SMZ) Mixture for Full-Depth Column Tests

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
Ammonia, as N	0.008	Y = 0.071 (0.57)	2.7 (0.3 to 3.9)
Gross alpha radioactivity, pCi/L	0.125	Y = 0.8 (0.68)	5.3 (3.9 to 6.8)
Gross beta radioactivity, pCi/L	0.125	Y = 5.8 (0.14)	9.4 (8.1 to 10.1)
Radium 226 + 228, pCi/L	0.125	Y = 0.14 (0.5)	0.92 (0.67 to 1.2)
Cadmium, filtered, µg/L	0.008	almost all effluent <LOD	28 (1 to 54)
Iron, filtered, µg/L	0.004	Y = 0.79 X	63 (44 to 109)
Magnesium, filtered, µg/L	0.035	Y = 2970 (0.20)	2480 (2140 to 3520)
Nickel, filtered, µg/L	0.035	Y = 8 (0.82)	27 (7 to 68)
Potassium, filtered, µg/L	0.004	Y = 4140 (0.09)	2410 (1960 to 3250)
Sodium, filtered, µg/L	0.035	Y = 1.1 X	17,200 (14,200 to 27,300)
Chromium, filtered, µg/L	0.035	Y = 0.7 X	14 (7 to 19)
Thallium, filtered, µg/L	0.004	Y = 8.1 (0.87)	64 (27 to 94)

Table 32. Removals for Rhyolite Sand - Surface Modified Zeolite - Granular Activated Carbon Mixture (R-SMZ-GAC) for Full-Depth Column Tests

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
Chloride	0.063	Y = 30 (0.18)	18 (1 to 34)
Fluoride	0.063	Y = 2.2 (0.25)	2.6 (1.7 to 3.1)
Sulfate, as SO_4	0.063	Y = 37 (0.29)	45 (39 to 51)
Boron, µg/L	0.031	almost all effluent <LOD	170 (<LOD to 509)
Ammonia, as N	0.008	Y = 0.013 (1.4)	2.7 (0.3 to 3.9)
Nitrite + nitrate as N	0.063	Y = 3.0 (0.84)	6.0 (4.9 to 7.1)
Gross alpha radioactivity, pCi/L	0.125	all effluent <LOD	5.3 (3.9 to 6.8)

Uranium, pCi/L	0.125	all eff. <LOD	1.2 (1.1 to 1.5)
Radium 226 + 228, pCi/L	0.125	Y = 0.31 (1.2)	0.92 (0.67 to 1.2)
Arsenic, filtered, µg/L	0.109	Y = 14 (0.34)	33 (<LOD to 109)
Aluminum, filtered, µg/L	0.008	Y = 45 (0.39)	73 (<LOD to 121)
Boron, filtered, µg/L	0.031	all effluent <LOD	177 (<LOD to 472)
Cadmium, filtered, µg/L	0.008	almost all effluent <LOD	28 (1 to 54)
Copper, filtered, µg/L	0.004	Y = 13 (0.40)	42 (23 to 69)
Iron, filtered, µg/L	0.008	Y = 0.37 X	63 (44 to 109)
Magnesium, filtered, µg/L	0.004	Y = 4300 (0.39)	2480 (2140 to 3520)
Manganese, filtered, µg/L	0.125	almost all effluent <LOD	3.4 (<LOD to 13)
Nickel, filtered, µg/L	0.004	Y = 0.3 X	27 (7 to 68)
Potassium, filtered, µg/L	0.004	Y = 8000 (0.23)	2410 (1960 to 3250)
Chromium, filtered, µg/L	0.004	Y = 0.27 X	14 (7 to 19)
Thallium, filtered, µg/L	0.004	almost all effluent <LOD	64 (27 to 94)
Antimony, filtered, µg/L	0.035	Y = 34 (0.39)	56 (39 to 86)
Nitrate, mg/L	0.063	Y = 3.0 (0.88)	6.0 (4.9 to 7.1)

Table 33. Removals for Rhyolite Sand - Surface Modified Zeolite - Granular Activated Carbon - Peat Moss (R-SMZ-GAC-PM) for Full-Depth Column Tests

Constituent, mg/L unless noted otherwise	p that effluent equals influent*	regression equation (or Y = constant, and COV also shown)**	Mean Influent Concentration (approximate range)***
Chloride	0.109	Y = 33 (0.39)	18 (1 to 34)
Ammonia, as N	0.008	Y = 0.037 (1.0)	2.7 (0.3 to 3.9)
Gross alpha radioactivity, pCi/L	0.125	Y = 0.5 (all <LOD)	5.3 (3.9 to 6.8)
Radium 226 + 228, pCi/L	0.125	Y = 0.18 (0.81)	0.92 (0.67 to 1.2)
Arsenic, filtered, µg/L	0.016	Y = 0.18 X + 13	33 (<LOD to 109)
Aluminum, filtered, µg/L	0.008	Y = 0.69 X	73 (<LOD to 121)
Boron, filtered, µg/L	0.031	all effluent <LOD	177 (<LOD to 472)
Cadmium, filtered, µg/L	0.008	almost all effluent <LOD	28 (1 to 54)
Copper, filtered, µg/L	0.004	Y = 21 (0.55)	42 (23 to 69)
Iron, filtered, µg/L	0.004	Y = 0.65 X	63 (44 to 109)
Magnesium, filtered, µg/L	0.004	Y = 3660 (0.26)	2480 (2140 to 3520)
Nickel, filtered, µg/L	0.004	Y = 5.1 (0.46)	27 (7 to 68)
Potassium, filtered, µg/L	0.004	Y = 6700 (0.27)	2410 (1960 to 3250)
Chromium, µg/L	0.004	Y = 10 (0.42)	64 (48 to 81)
Thallium, filtered, µg/L	0.004	Y = 7.4 (0.82)	64 (27 to 94)
Antimony, filtered, µg/L	0.035	Y = 0.33 (0.38)	56 (39 to 86)
Phosphate, as P, mg/L	0.063	Y = 1.9 (0.64)	0.90 (0.45 to 1.43)

Clark (2000) Dissertation Media Tests

As part of her dissertation, Clark (2000) also examined the retention of *E. coli* and enterococci bacteria in different biofilter media during long-term pilot-scale tests using pre-settled stormwater, as summarized in the Table 34. The overall ranges of observed removals was quite large. The estimated COV values should therefore be used to add this variation to the calculated effluent bacterial levels using a Monte Carlo process.

Table 34. Bacteria Removal by Filter Media

	E. coli			Enterococci		
Filter Media	Removal (%)	median removal	est. COV	Removals (%)	median removal	est. COV
Loam	0 – 40	20	1.1	25 – 75	50	0.4

Peat-sand	35 – 96	66	0.4	0 – 94	47	1.1
Compost-sand	0 – 61	32	1.1	20 – 73	47	0.4
Sand	0 – 88	44	1.1	16 – 89	53	1.1
Zeolite-sand	0 – 94	47	1.1	0 – 91	45	1.1

In addition, her tests on the compost-sand mixture in long-term column tests only indicated that filtered zinc was removed with suitable statistical relevance (removal rate of 82% COV = 0.24), as shown on Table 35.

Table 35. Average Percent Pollutant Removal (COV) in Laboratory-Scale Filters (only significant removals shown) (Source: Clark 1996)

Parameter	Carbon-Sand	Peat-Sand	Zeolite-Sand	Compost-Sand
Toxicity (filtered)	83 (0.41)	63 (0.5)	100 (0)	
Color (filtered)	26 (0.68)			
Carbonate	47 (0.77)	100 (0)		
Bicarbonate	23 (1.15)	100 (0)		
Chloride		17 (0.29)	7 (0.47)	
Nitrate	97 (0.04)			
Sulfate		5 (0.92)		
Hardness		52 (0.26)		
Dissolved Solids		45 (0.29)		
Zinc (filtered)	48 (0.78)	58 (0.57)	62 (0.46)	82 (0.24)
COD (filtered)	85 (0.4)			

*Only percent removals greater than zero are shown in this table.

Millburn, NJ, Dry Well Tests (Pitt and Talebi 2014)

Pitt and Talebi (2014) (summarized in Talebi and Pitt 2013) conducted tests in Millburn, New Jersey, investigating the performance of dry wells. As part of this research, tests were conducted to examining the retention of pollutants in the underlying soils. Samples were obtained immediately below the dry well and also deeper, indicating the differences in concentrations as the infiltrating passed through the soils. Data from three dry wells were combined, resulting in about 28 sets of data. Most of the dry well monitored sites had “BowtB” soil type (Boonton - Urban land, Boonton substratum complex, terminal moraine, well drained). These soils are all A and B soils and are classified as fine sandy loam, loamy sand, and gravelly fine sandy loam. The shallow monitoring well underdrain was constructed directly below the dry well near the surface of the gravel layer a deeper one was installed at least 0.6 m (2 ft) below the bottom of the gravel layer (the NJ state requirement for closest groundwater). The deep monitoring location was at least 1.2 m (4 ft) below the bottom of the dry well, as shown on Figure 4. Water samples were manually pumped from these monitoring well underdrains during or immediately after the rains and analyzed for a range of typical stormwater pollutants.

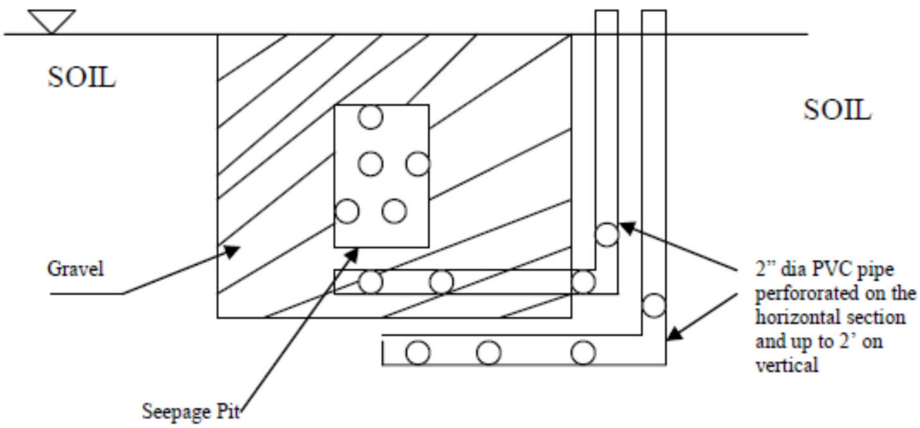

Figure 4. Millburn, NJ, dry well monitoring schematic.

Wisconsin Neenah Media 2 Biofilter Tests (Bannerman, personal communication)
Additional biofilter data investigating the retention of filtered pollutants is available from the Wisconsin Neenah DNR/USGS tests (Bannerman, personal communication). The following summarizes the observed retention relationships for the media 2 mixture (86% sand, 11% peat moss, and 3% Imbrium phosphorus removal media). These Wisconsin data are combined from three biofilters, having media depths of 1 to 3 ft (no significant differences were noted for the different depths). The influent TDS and chloride values had many non-detectable values, while the effluent values all increased. The increases were due to leaching of salts from the media, even during the long-term monitoring.

Table 36. Summary of Filtered Pollutant Retention in Soils beneath Millburn, NJ, Dry Wells

	% of influent values ND	% of effluent values ND	min influent conc	max influent conc	median reduction (%)	count (including ND)	influent COV	p of regression equation	p of intercept	p of slope term	final equation
total coliforms, #/100mL	0%	0%	43	36,294	-21	28	0.98	9.65E-05	4.62E-06	9.65E-05	log10 effluent = 0.473(log10 influent) + 2.23
E. coli, #/100mL	0%	0%	1	7,183	4	27	2.60	1.42E-05	0.012	1.42E-05	log10 effluent = 0.668(log10 influent) + 0.745
filtered N, mg/L	7%	0%	1	17	0	27	0.93	0.42	0.000012	0.42	effluent = influent
NO3+NO2, mg/L	0%	0%	0.1	1.95	-29	26	0.27	1.80E-02	n/a	1.80E-02	log10 effluent = 0.382(log10 influent)
filtered phosphorus, mg/L	0%	0%	0.04	0.67	6	28	0.12	7.60E-13	n/a	4.26E-13	log10 effluent = 0.893(log10 influent)
filtered COD, mg/L	0%	0%	19	73	-6	28	0.35	2.05E-23	n/a	4.77E-24	effluent = influent (slope = 0.99!)
filtered Pb, mg/L	12%	18%	0.003	0.31	-16	17	0.08	1.15E-08	n/a	5.80E-09	log10 effluent = 0.854 (log influent)
filtered Cu, mg/L	25%	25%	0.01	0	-63	4	0.02	3.40E-02	n/a	1.34E-02	log10 effluent = 0.813 (log influent)
filtered Zn, mg/L	23%	8%	0.01	0	-50	13	0.04	4.70E-01	0.0165	4.70E-01	effluent = influent

Table 37. Summary of Filtered Pollutant Retention in WI media 2 Biofilters (Wisconsin Neenah mix (86% sand, 11% peat moss, and 3% Imbrium))

	% of influent values ND	% of effluent values ND	min influent conc	max influent conc	median reduction (%)	count (including ND)	influent COV	p of regression equation	p of intercept	p of slope term	final equation
TDS (mg/L)	69%	0%	<50	152	-320	48	0.8	5.00E-16	n/a	6.00E-17	log effluent = 1.187(log influent)
Filtered phosphorus (mg/L)	0%	0%	0.008	0.06	7.5	44	0.5	0.013	0.046	0.013	log effluent = 0.548(log influent)-0.7297
Filtered copper (ug/L)	7%	57%	<2	6	58	14	0.4	0.65 (few data)	0.0296	0.66	effluent = 3 µg/L (COV = 0.24)
Filtered zinc (ug/L)	0%	44%	3	27	70	25	0.8	8.60E-06	n/a	5.40E-06	log effluent = 0.467 (log influent)
Ammonia (mg/L)	2%	39%	0.15	1.7	90	41	0.6	0.026	8.10E-06	0.026	log effluent = 1.049(log influent)-1.0028
Nitrate plus nitrite (mg/L)	0%	4%	0.061	0.59	17	23	0.7	0.00898	0.0226	0.00898	log effluent = 0.557(log influent)-0.358
Chloride (mg/L)	42%	4%	<1	11	-140	24	1.3	3.70E-07	n/a	1.90E+07	log effluent = 1.728 (log influent)
Fecal coliforms (#/100 mL)	5%	16%	1	17,000	71	19	2.9	0.00418	0.03	0.0042	log effluent = 0.446(log influent)+0.801
E. coli (#/100 mL)	17%	9%	1	1,842	-29	23	3.6	0.042	0.015	0.042	log effluent = 0.442(log influent)+0.799
Enterococci (#/100 mL)	0%	0%	4	4,200	11	27	1.6	3.40E-08	0.00035	3.40E-08	log effluent = 0.596(log influent)+0.70

Phosphorus Leaching from Compost Amendments

The addition of compost to biofilter mixtures has been shown to add phosphorus to the underdrain flows due to leaching of the nutrients from the material. In most cases, relatively small amounts of compost is added (just a few inches of material to the top of the biofilter to support plant growth, or about 10% of the mixture, for example). The International BMP Database includes effluent concentrations from many typical biofilters indicating about 0.25 mg/L filtered phosphorus in the effluent (see below). An extreme example of compost amendments is illustrated in the EPA report by Pitt, *et al.* (1999) (summarized below), where soil and compost was mixed 50/50, with phosphate subsurface concentrations of about 1.8 mg/L (compared to about 0.17 mg/L for soil only test plots), as shown below. Until further information is available, the calculated filtered phosphorus effluent concentration would be 0.25 mg/L at 10% compost additions, and 1.6 mg/L at 50% (maximum) compost additions.

Compost Amended Soils Tests (Pitt, *et al.* 1999)

A series of compost-amended soil (50/50 compost/soil mixtures) test plots were constructed in the Seattle area and monitored for several years by Pitt, *et al.* (2000). These test plots were sealed so no infiltration occurred. All of the underflow water was collected and analyzed and compared to the surface runoff concentrations for both amended and non-amended test plots. One of the notable findings was the subsurface flows from the compost amended soils had phosphate concentrations of 1.8 mg/L (COV = 1.02), compared to 0.17 mg/L (COV = 2.0) for subsurface flows from test plots of non-amended soils, as shown on Table 38. Therefore, for biofilters having significant compost material added (about 50%), the effluent concentrations of phosphorus is expected to be about 1.5 mg/L, with COV values of about 1.

Table 38. Average Concentrations (and COV) Values for Surface and Subsurface Runoff from Compost Amended and Non-Amended Test Plots (Pitt, *et al.* 1999)

Constituent (mg/L, unless noted)	Soil-only Plots		Soil plus Compost Plots	
	Surface Runoff	Subsurface Flows	Surface Runoff	Subsurface Flows
PO_4-P	0.27 (1.4)	0.17 (2.0)	1.9 (1.0)	1.8 (1.2)
TP	0.49 (1.0)	0.48 (2.2)	2.7 (0.9)	2.5 (1.1)
NH_4-N	0.65 (1.7)	0.23 (1.3)	4.1 (1.8)	3.5 (3.0)
NO_3-N	0.96 (1.4)	1.2 (2.5)	3.0 (1.6)	6.2 (2.8)
TN	2.5 (0.9)	1.9 (0.7)	8.4 (1.5)	10 (2.1)
Cl	2.4 (1.0)	2.1 (0.9)	6.7 (1.1)	5.0 (1.6)
SO_4-S	0.68 (1.1)	0.95 (2.0)	1.5 (0.9)	2.4 (1.4)
Al	11 (1.8)	1.7 (2.1)	0.7 (1.6)	2.4 (1.6)
Ca	12 (1.5)	17 (0.7)	18 (1.1)	35 (1.1)
Cu	0.01 (0.8)	0.01 (1.6)	0.02 (1.2)	0.02 (0.9)
Fe	4.6 (1.4)	2.8 (1.6)	1.2 (1.5)	2.6 (0.9)
K	5.4 (1.0)	4.6 (0.8)	30 (1.3)	34 (1.6)
Mg	3.9 (0.8)	5.0 (0.6)	5.8 (1.2)	10 (1.1)
Mn	0.75 (2.9)	0.41 (2.8)	0.36 (1.9)	0.80 (2.4)
Na	3.8 (0.9)	3.4 (0.5)	3.2 (0.8)	4.6 (1.2)
S	1.1 (0.8)	1.3 (1.5)	2.5 (0.8)	4.7 (1.6)
Zn	0.2 (1.2)	0.05 (2.2)	0.14 (1.1)	0.03 (1.8)
Si	26 (1.7)	8.9 (0.5)	4.2 (1.1)	11 (0.7)
10^{th} percentile size (μm)	2.9 (0.7)	3.1 (0.4)	2.8 (0.3)	3.5 (0.6)
50^{th} percentile size (μm)	12 (1.0)	13 (0.6)	15 (0.4)	14 (0.7)
90^{th} percentile size (μm)	45 (0.5)	41 (0.5)	46 (0.4)	47 (0.6)
Toxicity (% light decrease)	25 (0.7)	13 (0.5)	16 (0.8)	10 (1.1)

International BMP Database

The International BMP Database includes many summaries of observed influent and effluent concentrations from biofilters. Table 39 summarizes these overall performance expectations for different categories of stormwater controls. The biofilters and grass strip category includes typical compost additions (usually several inches top dressing). The dissolved phosphorus effluent concentrations were about 0.25 mg/L.

Table 39. Treated Stormwater Phosphorus Concentrations (from 2014 International BMP Database report)

	Total Phosphorus (mg/L)		Dissolved Phosphorus (mg/L)		Orthophosphate (mg/L)	
	median effluent concentration	75^{th} percentile effluent concentration	median effluent concentration	75th percentile effluent concentration	median effluent concentration	75th percentile effluent concentration
Biofilters – grass strips	0.17 (increased)	0.33 (increase)	0.25 (increase)	0.38 (increase)	0.06 (increase)	0.14 (increase)
Biofilters – grass swales	0.17 (increased	0.28 (increase)	0.07	0.25	0.08 (increase)	0.13 (increase)
Bioretention	0.24 (increase)	0.60 (increase)	NA	NA	0.26 (increase)	0.48 (increase)
Composite	0.13	0.22	0.08	0.13	no significant change	no significant change
Detention basins	0.2	0.32	no significant change	no significant change	NA	NA
Media filters	0.09	0.16	no significant change	no significant change	no significant change	no significant change
Porous pavement	0.1	0.16	0.05 (increase)	0.08 (increase)	0.07 (increase)	0.1
Retention pond	0.09	0.2	0.07	0.14	0.02	0.06
Wetland basin	0.09	0.2	0.05	0.13	no significant change	no significant change
Wetland basin/retention pond	0.09	0.2	0.06	0.14	0.024	0.07
Wetland channel	no significant change	no significant change	no significant change	no significant change	0.06 (increase)	0.08 (increase)

Retention Capacity of Filtered Pollutants in Biofilter Media Components and Mixtures

There are usually limits on how much of the filtered pollutants can be retained by the biofilter media. Extensive capacity tests were conducted by Pitt and Clark (2000) as part of the Boeing biofilter media development research. These were determined by long-term column tests to identify when breakthrough occurred. The capacities were determined by knowing the amount of pollutant loaded onto the columns during the tests.

Table 40. Media Capacities for Filtered Pollutants for Biofilter Media Components and Mixtures (Pitt and Clark 2000)

	GAC	Peat Moss	Rhyolite Sand	Site Sand	Site Zeolite	SMZ	R-SMZ	R-SMZ-GAC	R-SMZ-GAC-PM	Site Sand-GAC-Site Zeolite Layered
	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media	mg pol/gm media
Sulfate	0.64312	-0.00001	0.02962	0.01563	0.06703	0.09118	0.04722	0.27368	0.05495	0.31247
Calcium, Filtered	0.37527	6.35465	0.12236	0.01754	0.25430	0.08183	0.05581	0.07213	0.13782	0.08118
Chloride	0.00997	-0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00663	0.00000
Fluoride	0.02609	0.30338	0.01578	0.00252	0.03110	0.01247	0.00632	0.00777	0.00955	0.00791
Potassium, Filtered	0.00000	0.00212	0.00000	0.00005	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Sodium, Filtered	0.03348	-0.00001	0.00000	0.00793	0.00000	0.02424	0.00000	0.00000	0.00000	0.00000
Ammonia	0.23577	0.05586	0.12236	0.00073	0.21827	0.16521	0.06593	0.08856	0.10205	0.06681
Nitrate	0.52873	0.01102	0.01190	0.00338	0.00339	0.00873	0.00445	0.10058	0.10423	0.11289
Nitrite	0.00019	0.00000	0.00000	0.00000	0.00018	0.00011	0.00000	0.00015	0.00008	0.00028
Phosphate	0.00000	-0.00001	0.00000	0.00205	0.05003	0.00089	0.00012	0.00000	0.00000	0.00000
Aluminum, Filtered	0.00371	-0.00001	0.00025	0.00011	0.00008	0.00018	0.00004	0.00108	0.00010	0.00003
Antimony, Filtered	0.00273	0.01589	0.00060	0.00017	0.00112	0.00053	0.00034	0.00036	0.00102	0.00063
Arsenic, Filtered	0.00213	0.00000	0.00068	0.00014	0.00166	0.00077	0.00020	0.00061	0.00059	0.00050
Boron, Filtered	0.01071	0.01112	0.00000	0.00025	0.00055	0.00000	0.00071	0.00361	0.00423	0.00289
Cadmium, Filtered	0.00251	0.00892	0.00134	0.00017	0.00213	0.00161	0.00063	0.00085	0.00099	0.00068
Chromium, Filtered	0.00123	0.00350	0.00005	0.00001	0.00001	0.00003	0.00000	0.00036	0.00031	0.00031
Copper, Filtered	0.00359	0.00825	0.00019	0.00005	0.00098	0.00000	0.00000	0.00107	0.00090	0.00084
Iron, Filtered	0.00511	0.00000	0.00000	0.00015	0.00000	0.00000	0.00000	0.00136	0.00000	0.00119
Magnesium, Filtered	0.00107	0.00799	0.00000	0.00000	0.09224	0.00000	0.00000	0.00000	0.00000	0.00000
Manganese, Filtered	0.00027	-0.00001	0.00000	0.00000	0.00009	0.00000	0.00000	0.00009	0.00000	0.00007
Nickel, Filtered	0.00232	0.00779	0.00108	0.00011	0.00136	0.00147	0.00048	0.00065	0.00086	0.00057
Thallium, Filtered	0.00564	0.01768	0.00305	0.00033	0.00479	0.00365	0.00138	0.00189	0.00214	0.00156
Zinc, Filtered	0.00000	-0.00001	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00005

yellow high-lighted cells are > values shown

orange high-lighted negative values are washouts (leaching?)

Table 41. Media Mixture Capacities for Radioactive Stormwater Constituents (Pitt and Clark 2000)

	R-SMZ	**R-SMZ-GAC**	**R-SMZ-GAC-PM**	**Site Sand-GAC-Site Zeolite Layered**
	pCi pol/gm media	pCi pol/gm media	pCi pol/gm media	pCi pol/gm media
Gross Alpha	0.09690	0.13504	0.15613	0.10528
Gross Beta	0.03680	0.01535	0.07937	0.06258
Radium-226	0.00411	0.00000	0.00672	0.00474
Radium-228	0.00000	0.00505	0.00750	0.00000
Alpha Radium	0.01662	0.01631	0.02373	0.01725
Strontium-90 (very low influent)*	0.00000	0.00000	0.00000	0.00000
Tritium (very low influent)*	0.00000	0.00000	0.00000	0.00000
Uranium	0.02361	0.03498	0.04082	0.00000

Clark (2000) also calculated the retention capacity for various stormwater filtered pollutants for compost-sand mixtures. This mixture as 50/50 and the capacity was assumed to be associated with the compost component. Other filter study results by Clark and Pitt (2009b) describe issues associated with anaerobic conditions in the media and how that influences retention of retained pollutants and the stability of the media.

Table 42. Calculated Capacity of Compost-Sand Media (Clark 2000)

Pollutant	compost-sand mg/g of compost	compost-sand mg/cm^3 of compost
Carbonate	2.200	4.151
Bicarbonate	0.000	0.000
Sodium	0.000	0.000
Potassium	0.000	0.000
Calcium	0.000	0.000
Magnesium	0.755	1.425
Nitrate	0.015	0.028
Ammonia	0.000	0.000
Phosphate	0.195	0.368
Iron	0.000	0.000
Copper	0.030	0.057
Lead	0.000	0.000
Zinc	1.100	2.075

Effects of Contact Time of Filtered Pollutant Retention by Biofilter Media Components and Mixtures

The Boeing media development tests (Pitt and Clark 2010) included measurements to determine the effects of different contact times of the stormwater with the media on pollutant retention. These tests were conducted using conventional batch reactor tests, and also a series of column tests having different media depths. Table 43 summarizes these results indicating the expected minimum contact time needed to obtain the removals noted previously. In addition, rate factors (derived from standard ln/ln kinetic plots) which indicate how the pollutant retention changes with additional contact time. The yellow high-lighted cells indicated losses of retention with increased contact time. This can be caused by leaching of the pollutants from the media, additional ion exchange of these constituents with other constituents, or decomposition of the media and release of prior retain pollutants. In most cases, the additional contact time results in increased pollutant retention. As noted in this table, some media (especially peat moss) results in substantial retention of the heavy metals with short contact times, while other media may require more than an hour of contact time for the reported retention levels. The following are some of the findings from these media tests for the different media components:

- GAC: most consistent removal and reasonably fast (10 min) removal for organic and metallic compounds; however, rapid (6 min) leaching of nutrients and slow leaching (>6 hrs) for major ions.
- SMZ: relatively slow (at least an hour) and is less consistent for most constituents. Leaching occurred after about 20 min for nutrients and after about 2 hours for metals.
- Rhyolite sand: relatively fast (about 15 min) for nutrients and slow for major ions and metals (>1.5 to 2.5 hrs); no leaching observed.
- Peat: very fast (< 5 min) for metals; very slow and inconsistent for other constituents. Leaching of carbon-containing constituents (organic surrogates) occurred after about 10 minutes, and after about 30 minutes for some major ions and nutrients.
- Site zeolite: very last (1 min) for some organics and nutrients; slow (>1 to 2 hrs) for major ions and metals. Rapid leaching (after 1 min) occurred for some major ions and metals.

These contact time tests were only conducted on the individual components. The combined effects of mixtures in typical biofilters can be calculated based on each component. Also shown are some example calculations showing the effects of these factors on the expected maximum pollutant retentions for 10 min, 100 min (1.7 hrs), and 1,000 minutes (17 hrs). Most biofilters with 0.5 m of media provide substantial media contact time (several hours). WinSLAMM calculates the contact time and these factors can be used to modify the resultant retention.

Table 43. Percent of maximum benefit after contact times: these assume linear changes in reductions with contact time (as illustrated in plots; not much different from theoretical ln/ln plots)

	GAC min time (min)	GAC %/min (after min time)	SMZ min time (min)	SMZ %/min (after min time)	R-sand min time (min)	R-sand %/min (after min time)	PM min time (min)	PM %/min (after min time)	site Z min time (min)	site Z %/min (after min time)
Common Constituents										
Conductivity							100	0.044		
Hardness	80	0.054								
ORP	10	0.020								
pH	10	-0.030								
Carbon Behavior Indicators										
Color	10	0.020	3000	0.045	300	-0.214	3	-0.040		
UV-254	5	0.018	5	0.002			10	-0.030	1	0.008
COD					10	-0.020	20	-0.306		
Major Ions										
Calcium	100	0.044								
Magnesium	100	-0.012	100	-0.006	500	-0.004	30	-0.155	100	0.014
Sodium	1000	-0.010							1	-0.036
Potassium	1	-0.300	100	-0.006	100	-0.004			1	-0.012
Sulfate	200	0.050	300	0.029	300	0.057			100	0.004
Fluoride			1	0.020	1	0.020	100	0.044	200	0.017
Nutrients										
Ammonia	200	0.025	100	0.010	20	0.012	2000	0.017	1	0.090
Nitrate	20	0.061								
Total Nitrogen			20	-0.040			50	-0.158	3	-2.062
Total Phosphorus	10	-0.180			20	0.031	10	-0.025		
Phosphate	1	-0.040			1	0.006	1000	0.015		
Heavy Metals and Trace Constituents										
Aluminum			100	0.056					10	0.023
Antimony	10	0.051	10	0.020			1	0.018	100	0.008
Arsenic	10	0.222					1	0.060	1	-0.250
Boron	30	0.016	30	0.041	100	0.067				
Cadmium	5	0.080	100	0.006	100	0.008	1	0.018	100	0.016
Chromium	1	1.010	50	0.042	100	0.016	1	0.060	30	0.020
Copper	1	0.080	100	0.044	100	0.044	1	0.080	10	0.071
Lead	1	0.016	1	5.556			1	0.505	100	0.020
Manganese	10	0.345	100	-0.020					100	0.044
Nickel	5	0.016	100	0.022	100	0.004	1	0.016	50	0.014
Thallium	5	0.045	5	0.080	30	0.018			10	0.101

yellow high-lighted cells are negative values

Table 44. Example Percentage of maximum Benefit after Different Contact Times (truncated at 100%)

	% reductions after contact times for GAC:			% reductions after contact times for SMZ:			% reductions after contact times for R-sand:			% reductions after contact times for peat:			% reductions after contact times for site Z:		
	10 min	100 min (1.7 hrs)	1,000 min (17 hrs)	10 min	100 min	1,000 min	10 min	100 min	1,000 min	10 min	100 min	1,000 min	10 min	100 min	1,000 min
Common Constituents															
Conductivity											0.0	40.0			
Hardness		1.1	50.0												
ORP	0.0	1.8	20.0												
pH	0.0	-2.7	-30.0												
Carbon Behavior Indicators															
Color	0.0	1.8	19.8						-150.0	-0.3	-3.9	-39.9			
UV-254	0.1	1.7	17.9	0.0	0.2	2.0				0.0	-2.7	-29.8	0.1	0.8	8.0
COD							0.0	-1.8	-19.8		-24	-300			
Major Ions															
Calcium		0.0	40.0												
Magnesium		0.0	-11.0		0.0	-5.5			-2.2		-10.8	-150.0		0.0	12.4
Sodium			0.0										-0.3	-3.6	-36.0
Potassium	-2.7	-29.7	-299.8			-5.5		0.0	-3.7				-0.1	-1.2	-12.0
Sulfate			40.0		-5.7	20.0			40.0					0.0	3.7
Fluoride				0.2	2.0	20.0	0.2	2.0	20.0		0.0	40.0			13.3
Nutrients															
Ammonia			20.0		0.0	9.2		1.0	11.8				0.8	8.9	90.0
Nitrate		4.9	60.0												
Total Nitrogen					-3.2	-39.4					-7.9	-150	-14.4	-200	-2055
Total Phosphorus	0.0	-16.2	-178					2.4	30.0	0.0	-2.3	-24.9			
Phosphate	-0.4	-4.0	-40.0				0.1	0.6	6.0			0.0			
Heavy Metals and Trace Constituents															
Aluminum					0.0	50.0							0.0	2.1	23.2
Antimony	0.0	4.5	50.0	0.0	1.8	20.0				0.2	1.8	18.0		0.0	7.3
Arsenic		20.0	100.0							0.5	5.9	60.0	-2.3	-24.8	-250
Boron		1.1	15.6		2.9	40.0		0.0	60.0						
Cadmium	0.4	7.6	80.0		0.0	5.5		0.0	7.3	0.2	1.8	18.0		0.0	14.7
Chromium	9.1	100.0	100.0		2.1	40.0		0.0	14.7	0.5	5.9	60.0		1.4	19.5
Copper	0.7	7.9	80.0		0.0	40.0		0.0	40.0	0.7	7.9	80.0	0.0	6.4	70.0
Lead	0.1	1.6	16.0	50.0	100.0	100.0		0.0	0.0	4.5	50.0	100.0		0.0	18.4
Manganese	0.0	31.0	100.0		0.0	-18.4								0.0	40.0
Nickel	0.1	1.5	15.9		0.0	20.0		0.0	3.7	0.1	1.6	16.0		0.7	13.4
Thallium	0.2	4.3	44.9	0.4	7.6	80.0		1.3	17.6				0.0	9.1	100.0

Clark (2000) also measured contact time effects on the retention of stormwater pollutants in biofilter media. The following equation is the ratio of the effluent to the influent concentrations (after ln transformations) based on the intercept (ln*b*) and the slope (-kt) of the relationship:

$$\ln\left(\frac{C_e}{C_0}\right) = \ln b - kt$$

The calculated ratios are used to determine the percentages of the removals observed at different contact times. For example, if the maximum removal is 50%, but only 10% available after 100 minutes contact (using the above equation), then the actual removal would be 5% for that contact period.

Table 45. Contact Time Kinetics for Pollutant Retention for Biofilter Media (from Clark 2000)

		Sand	Carbon-Sand	Peat-Sand	Compost-Sand
carbonate	ln b	0	0	0	0
	k (min-1)	n/a	n/a	0.041	n/a
bicarbonate	ln b	0	0	0	0
	k (min-1)	n/a	0.0026	n/a	0.0058
calcium	ln b	0	0	-0.3006	0
	k (min-1)	n/a	n/a	0.0082	0.0058
magnesium	ln b	0	0	-0.1697	0
	k (min-1)	n/a	n/a	0.005	0.0026
potassium	ln b	0	0	0	-0.5055
	k (min-1)	n/a	n/a	0.0012	0.0007
sodium	ln b	0	0	0	0
	k (min-1)	0.0014	n/a	n/a	0.0011
sulfate	ln b	0	0	0	0
	k (min-1)	n/a	n/a	0.0058	n/a
ammonia	ln b	0	0	-3.3069	0
	k (min-1)	0.0019	0.0176	0.0202	0.0783
nitrate	ln b	0	0	0	0
	k (min-1)	0.001	n/a	n/a	0.0204
phosphate	ln b	0	0	0	0
	k (min-1)	n/a	n/a	n/a	n/a
copper	ln b	0	0	-1.0193	0
	k (min-1)	n/a	n/a	0.0079	0.0093
lead	ln b	0.3437	0	-3.1694	0
	k (min-1)	0.0151	n/a	0.0085	n/a
zinc	ln b	0	0	-0.5112	0
	k (min-1)	n/a	n/a	0.0105	n/a
iron	ln b	0	0	-3.1988	0
	k (min-1)	n/a	n/a	0.0155	0.018

Numeric Example for Biofilter Media Performance Included in WinSLAMM

The follow is an example showing how the information in this memo is used in WinSLAMM to calculate the flow rate through a biofilter and its particulate removal and filter pollutant removal performance. Clogging calculations and media sorption capacity are also calculated. The following describes the site and runoff conditions (for one example rain event of 1 inch):

Drainage area:

One acre (43,560 ft^2 or 4,050 m^2) pavement

Stormwater characteristic (non-filtered forms of phosphorus and copper, along with other particulate-bound pollutants, are removed along with the TSS, so only a selection of filtered pollutants are listed below as examples, along with the TSS and bacteria):

TSS: 300 mg/L
Ammonia as N: 0.9 mg/L
Nitrates as N: 20 mg/L
Phosphates as P: 2.3 mg/L
Cu, filtered: 15 ug/L
E. coli: 135 #/100 mL
Enterococci: 50 #/100 mL

Particle size distribution of stormwater particulates

stormwater PSD size range	Percentage of particulates in each stormwater influent PSD range
<3	10
3-12	10
13-30	15
31-60	25
61-150	25
151-300	10
301-2000	5
	100

Biofilter area:

4% of paved drainage area (1,742 ft^2 or 162 m^2)

Media mixture:

granular activated carbon (30%)
Peat moss (30%)
Fine sand (40%)

Media depth and void ratio:

18 inches (0.46 m)
Void ratio: 25%

Step 1: Particle size distribution of the media mixture

The PSD of the media mixture allows the median size (D50) and the uniformity (Cu = D60/D10) to be determined. These values are needed to determine several performance aspects of the biofilter, including the flow rate through the media mixture and the stormwater particulate retention by the media. Table 46 shows the calculations to obtain the mixture psd. The percentages in the media size ranges are from Master Table 1b. Figure 5 is a PSD plot for the resulting mixture.

Table 46. Calculations to Obtain Media Mixture PSD

media size range (µm)	fine sand % in range	X0.4	GAC % in range	X0.3	Peat % in range	X0.3	sum for mixture % in range	size µm	accumulative percentage
<3	0	0	0	0	0	0	0	3	0
3-12	0	0	0	0	0	0	0	12	0
13-30	0	0	0	0	1	0.3	0.3	30	0.3
31-60	1	0.4	0	0	2	0.6	1	60	1.3
61-150	21	8.4	0	0	12	3.6	12	150	13.3
151-300	33	13.2	1	0.3	17	5.1	18.6	300	31.9
301-1000	37	14.8	9	2.7	28	8.4	25.9	1000	57.8
1001-2000	4	1.6	36	10.8	10	3	15.4	2000	73.2
2001 - 3000	2	0.8	36	10.8	5	1.5	13.1	3000	86.3
3001-4000	2	0.8	13	3.9	7	2.1	6.8	4000	93.1
4001-6000	0	0	5	1.5	9	2.7	4.2	6000	97.3
6001 - 8000	0	0	0	0	2	0.6	0.6	8000	97.9
>8000	0	0	0	0	7	2.1	2.1		
sum:	100	40	100	30	100	30	100		

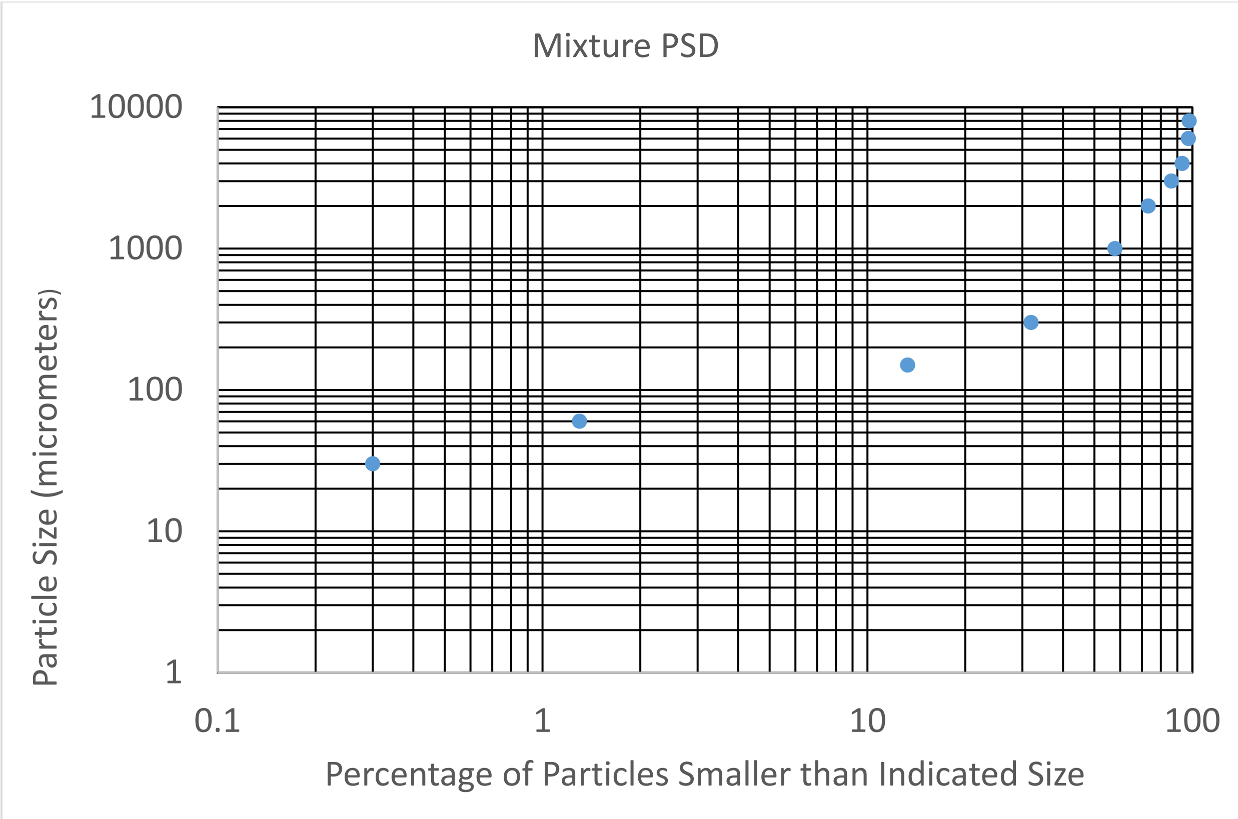

Figure 5. Calculated PSD plot for media mixture.

The following particle sizes correspond to the associated percentage distributions:

D10: 120 µm
D50: 850 µm
D60: 1,100 µm

Therefore, the median size for the media mixture is 850 µm and the uniformity coefficient (D60/D10), Cu, is 9.2

Step 2: Stormwater particulate removal by particle size range

Based on the median particle size of the media mixture, Table 11 for low to high concentrations (50 to 500 SSC mg/L), intermediate media (about 1000 to 2000 um) is used to calculate the particulate retention of the mixed media. Table 10 is used if the media median particle size is <650 µm, Table 11 is used if the median particle size is 650 to 3,500 µm, and Table 12 is used if the median particle size is >3,500 µm.

Table 47. Particulate Solids Removal Calculations

	Fraction of material in each stormwater influent PSD Range	inf part solids conc. Total = 300 mg/L	effluent for intermediate media mixture	effluent % psd	accumulative %

			(from Table 11 for approximate size ranges)		
stormwater PSD Range		conc in size range			
<3	10	30	30.0*	36.9	36.9
3-12	10	30	26.8	33.0	69.9
13-30	15	45	17.1	21.0	90.9
31-60	25	75	3.33	4.1	95.0
61-150	25	75	3.33	4.1	99.1
151-300	10	30	0.7	0.9	100.0
301-2000	5	15	0	0.0	100.0
	100	300 mg/L	81.3 mg/L	100	

*effluent concentration cannot be greater than influent concentration for each particle size range, except for <3 µm where increased concentration can be associated with fines being washed from media.

Therefore, the particulate solids concentrations decreased from 300 to 81 mg/L for this example event (about 73% reduction in concentration). The mass concentration reduction could be greater, depending on the runoff volume losses due to infiltration. Particulate forms of other pollutants would also be reduced depending on their fraction in each particle size range. Currently, WinSLAMM applies the bulk solids reduction (73% here) to the particulate pollutant fraction. An upcoming update to WinSLAMM will calculate pollutant reductions based on their specific associations with each size range.

Step 3: Stormwater flow rate through media

Master Table 2 lists the infiltration rate values for individual media components and for selected mixtures, as shown below.

	in/hr
fine sand	13
GAC	40
peat	use peat/sand equations

Because of the peat content, special equations using the median particle size and uniformity (and compaction) values are used to calculate the infiltration rate for the media mixture. In this case, the organic content is high (>10%), as the peat fraction is 30%.

hand compaction with high organic matter: $\log Fc = 1.84 + 0.000522\,(D50) - 0.0648(Cu)$

For this example, the log Fc value is 1.68, and the resulting Fc is therefore 48.7 cm/hr, or 19.2 in/hr. This is the initial flow rate through the media before it is decreased by clogging.

Step 4: Flow rate decreases due to clogging

Master Table 2 also includes information concerning the maximum particulate solids loading expected before clogging failure. The clogging value for a mixture is calculated based on the weighted mixture components. Final values much larger than 20 kg/m2 should be suspect, as that is the value observed in the field. Also, if this value is reached before about 10 years, the biofilter will likely cease to function due to clogging. However, if this load value takes more than 10 years, and the plants in the biofilter remain healthy and vigorous, the plants can incorporate this material into the surface soil material and the plant roots can keep the system operating (but with reduced surface storage volumes). The following table shows this weighted calculation for the maximum sediment load before clogging:

	Maximum sediment load, from Master Table 2, kg/m^2	% in mixture	weighted capacity
fine sand	10	40	4
GAC	38 (coarse material)	30	11.4
peat	20	30	6
		sum:	21.4 kg/m^2

The biofilter being examined has a surface area of about 162 m^2. The sediment discharged to the biofilter is calculated for each individual event, and the amount retained is calculated. For a one-inch rain over a one acre paved parking area, the runoff volume would be about 87 m^3 (assuming an Rv of 0.85). The TSS concentration is 300 mg/L and 73% is retained in the biofilter, based on prior calculations. The total sediment load retained in the biofilter for this event is therefore about 0.12 kg/m^2. The next event would therefore have a slightly reduced flow rate (reduced by the ratio of 0.12/21.4), or about 19.16 in/hr. After one year, the total annual accumulation is examined. If it is > 1/10 of the maximum (or 2.14 kg/m^2), then the rate continues to decrease after each event and the biofilter is shut down due to clogging when the 21.4 kg/m^2 maximum accumulation is reached. For this example, the maximum load may be reached after about 180 inches of rain. For sites having more than about 18 inches of rain per year, the biofilter may prematurely clog. If the total accumulation after one year is <1/10 of the maximum, the biofilter is likely to continue to function without clogging (requires excellent vegetation cover). In this case, the flow rate is not decreased any further after the first year. However, the surface storage of the biofilter is always decreased after each event based on the accumulated sediment after each rain.

Step 5: Retention of filtered pollutants

Master Table 3 also notes the procedures to calculate the retention of the filtered pollutants. For the three media material in the mixture, the Boeing equations are used, as shown on Tables 25, 26, and 28. These calculations are only for the filtered forms of the pollutants as the particulate forms are removed along with the particulate solids. The following tables summarize these calculations.

	influent concentration	GAC removal equation	peat removal equation	sand removal equation
copper (filtered), ug/L	15	Y = 6.8 (0.64)*	Y = 12.3 (0.26)	Y = X
ammonia, mg/L	0.9	Y = 0.27 (2.1)	Y = X	Y = 0.54X
nitrate, mg/L	20	Y = 46 (0.63)	Y = X	Y = X
phosphate, mg/L	2.3	Y = 3.7 (0.62)	Y = X	Y = 0.48X

*coefficient of variation (COV)

	effluent for media component			weighted calculation				
	GAC	peat	sand	GAC X 0.3	peat X 0.3	sand X 0.4	sum (final conc)	% reductions for filtered form
copper (filtered),	6.8	12.3	15	2.04	3.69	6.0	11.73	21.8
ammonia	0.27	0.9	0.486	0.081	0.27	0.1944	0.5454	39.4
nitrate	46	20	20	13.8	6.0	8.0	27.8	-39.0
phosphate	3.7	2.3	1.104	1.11	0.69	0.4416	2.2416	2.5

Step 5.1 Bacteria retention by media mixture

Master Table 3 also indicates the procedures for calculating the retention of bacteria in the biofilters. For these media components, Table 34 is used. The following shows these weighted calculations for these media components for *E. coli* and enterococci (using the median values).

	Bacteria retention method from Master table 3	*E. coli* median removal (%)	Enterococci median removal (%)	fraction in mixture
fine sand	Clark dissert sand	44	53	0.4
GAC	no removal	0	0	0.3
peat	Clark dissert peat-sand	66	47	0.3
weighted removal (%)		37.4	35.3	
COV		0.8	1.1	

	Influent concentration (#/100 mL)	Weighted % reduction	Effluent concentration (#/100 mL)
E. coli	135	37.4	85
Enterococci	50	35.3	32

Step 5.2 Residence/contact time effects on filtered pollutant removal
The contact time of the stormwater with the media only affects the filtered pollutants (not the particulate-bound pollutants). Table 43 shows the percent increased removals (or leaching) after the minimum contact time is reached. These modifications in removals are only applicable for thin media use. The prior removal calculations are based on the full-depth media (about 18 inches) for well-mixed media. Layered media results in uneven contact times for each media type, while finer media material mixed with coarse material results in a moderated and constant contact time for all media. The calculated contact time for this media mixture example is about 14 minutes. Longer contact times can also occur with the use of sealed bottoms of biofilters and restricted underdrains. The following shows the contact time effects for these media components for the four filtered pollutants:

	GAC	GAC	R-sand	R-sand	PM	PM
	min time (min)	%/min (after min time)	min time (min)	%/min (after min time)	min time (min)	%/min (after min time)
Ammonia	200	0.025	20	0.012	2000	0.017
Nitrate	20	0.061				
Phosphate	1	-0.04	1	0.006	1000	0.015
Copper	1	0.08	100	0.044	1	0.08

Ammonia is mostly removed by the Rhyolite sand due to the very long contact times required for the GAC and peat for ammonia removal. Nitrate is only shown to be removed by the GAC, while GAC and Rhyolite sand affect phosphate and GAC and peat affect the copper for the contact times available.

Step 5.3 Media capacity before breakthrough
Table 40 lists the media capacities for the different filtered pollutants for various media components, as summarized below:

mg pollutant/kg media	GAC	peat	sand
copper (filtered)	0.00359	0.00825	
ammonia	0.23577		0.00073
nitrate	0.52873		0.00338
phosphate			0.00205

The following table shows the weighted capacity of the media mixture for these four filtered pollutants:

	weighted capacity			mg pollutant/gram media	mg pollutant capacity for biofilter
	GAC 0.3	peat 0.3	sand 0.4	total capacity	
copper (filtered)	0.001077	0.002475	0	0.003552	394,453
ammonia	0.070731	0	0.000292	0.071023	7,887,175
nitrate	0.158619	0	0.001352	0.159971	17,764,940
phosphate	0	0	0.00082	0.00082	91,062

Step 5.4 Media run time before breakthrough
These media capacity values are tracked after each event. The filtered pollutant removals do not change as the capacity is consumed, but abruptly stop being retained when the capacities are reached (breakthrough, with effluent concentrations = influent concentrations).

pollutant	influent conc for example event	effluent conc for example event	retained conc for example event	retained mass for example event	Retained mass (mg) for example event
copper (filtered), ug/L	15	11.73	3.27	285,798 ug	286 mg
ammonia, mg/L	0.9	0.5454	0.3546	30,992 mg	30,992 mg
nitrate, mg/L	20	27.8	-7.8	n/a	n/a
phosphate, mg/L	2.3	2.2416	0.0584	5,104 mg	5,104 mg

	mg pollutant capacity for biofilter	fraction of total consumed by example 1 inch rain	approx inches of rain before breakthrough
copper (filtered)	394,453	0.000725	1,380
ammonia	7,887,175	0.003929	254
nitrate	17,764,940	n/a	n/a
phosphate	91,062	0.056052	18

The media mixture has limited capacity for phosphate, while the ammonia capacity is expected to last slightly longer than for the TSS clogging period, while the capacity for the filtered copper is very large and expected to last for a long period. Negative removals (such as for nitrates) do not recover media capacity and usually indicate release from the media material.

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Appendix A1: Media Test Materials and Observed Treatment Flow Rates

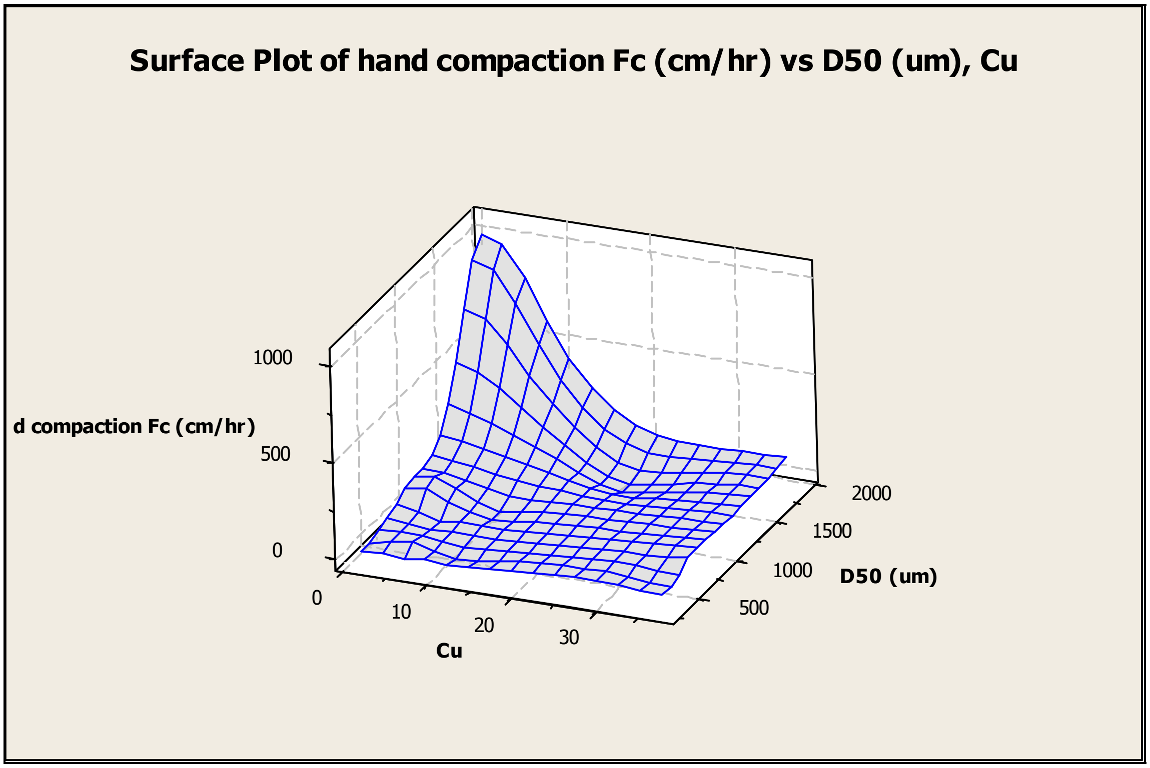
Media Test Materials					Hand Compactions		Standard Proctor Compaction		Modified Proctor Compaction	
Components	Mixture	D_{50} (um)	C_u	% organic matter	F_c (cm/hr) and COV	density (g/cm^3)	F_c (cm/hr) and COV	density (g/cm^3)	F_c (cm/hr) and COV	density (g/cm^3)
6/10 sand from Atlanta, 10/30 sand Atlanta, and peat	10% Peat, 45% 6/10 Sand, and 45% of 10/30 Sand	1875	2.1	10	1028 (0.36)	1.52	1005 (0.24)	1.54	1001 (0.35)	1.58
6/10 sand from Atlanta, 10/30 sand Atlanta, and peat	25% Peat, 37.5% 6/10 Sand, and 37.5% of 10/30 Sand	1875	2	25	805 (0.28)	1.38	665 (0.48)	1.46	452 (0.58)	1.47
6/10 sand from Atlanta, 10/30 sand Atlanta, and peat	50% Peat, 25% 6/10 Sand, and 25% of 10/30 Sand	1625	2.5	50	282 (0.31)	0.96	126 (0.24)	1.18	110 (0.34)	1.23
Concrete Sand from Atlanta , 10/30 Sand from Atlanta , and Peat	10% Peat, 45% Concrete Sand, and 45% of 10/30 Sand	900	3.8	10	159 (0.2)	1.7	122 (0.11)	1.8	72.3 (0.87)	1.82
Concrete Sand from Atlanta , 10/30 Sand from Atlanta , and Pea	25% Peat, 37.5% Concrete Sand, and 37.5% of 10/30 Sand	950	4	25	158 (0.4)	1.5	130 (0.28)	1.6	91.2 (0.22)	1.67
Concrete Sand from Atlanta , 10/30 Sand from Atlanta , and Pea	50% Peat, 25% Concrete Sand, and 25% of 10/30 Sand	975	4.3	50	275 (31)	1.13	89.8 (0.12)	1.31	72.2 (0.1)	1.32

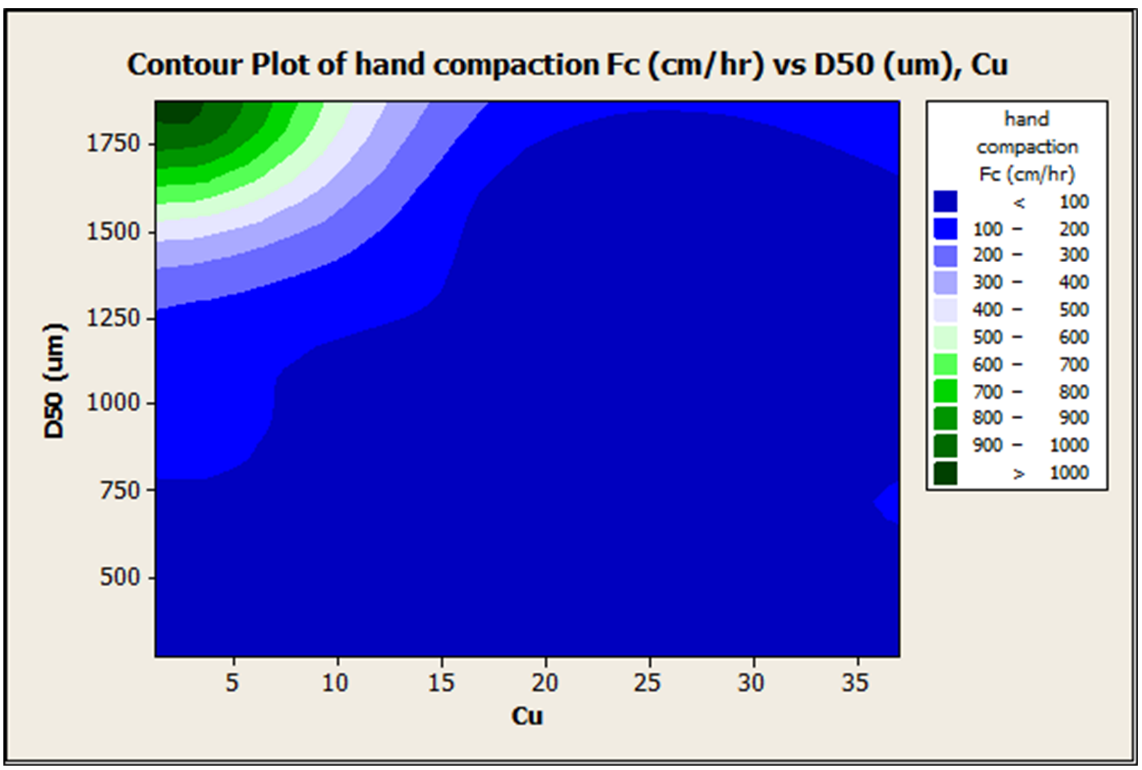
Media Test Materials (continued)					Hand Compactions		Standard Proctor Compaction		Modified Proctor Compaction	
Components	Mixture	D_{50} (um)	C_u	% organic matter	F_c (cm/hr) and COV	density (g/cm^3)	F_c (cm/hr) and COV	density (g/cm^3)	F_c (cm/hr) and COV	density (g/cm^3)
Sand from Ground Floor (GF) Landscape Supply, Northport, AL, 10/30 Sand from Atlanta, and Pea	10% Peat, 45% GF Sand, and 45% of 10/30 Sand	900	11.4	10	15.07 (0.24)	1.57	6.47 (0.81)	1.66	3.47 (1.42)	1.64
Sand from Ground Floor (GF) Landscape Supply, Northport, AL, 10/30 Sand from Atlanta, and Pea	25% Peat, 37.5% GF Sand, and 37.5% of 10/30 Sand	850	11.4	25	20.74 (0.3)	1.43	8.89 (0.91)	1.49	6.86 (0.84)	1.48
Sand from Ground Floor (GF) Landscape Supply, Northport, AL, 10/30 Sand from Atlanta, and Pea	50% Peat, 25% GF Sand, and 25% of 10/30 Sand	850	11.4	50	66.04 (0.25)	0.95	26.49 (0.3)	1.02	11.68 (0.72)	1.17
Sand from Ground Floor (GF) Landscape Supply, Northport, AL and Peat	10% Peat and 90% GF Sand	340	1.3	10	8.13 (1.49)	1.28	7.75 (0.77)	1.29	5.50 (0.81)	1.35
Sand from Ground Floor (GF) Landscape Supply, Northport, AL and Peat	25% Peat & 75% GF Sand	300	3.5	25	14.31 (0.52)	1.14	6.18 (1.2)	1.1	5.0 (0.81)	1.2
Sand from Ground Floor (GF) Landscape Supply, Northport, AL and Peat	50% peat and 50% GF sand	300	3.3	50	41.87 (0.9)	0.74	12.02 (0.2)	0.96	7.11 (0.84)	1.03

Media Test Materials (continued)					Hand Compactions		Standard Proctor Compaction		Modified Proctor Compaction	
Components	Mixture	D_{50} (um)	C_u	% organic matter	F_c (cm/hr) and COV	density (g/cm^3)	F_c (cm/hr) and COV	density (g/cm^3)	F_c (cm/hr) and COV	density (g/cm^3)
Sand from Ground Floor (GF) Landscape Supply, Northport, AL, 6/10 Sand from Atlanta, and Peat	10% Peat, 45% GF Sand, and 45% of 6/10 Sand	1500	21.9	10	5.76 (1.35)	1.61	5.50 (0.7)	1.64	5.16 (0.52)	1.63
Sand from Ground Floor (GF) Landscape Supply, Northport, AL, 6/10 Sand from Atlanta, and Peat	25% Peat, 37.5% GF Sand, and 37.5% of 6/10 Sand	1500	16.2	25	16.26 (0.79)	1.46	6.86 (0.93)	1.5	6.63 (0.61)	1.52
Sand from Ground Floor (GF) Landscape Supply, Northport, AL, 6/10 Sand from Atlanta, and Peat	50% Peat, 25% GF Sand, and 25% of 6/10 Sand	400	20	50	20.9 (0.9)	1.1	10.2 (0.94)	1.11	9.06 (0.7)	1.1
Tuscaloosa surface soils	15th St. E and 6th Ave. E., (McDonalds)	700	37	6.0	103.7 (1.1)	1.37	3.58 (0.36)	1.64	0.04 (1.1)	1.72
Tuscaloosa surface soils	25th Ave. E and University Blvd.	270	6	2.1	15.8 (0.23)	1.42	2.6 (0.11)	1.62	2.8 (0.24)	1.67
Tuscaloosa surface soils	21st Ave. E. and University Blvd.	400	12	3.3	3.2 (0.18)	1.39	1 (0.57)	1.52	0.1 (0.74)	1.59
Tuscaloosa surface soils	17th Ave. E. and University Blvd.	400	37	4.8	33.9 (0.63)	1.39	1 (0.23)	1.64	0.16 (0.37)	1.79
Wisconsin biofilter media		400	5.6	4	63.6 (0.3)	1.51	15.1 (0.2)	1.74	10.7 (0.2)	1.8
North Carolina biofilter media		700	6	1.5	18.8 (0.68)	1.24	10.2 (0.4)	1.34	5.1 (0.16)	1.36
Kansas City biofilter media		1900	39	14.8	1.4 (0.36)	1.1	1.61 (0.41)	1.13	0.34 (n/a)	1.27

Appendix A2: Statistical Analyses of Sand-Based Media Treatment Flow Rates

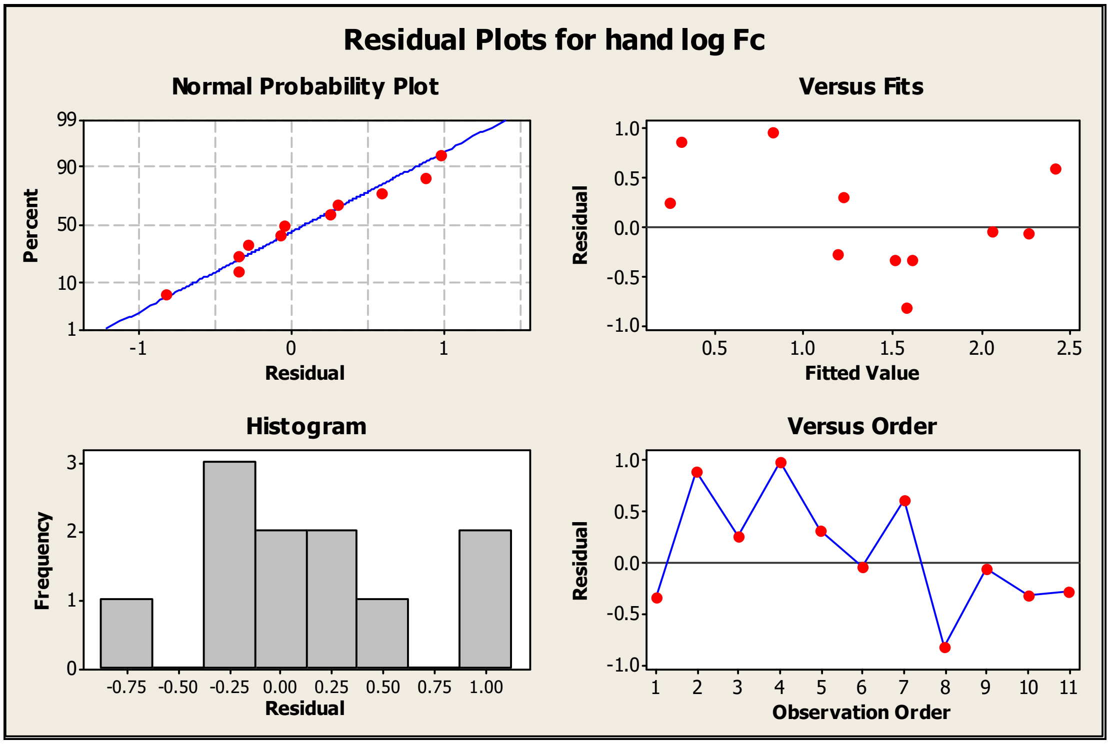
Low Organic Matter Content and Low Compaction



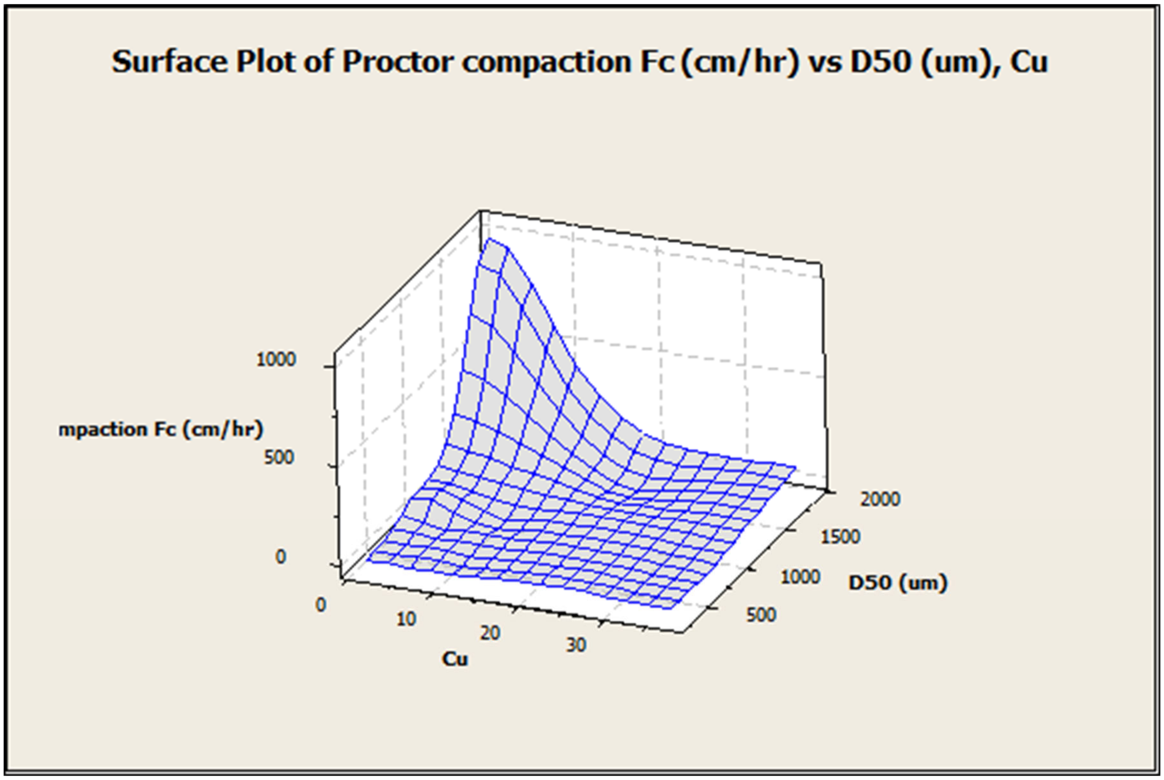


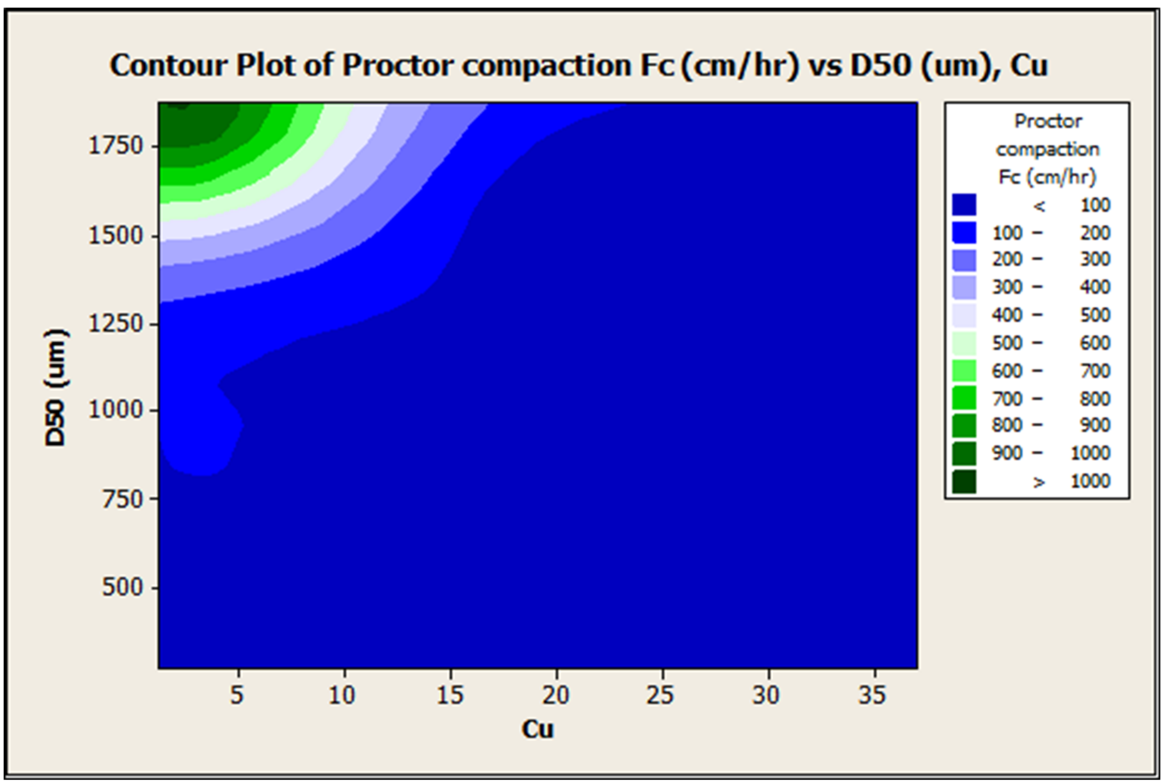
General Regression Analysis: hand log Fc versus D50 sqr, Cu sqr, D50 (um), Cu

```
Regression Equation

hand log Fc  =  -1.72378e-006 D50 sqr + 0.0040969 Cu sqr + 0.00469226 D50 (um)
                - 0.161734 Cu


Coefficients

Term           Coef    SE Coef         T      P            95% CI
D50 sqr   -0.000002  0.0000007  -2.49115  0.042  (-0.000003, -0.0000001)
Cu sqr     0.004097  0.0020076   2.04069  0.081  (-0.000650,  0.0088441)
D50 (um)   0.004692  0.0013249   3.54160  0.009  ( 0.001559,  0.0078251)
Cu        -0.161734  0.0823296  -1.96447  0.090  (-0.356412,  0.0329449)


Summary of Model

S = 0.680555     R-Sq = 89.08%        R-Sq(adj) = 82.84%
PRESS = 16.3884  R-Sq(pred) = 44.79%


Analysis of Variance

Source      DF   Seq SS   Adj SS   Adj MS        F          P
Regression   4  26.4434  26.4434  6.61085  14.2735  0.0017727
  D50 sqr    1  15.7805   2.8743  2.87426   6.2058  0.0415266
  Cu sqr     1   3.6088   1.9288  1.92877   4.1644  0.0806312
  D50 (um)   1   5.2667   5.8093  5.80933  12.5429  0.0094495
  Cu         1   1.7874   1.7874  1.78738   3.8591  0.0902241
Error        7   3.2421   3.2421  0.46316
Total       11  29.6855


Fits and Diagnostics for Unusual Observations

Obs  hand log Fc      Fit    SE Fit  Residual  St Resid
  7      3.01199  2.41625  0.613837  0.595743   2.02724  R

R denotes an observation with a large standardized residual.


Durbin-Watson Statistic

Durbin-Watson statistic = 1.86917
```


Residual Plots for hand log Fc
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

Low Organic Matter Content and Moderate Compaction





General Regression Analysis: proctor log versus D50 sqr, Cu sqr, D50 (um), Cu

Regression Equation

```
proctor log Fc  =  -1.29188e-006 D50 sqr + 0.00356202 Cu sqr + 0.00407119 D50
                   (um) - 0.174961 Cu
```

Coefficients

Term	Coef	SE Coef	T	P	95% CI
D50 sqr	-0.000001	0.0000004	-3.49524	0.010	(-0.000002, -0.0000004)
Cu sqr	0.003562	0.0010724	3.32164	0.013	(0.001026, 0.0060978)
D50 (um)	0.004071	0.0007077	5.75274	0.001	(0.002398, 0.0057446)
Cu	-0.174961	0.0439765	-3.97851	0.005	(-0.278949, -0.0709729)

Summary of Model

```
S = 0.363520      R-Sq = 94.93%        R-Sq(adj) = 92.03%
PRESS = 3.61422   R-Sq(pred) = 80.19%
```

Analysis of Variance

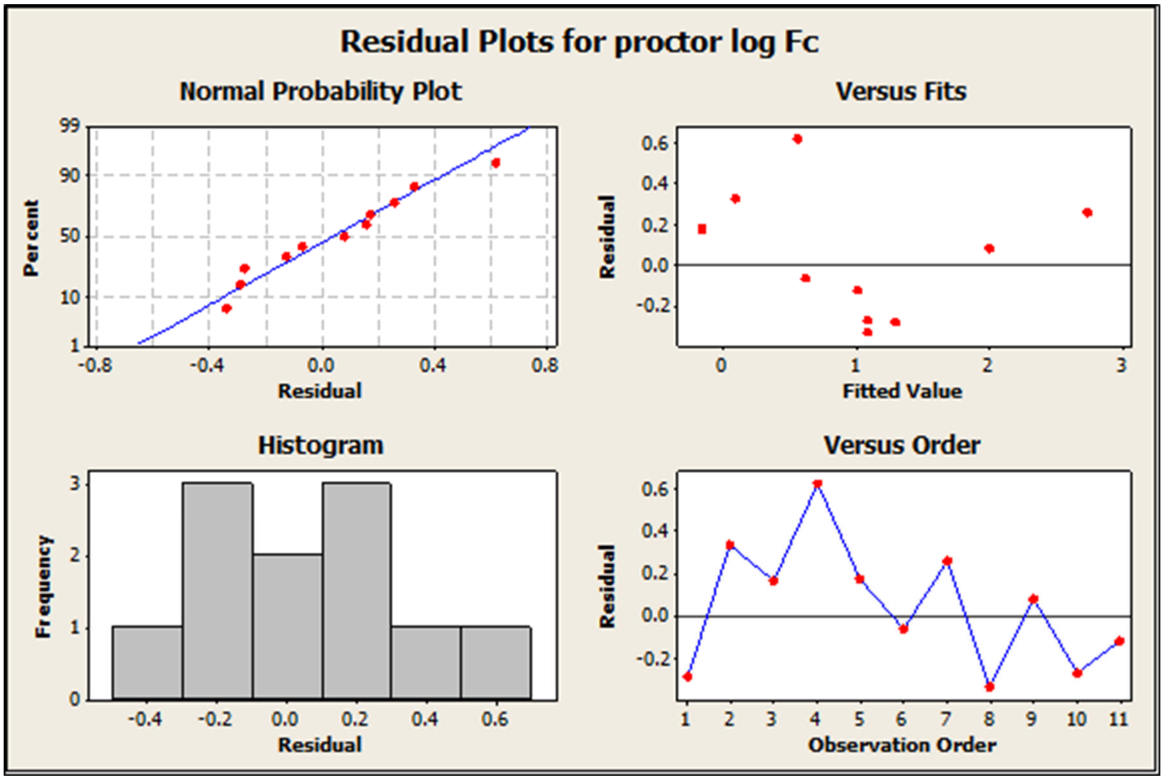
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	4	17.3237	17.3237	4.33092	32.7736	0.0001268
D50 sqr	1	12.6908	1.6144	1.61439	12.2167	0.0100574
Cu sqr	1	0.0405	1.4580	1.45801	11.0333	0.0127363
D50 (um)	1	2.5007	4.3733	4.37326	33.0940	0.0006965
Cu	1	2.0917	2.0917	2.09169	15.8285	0.0053340
Error	7	0.9250	0.9250	0.13215		
Total	11	18.2487				

Fits and Diagnostics for Unusual Observations

No unusual observations

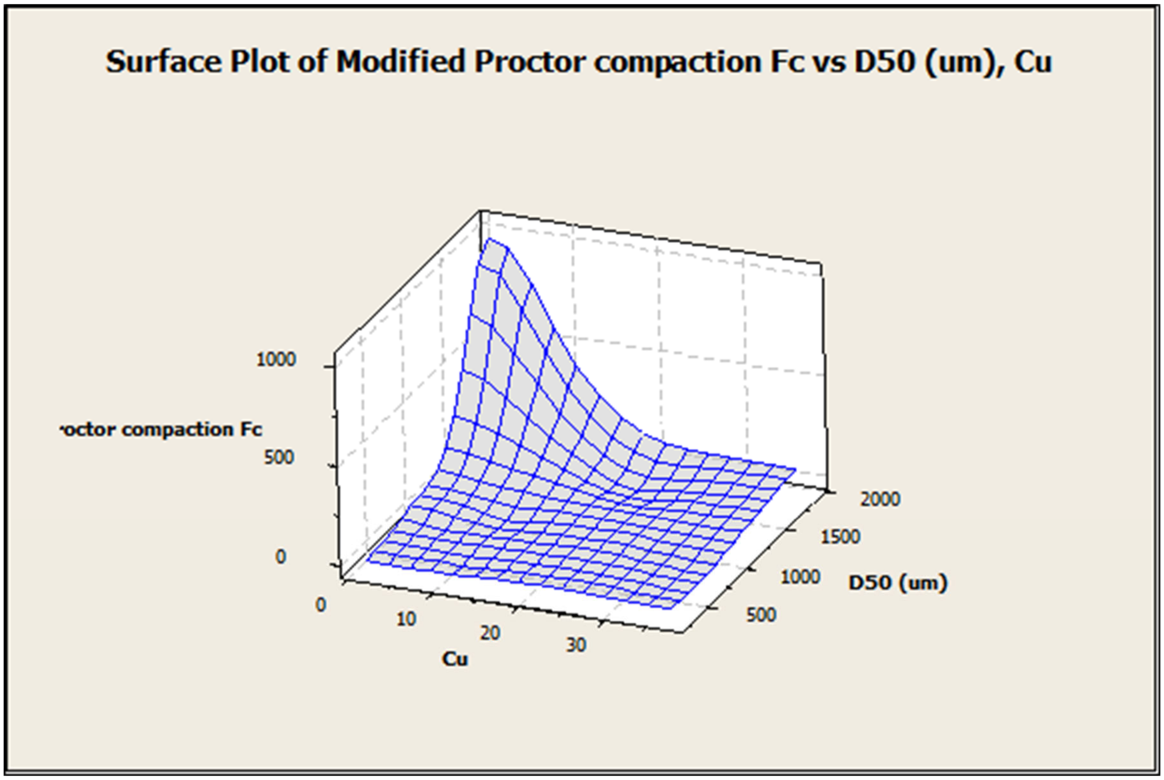
Durbin-Watson Statistic

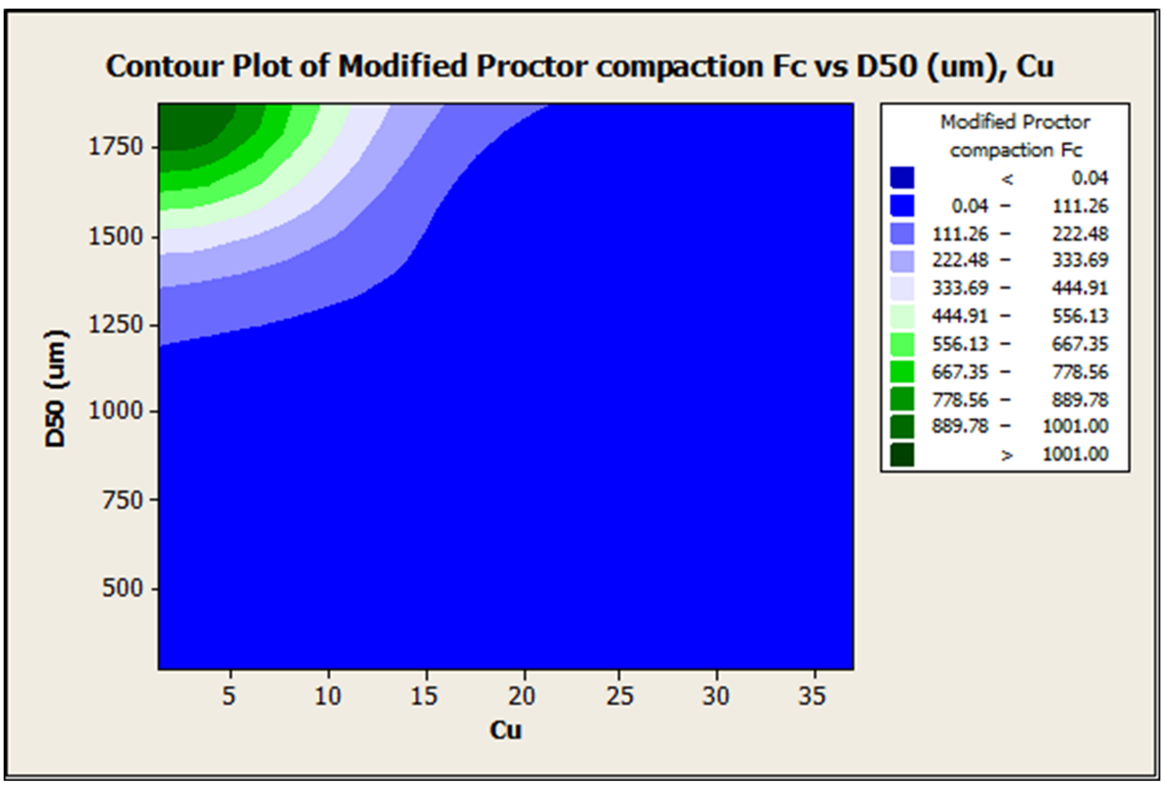
Durbin-Watson statistic = 1.80960



Residual Plots for proctor log Fc
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

Low Organic Matter Content and High Compaction





General Regression Analysis: mod proctor log Fc versus D50 (um), Cu

Regression Equation

```
mod proctor log Fc  =  0.00161573 D50 (um) - 0.0589628 Cu
```

Coefficients

Term	Coef	SE Coef	T	P	95% CI
D50 (um)	0.0016157	0.0002317	6.97380	0.000	(0.0010916, 0.0021398)
Cu	-0.0589628	0.0115814	-5.09117	0.001	(-0.0851617, -0.0327639)

Summary of Model

```
S = 0.568243      R-Sq = 84.83%        R-Sq(adj) = 81.46%
PRESS = 4.79578   R-Sq(pred) = 74.96%
```

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	16.2488	16.2488	8.1244	25.1606	0.0002064
D50 (um)	1	7.8792	15.7039	15.7039	48.6339	0.0000651
Cu	1	8.3696	8.3696	8.3696	25.9200	0.0006529
Error	9	2.9061	2.9061	0.3229		
Total	11	19.1549				

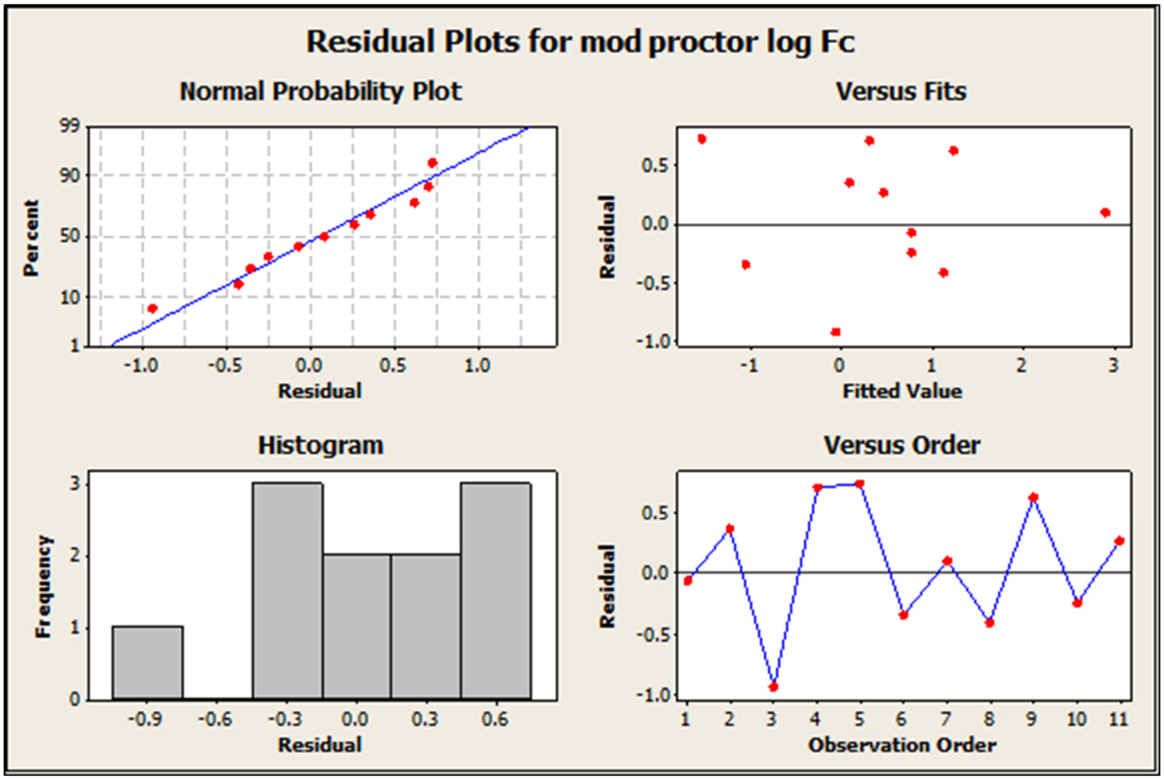
Fits and Diagnostics for Unusual Observations

Obs	mod proctor log Fc	Fit	SE Fit	Residual	St Resid	
7	3.00043	2.90567	0.420821	0.0947592	0.248157	X

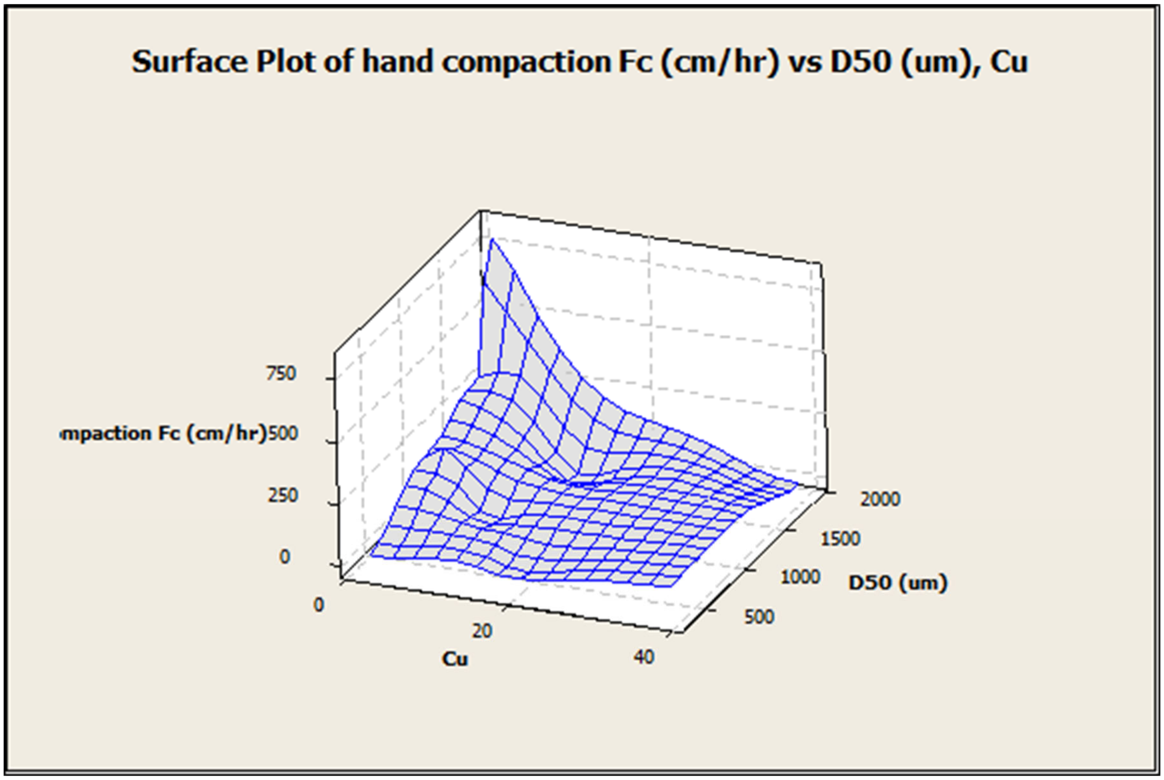
X denotes an observation whose X value gives it large leverage.

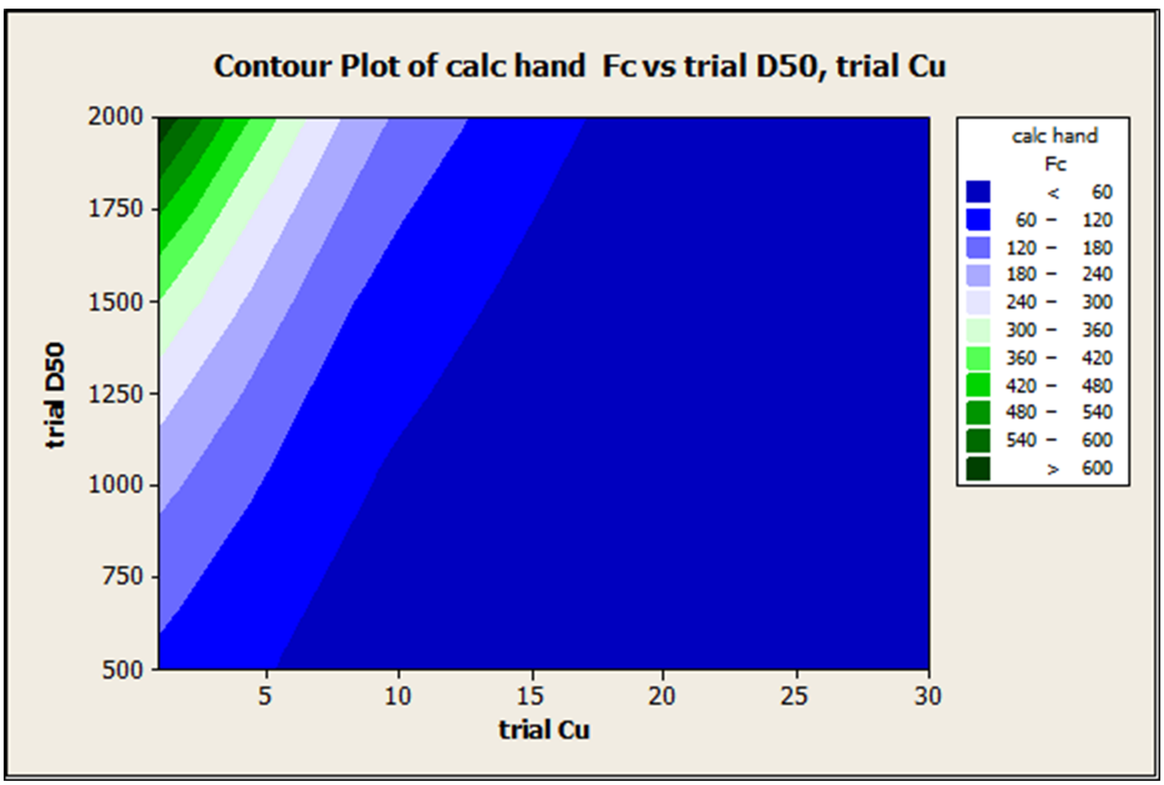
Durbin-Watson Statistic

Durbin-Watson statistic = 2.88217


Residual Plots for mod proctor log Fc
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

High Organic Matter Content and Low Compaction





General Regression Analysis: hand log Fc versus D50 (um), Cu

Regression Equation

hand log Fc = 1.83529 + 0.000522149 D50 (um) - 0.0647993 Cu

Coefficients

Term	Coef	SE Coef	T	P
Constant	1.83529	0.251425	7.29957	0.000
D50 (um)	0.00052	0.000216	2.41699	0.042
Cu	-0.06480	0.011542	-5.61432	0.001

Summary of Model

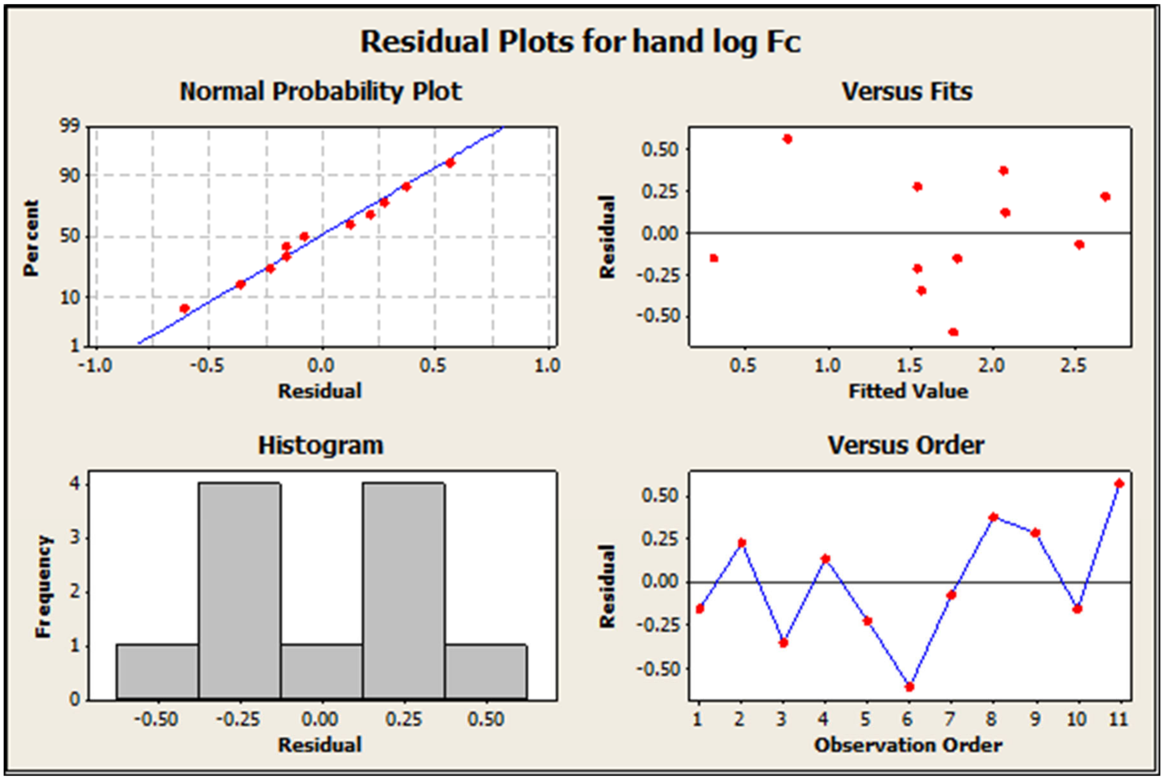
S = 0.389282 R-Sq = 80.04% R-Sq(adj) = 75.04%
PRESS = 2.68992 R-Sq(pred) = 55.70%

Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	4.86000	4.86000	2.43000	16.0354	0.001589
D50 (um)	1	0.08336	0.88527	0.88527	5.8418	0.042047
Cu	1	4.77664	4.77664	4.77664	31.5206	0.000502
Error	8	1.21232	1.21232	0.15154		
Lack-of-Fit	7	1.08582	1.08582	0.15512	1.2262	0.603501
Pure Error	1	0.12650	0.12650	0.12650		
Total	10	6.07233				

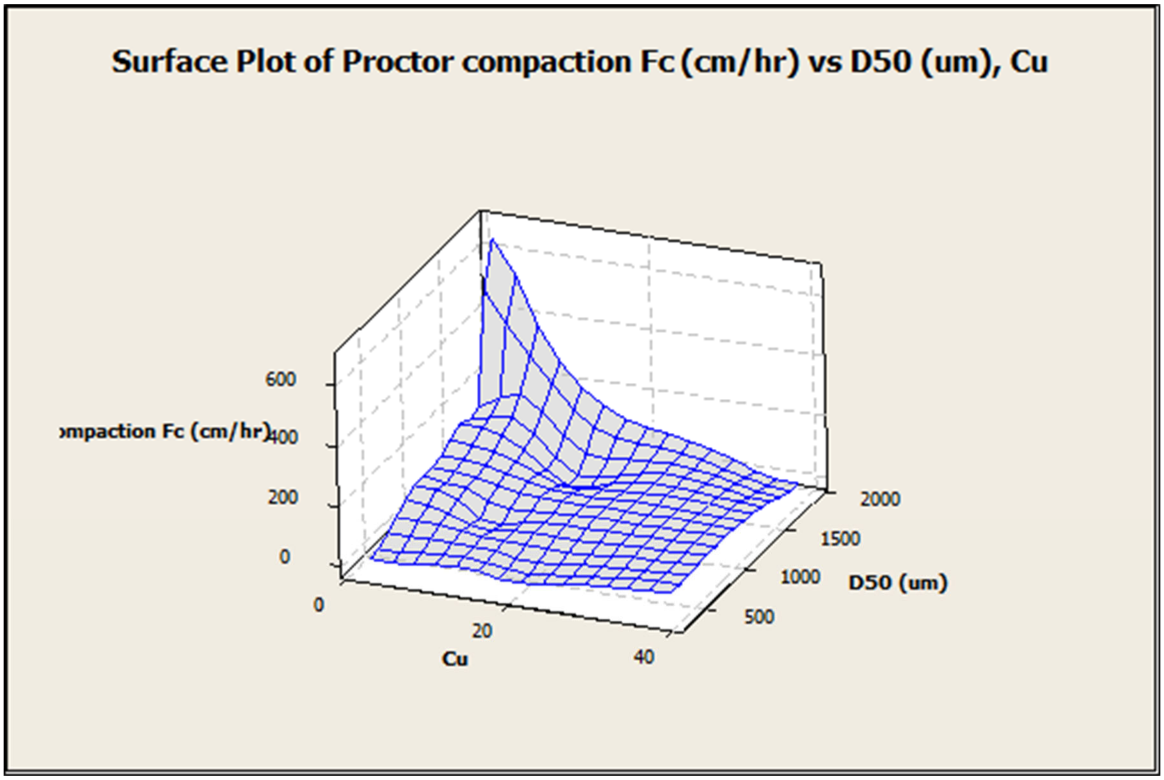
Fits and Diagnostics for Unusual Observations

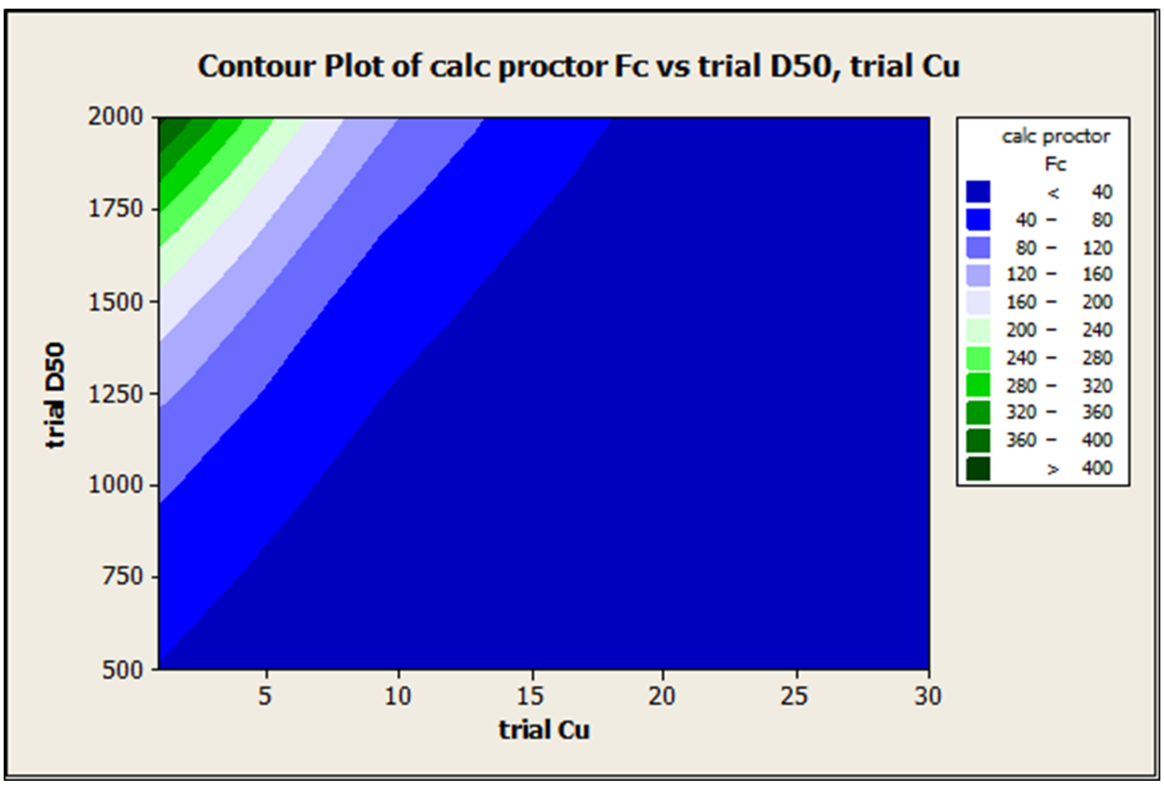
No unusual observations



Residual Plots for hand log Fc
Normal Probability Plot
Percent
99
90
50
10
1
-1.0
-0.5
0.0
0.5
1.0
Residual
Versus Fits
Residual
0.50
0.25
0.00
-0.25
-0.50
0.5
1.0
1.5
2.0
2.5
Fitted Value
Histogram
Frequency
4
3
2
1
0
-0.50
-0.25
0.00
0.25
0.50
Residual
Versus Order
Residual
0.50
0.25
0.00
-0.25
-0.50
1
2
3
4
5
6
7
8
9
10
11
Observation Order

High Organic Matter Content and Moderate Compaction





General Regression Analysis: proctor log Fc versus D50 (um), Cu

Regression Equation

proctor log Fc = 1.30875 + 0.000682833 D50 (um) - 0.0593612 Cu

Coefficients

Term	Coef	SE Coef	T	P
Constant	1.30875	0.276733	4.72929	0.001
D50 (um)	0.00068	0.000238	2.87172	0.021
Cu	-0.05936	0.012704	-4.67280	0.002

Summary of Model

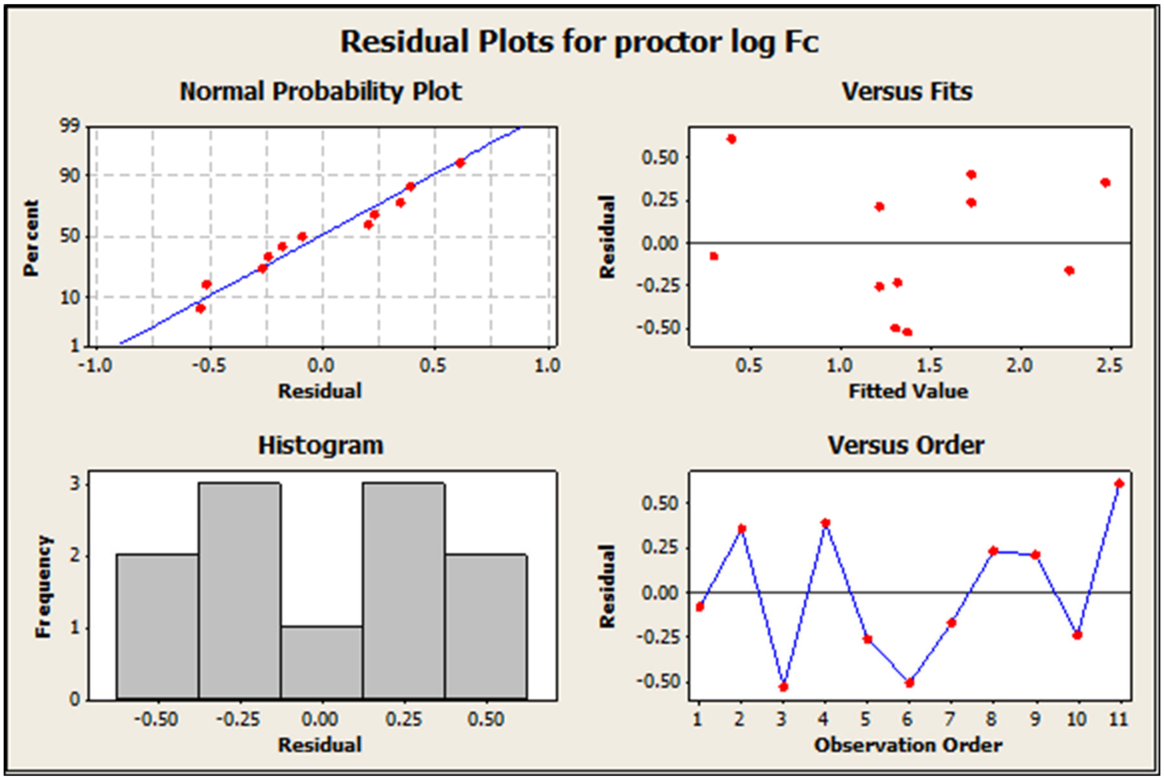
S = 0.428466   R-Sq = 75.11%   R-Sq(adj) = 68.89%
PRESS = 2.90642   R-Sq(pred) = 50.75%

Analysis of Variance

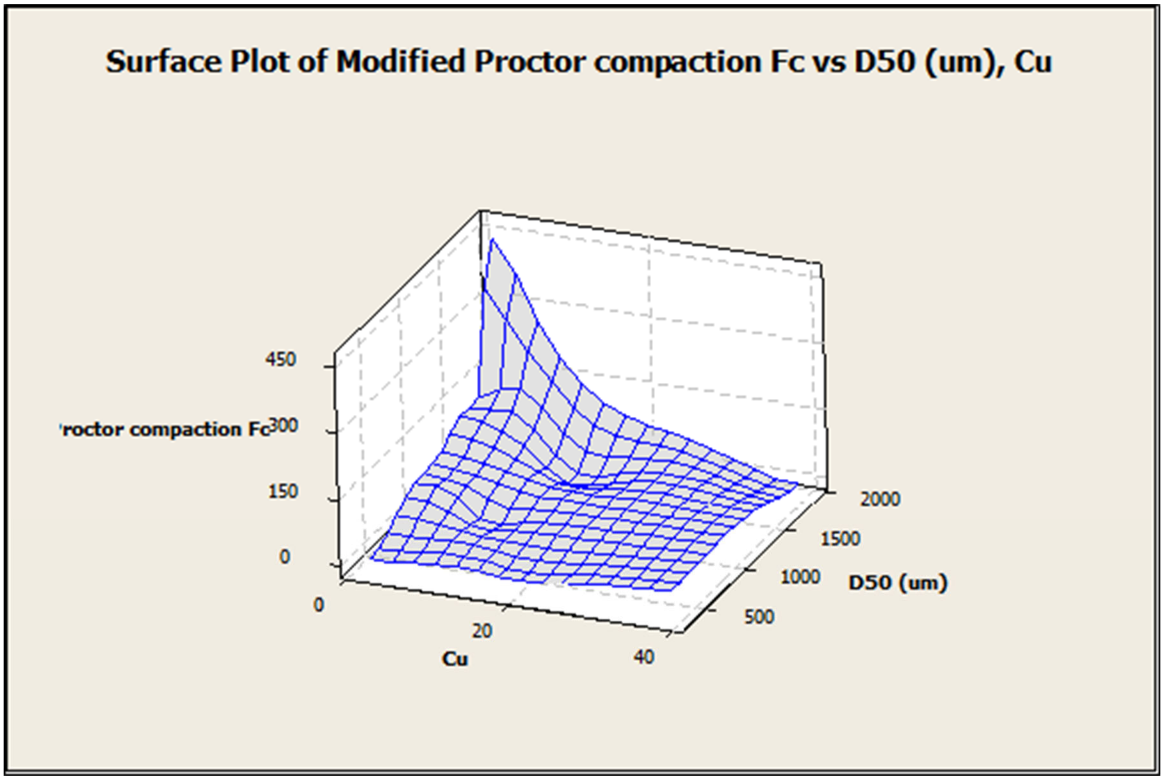
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	4.43287	4.43287	2.21643	12.0732	0.003836
D50 (um)	1	0.42432	1.51397	1.51397	8.2468	0.020774
Cu	1	4.00855	4.00855	4.00855	21.8351	0.001597
Error	8	1.46867	1.46867	0.18358		
Lack-of-Fit	7	1.35624	1.35624	0.19375	1.7234	0.528907
Pure Error	1	0.11242	0.11242	0.11242		
Total	10	5.90154				

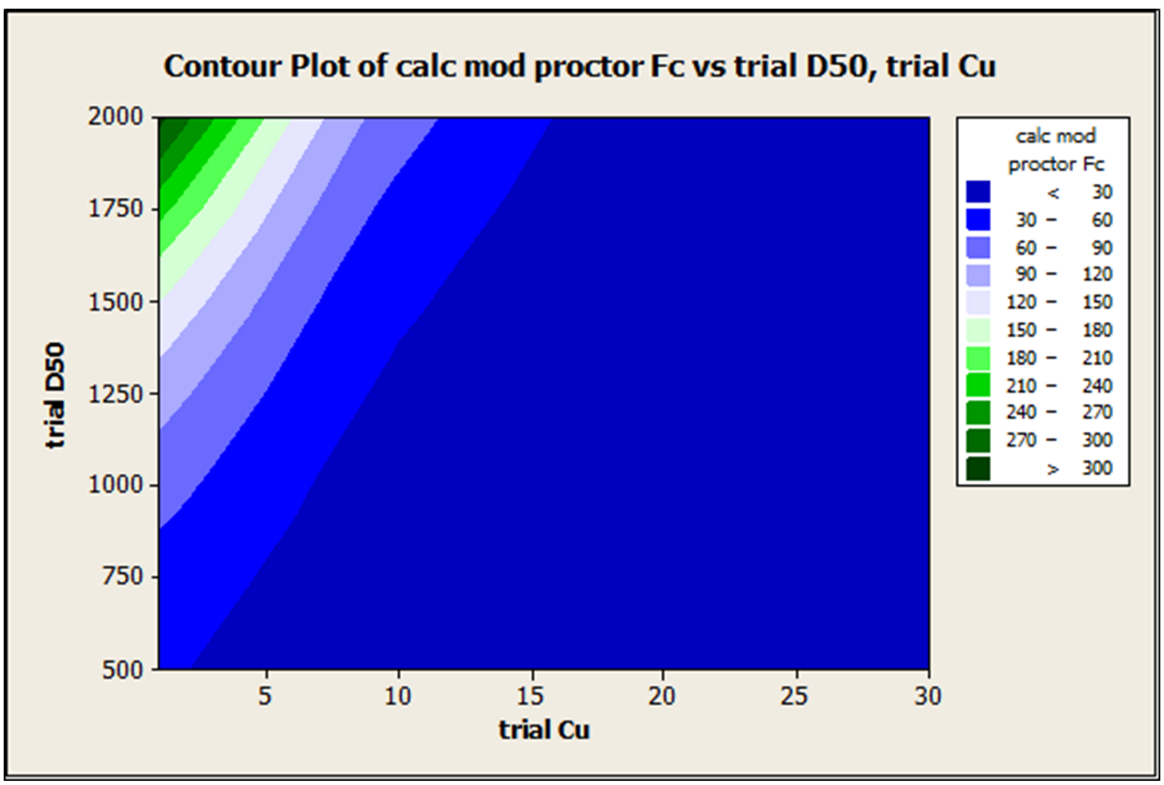
Fits and Diagnostics for Unusual Observations

No unusual observations


Residual Plots for proctor log Fc
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

High Organic Matter Content and High Compaction





General Regression Analysis: mod proctor log Fc versus D50 (um), Cu

Regression Equation

mod proctor log Fc = 1.28385 + 0.000640163 D50 (um) - 0.0699013 Cu

Coefficients

Term	Coef	SE Coef	T	P
Constant	1.28385	0.286764	4.47701	0.002
D50 (um)	0.00064	0.000246	2.59810	0.032
Cu	-0.06990	0.013164	-5.31002	0.001

Summary of Model

S = 0.443997   R-Sq = 78.53%   R-Sq(adj) = 73.16%
PRESS = 4.31989   R-Sq(pred) = 41.18%

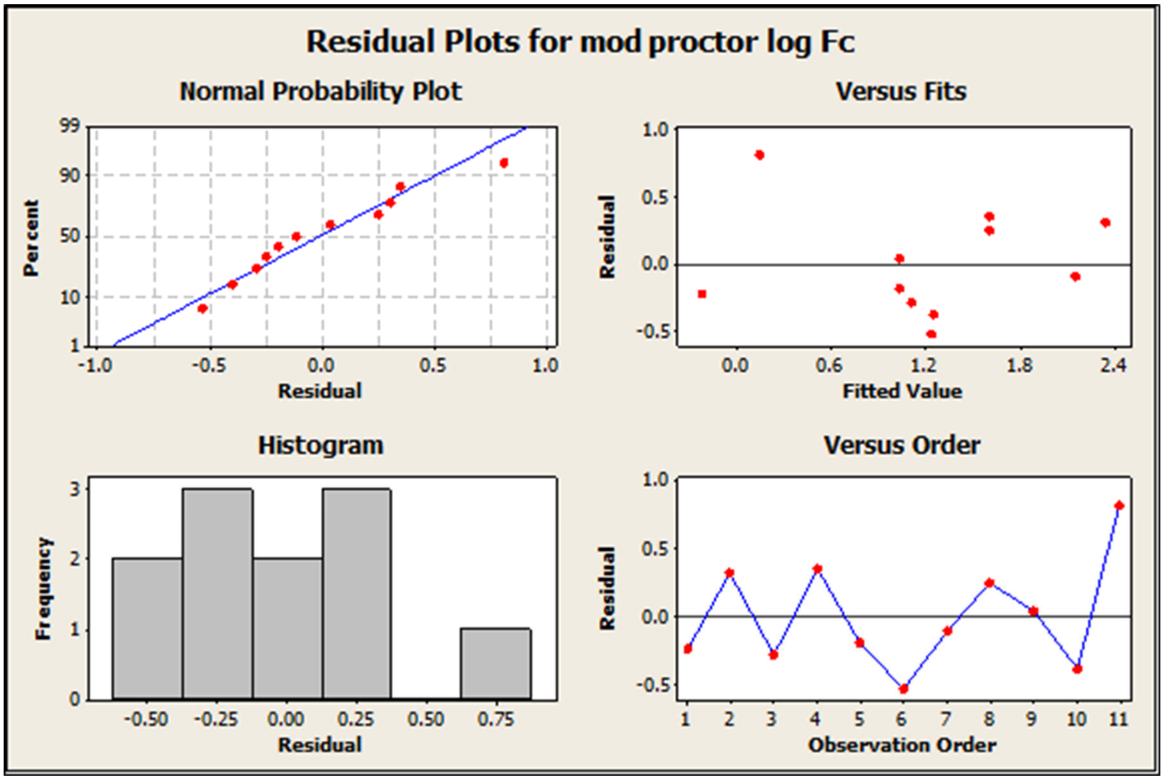
Analysis of Variance

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	2	5.76725	5.76725	2.88362	14.6278	0.002126
D50 (um)	1	0.20880	1.33067	1.33067	6.7501	0.031712
Cu	1	5.55844	5.55844	5.55844	28.1964	0.000720
Error	8	1.57707	1.57707	0.19713		
Lack-of-Fit	7	1.55036	1.55036	0.22148	8.2927	0.261396
Pure Error	1	0.02671	0.02671	0.02671		
Total	10	7.34431				

Fits and Diagnostics for Unusual Observations

Obs	mod proctor log Fc	Fit	SE Fit	Residual	St Resid	
11	0.957128	0.141885	0.265194	0.815244	2.28938	R

R denotes an observation with a large standardized residual.


Residual Plots for mod proctor log Fc
Normal Probability Plot
Percent
Residual
Versus Fits
Residual
Fitted Value
Histogram
Frequency
Residual
Versus Order
Residual
Observation Order

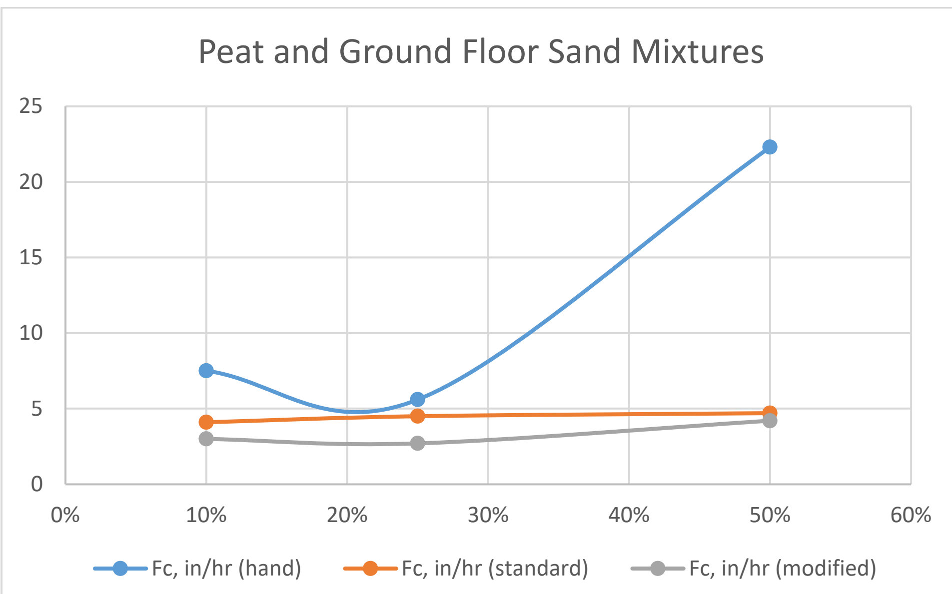
Appendix B: Peat-Sand Mixture Flow Rate Statistical Analyses

The following data are from Sileshi's (2013) tests in sand and peat mixtures. The following show the resulting significant regression equations for the final infiltration rates (Fc) as a function of the amount of peat and compaction, for different sand textures.

Fine Sandy Mixtures

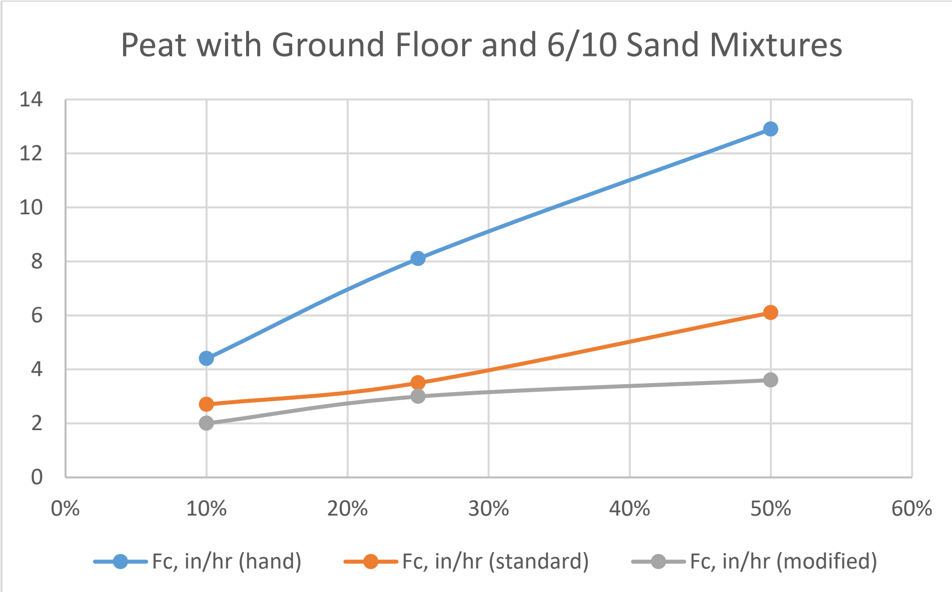
Peat and Ground Floor sand mixtures:

peat % (balance sand):	10%	25%	50%
Fc, in/hr (hand)	7.5	5.6	22.3
Fc, in/hr (standard)	4.1	4.5	4.7
Fc, in/hr (modified)	3	2.7	4.2
COV (hand)	0.2	0.5	0.3
COV (standard)	0.2	0.2	0.2
COV (modified)	0.3	0.2	0.1



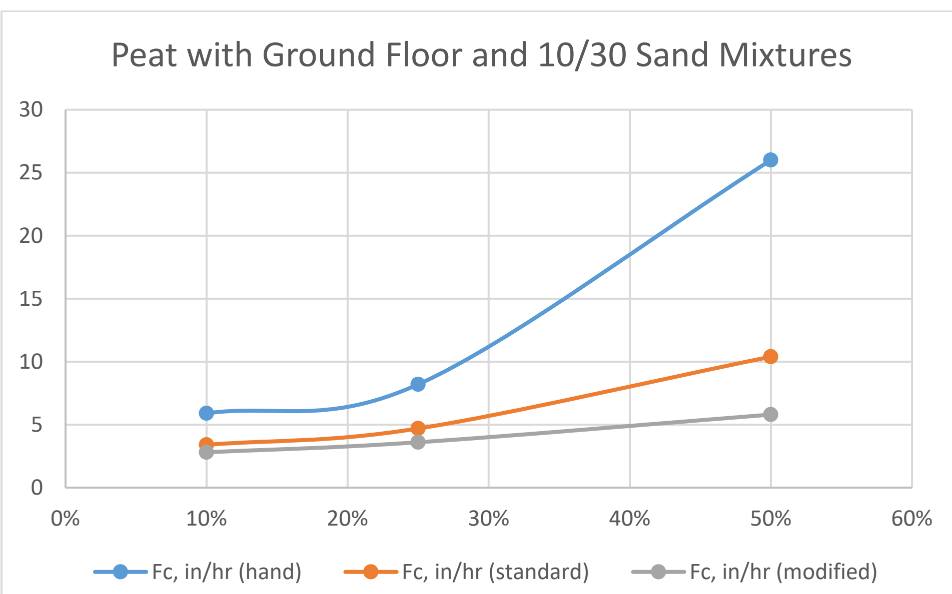
Peat and Ground Floor and 6/10 sand mixtures:

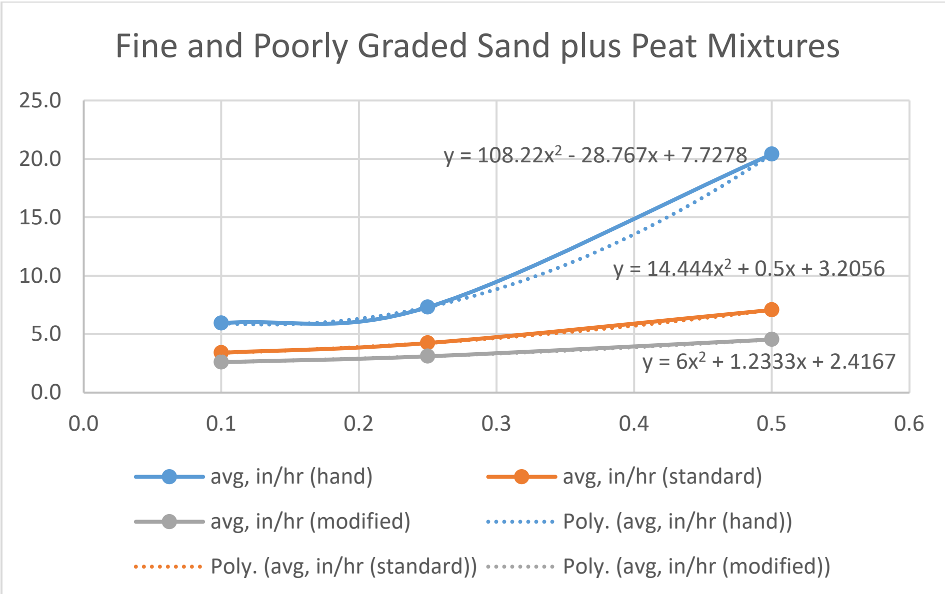
peat % (balance sand):	10%	25%	50%
Fc, in/hr (hand)	4.4	8.1	12.9
Fc, in/hr (standard)	2.7	3.5	6.1
Fc, in/hr (modified)	2	3	3.6
COV (hand)	0.3	0.3	0.2
COV (standard)	0.3	0.4	0.3
COV (modified)	0.5	0.2	0.7



Peat and Ground Floor and 10/30 sand mixtures:

peat % (balance sand):	10%	25%	50%
Fc, in/hr (hand)	5.9	8.2	26
Fc, in/hr (standard)	3.4	4.7	10.4
Fc, in/hr (modified)	2.8	3.6	5.8
COV (hand)	0.2	0.3	0.3
COV (standard)	0.2	0.4	0.3
COV (modified)	0.2	0.3	0.3

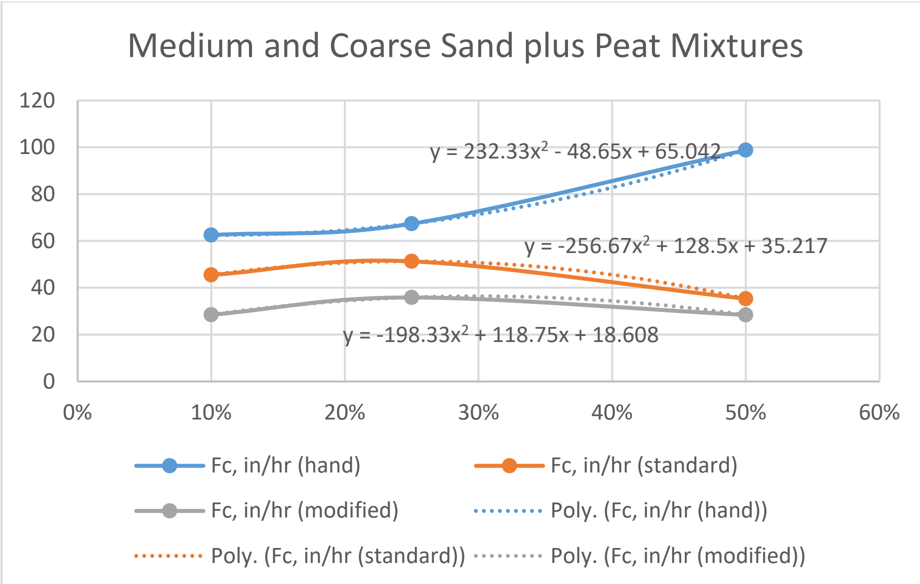




Coarse Sandy Mixtures

Peat and concrete sand and 10/30 sand mixtures:

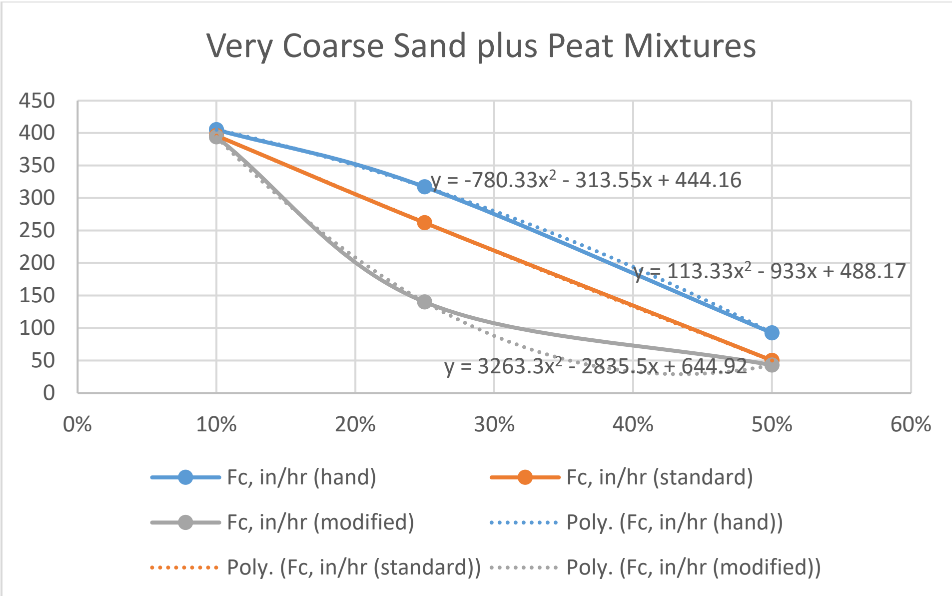
peat % (balance sand):	10%	25%	50%
Fc, in/hr (hand)	62.5	67.4	98.8
Fc, in/hr (standard)	45.5	51.3	35.3
Fc, in/hr (modified)	28.5	35.9	28.4
COV (hand)	0.2	0.3	-0.3
COV (standard)	0.1	0.3	0.1
COV (modified)	0.9	0.2	0.1



Very Coarse Sandy Mixtures

Peat and 6/10 and 10/30 sand mixtures (very coarse):

peat % (balance sand):	10%	25%	50%
Fc, in/hr (hand)	405	317	92.3
Fc, in/hr (standard)	396	262	50
Fc, in/hr (modified)	394	140	43
COV (hand)	0.4	0.3	0.6
COV (standard)	0.2	0.5	0.2
COV (modified)	0.3	0.5	0.3

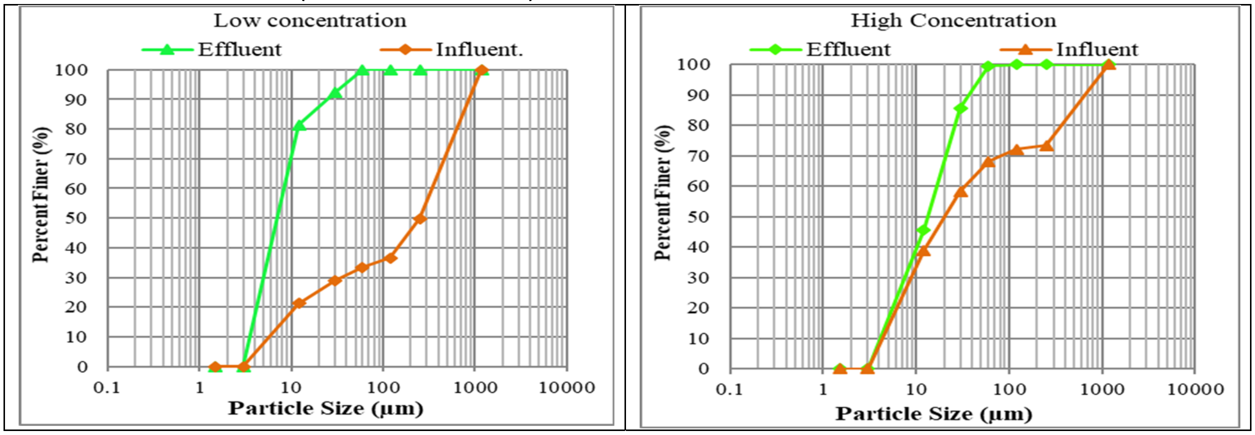


Very Coarse Sand plus Peat Mixtures
450
400
350
300
250
200
150
100
50
0
0%
10%
20%
30%
40%
50%
60%
y = -780.33x² - 313.55x + 444.16
y = 113.33x² - 933x + 488.17
y = 3263.3x² - 2835.5x + 644.92
Fc, in/hr (hand)
Fc, in/hr (standard)
Fc, in/hr (modified)
Poly. (Fc, in/hr (hand))
Poly. (Fc, in/hr (standard))
Poly. (Fc, in/hr (modified))

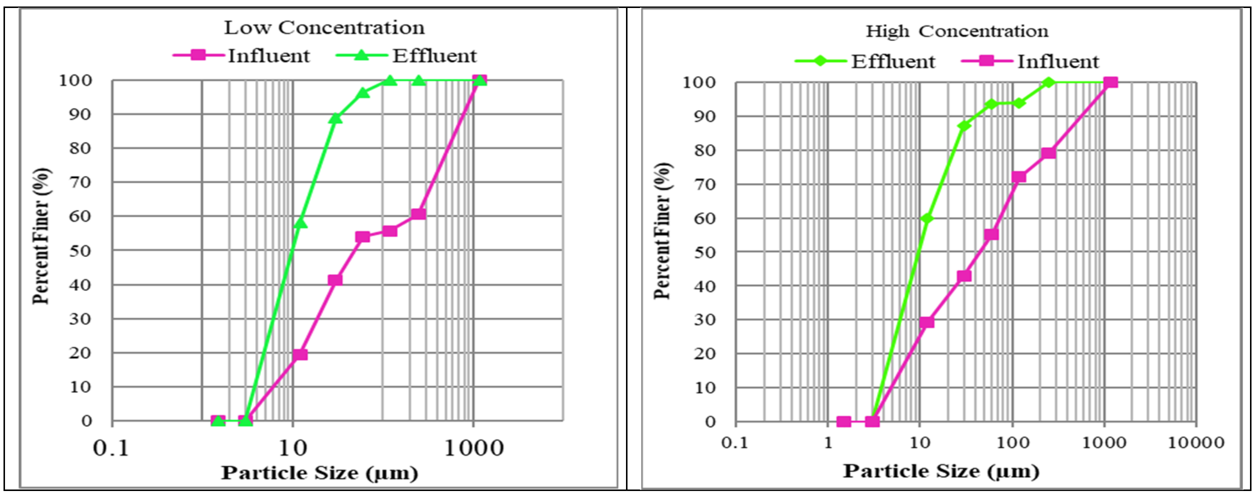
Appendix C1: Particulate Retention by Particle Size

Data from Sileshi (2013):

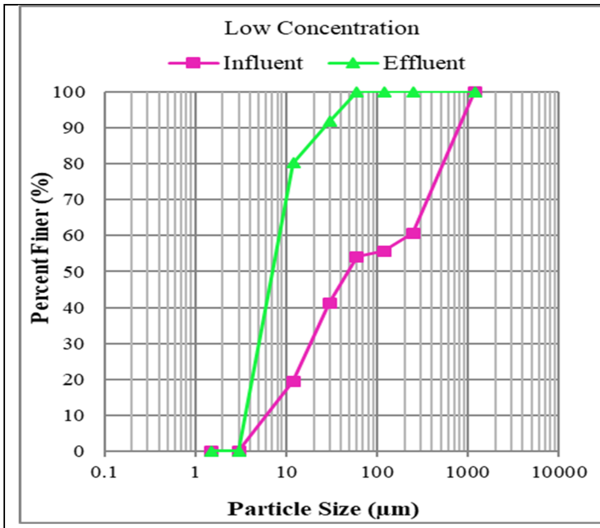
Fine and Clean Mixtures (about 300 um D50):

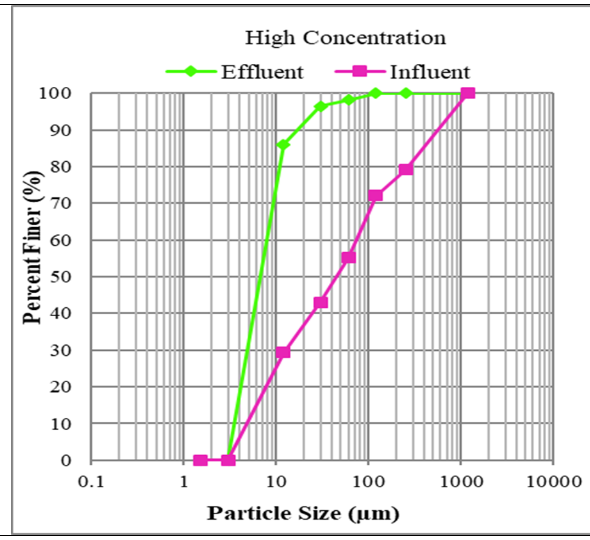


Particle size Distribution Plot Using Sand and Peat (D50 = 300 um & Cu = 3.3) and Density = 1.03 g/cc



50% Peat and 50% Tuscaloosa Surface Soil (D50 = 325 um & Cu = 7) and Density = 0.85g/cc





10% Peat and 90% Sand (D50 = 340 um & Cu = 1.3) and Density = 1.28 g/cc

Low Concentrations, fine media (about 300 um)

range	inf conc	inf conc	inf conc	average		efl conc	efl conc	efl conc	average		% reduc of averages
>1000	6.18	4.12	5.15	5.15		0.00	0.00	0.00	0.00		100.00
300 to 1000	39.14	32.96	27.81	33.30		0.00	0.00	0.00	0.00		100.00
100 to 300	20.60	9.27	12.36	14.08		0.00	0.16	0.00	0.05		99.62
30 to 100	7.21	11.33	14.42	10.99		0.28	0.40	0.32	0.33		96.97
10 to 30	11.33	27.81	25.75	21.63		0.88	3.44	0.88	1.73		91.99
3 to 10	18.54	14.42	15.45	16.14		2.84	3.04	2.80	2.89		82.07
1 to 3	0.00	3.09	2.06	1.72		0.00	0.96	0.00	0.32		81.36
<1	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		n/a
sum:	103.00	103.00	103.00	103.00		4.00	8.00	4.00	5.33		94.82

High Concentrations, fine media (about 300 um)

range	inf conc	inf conc	inf conc	average		efl conc	efl conc	efl conc	average		% reduc of averages
>1000	23.94	23.94	31.92	26.60		0.00	0.00	0.00	0.00		100.00
300 to 1000	159.60	127.68	111.72	133.00		0.00	0.00	0.00	0.00		100.00
100 to 300	47.88	119.70	127.68	98.42		0.00	0.18	0.04	0.07		99.93
30 to 100	103.74	183.54	183.54	156.94		0.52	0.21	0.08	0.27		99.83
10 to 30	207.48	151.62	151.62	170.24		1.96	1.11	1.00	1.36		99.20
3 to 10	247.38	167.58	191.52	202.16		1.52	1.50	2.88	1.97		99.03
1 to 3	7.98	23.94	0.00	10.64		0.00	0.00	0.00	0.00		100.00
<1	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00		n/a
sum:	798.00	798.00	798.00	798.00		4.00	3.00	4.00	3.67		99.54

The following tables show the observed influent and effluent concentrations, by particle size, for the low to high concentration tests for the fine media combined (effluent were not found to be significantly different). The intermediate and coarse media test results were kept separate.

Low to High Concentrations (100 to 800 SSC mg/L), fine media (about 300 um)

>1000 um		300 to 1000 um		100 to 300 um		30 to 100 um		10 to 30 um		3 to 10 um		1 to 3 um		total	
inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl
6.18	0.00	39.14	0.00	20.60	0.00	7.21	0.28	11.33	0.88	18.54	2.84	0.00	0.00	103.00	4.00
4.12	0.00	32.96	0.00	9.27	0.16	11.33	0.40	27.81	3.44	14.42	3.04	3.09	0.96	103.00	8.00
5.15	0.00	27.81	0.00	12.36	0.00	14.42	0.32	25.75	0.88	15.45	2.80	2.06	0.00	103.00	4.00
23.94	0.00	159.60	0.00	47.88	0.00	103.74	0.52	207.48	1.96	247.38	1.52	7.98	0.00	798.00	4
23.94	0.00	127.68	0.00	119.70	0.18	183.54	0.21	151.62	1.11	167.58	1.50	23.94	0.00	798.00	3
31.92	0.00	111.72	0.00	127.68	0.04	183.54	0.08	151.62	1.00	191.52	2.88	0.00	0.00	798.00	4
no sign regression		no sign regression		no sign regression		intercept sign		intercept sign		intercept sign		no likely removal		intercept sign	
mean	efl = 0	mean	efl = 0	mean	efl = 0.06	mean	efl = 0.30	mean	efl = 1.55	mean	efl = 2.43			mean	efl = 4.5
COV	n/a	COV	n/a	COV	1.33	COV	0.50	COV	0.66	COV	0.30			COV	0.39

Effluent particle size data are not available for the intermediate and very coarse media. Therefore, the particle size distributions for the effluent for the fine media shown above were used to distribute the total SSC concentration for these coarser textured media, shown below.

Low to High Concentrations (50 to 500 SSC mg/L), intermediate media (about 1000 to 2000 um)

>1000 um		300 to 1000 um		100 to 300 um		30 to 100 um		10 to 30 um		3 to 10 um		1 to 3 um		total	
inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl
												no likely removal		no sign regression	
mean	efl = 0	mean	efl = 0	mean	efl = 0.70	mean	efl = 3.33	mean	efl = 17.1	mean	efl = 26.8			mean	49.6
														COV	0.63

total	total
inf	efl
57	74
57	63
57	23
439	78
439	10
no sign regression	
mean	49.6
stdev	31.05318
COV	0.626072

Low to High Concentrations (50 to 500 SSC mg/L) Very Coarse Media (pea gravel and coarse gravel; >5,000 um D50)

>1000 um		300 to 1000 um		100 to 300 um		30 to 100 um		10 to 30 um		3 to 10 um		1 to 3 um		total	
inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl	inf	efl
												no likely removal		no sign intercept; see ANOVA below	
														y = 1.69 x	
mean	efl = 0	mean	efl = 0	mean	efl = 6.17	mean	efl = 29.4	mean	efl = 150	mean	efl = 237			mean	438
														COV	0.75

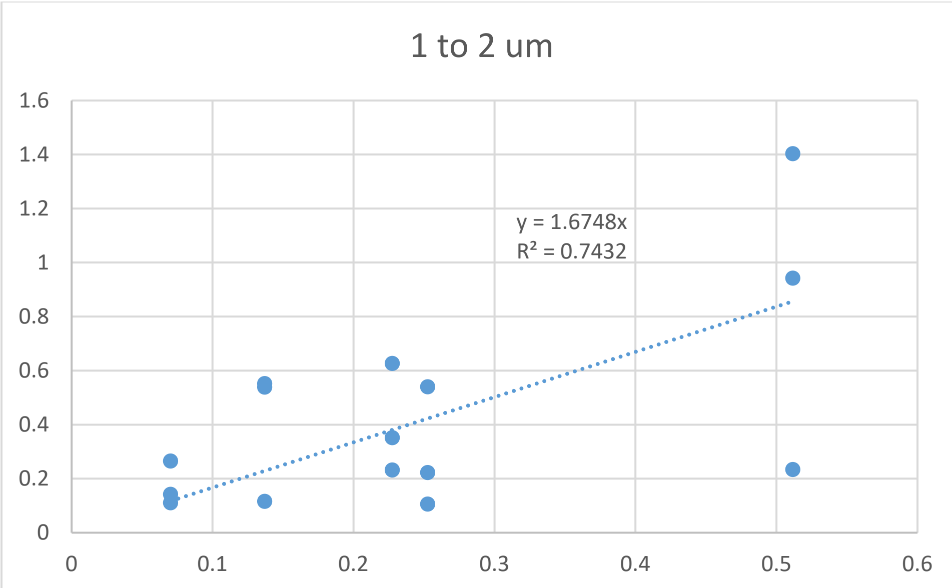
total	total
inf	efl
57	199
57	164
57	101
57	95
439	712
439	899
439	642
439	693

Regression Statistics						
Multiple R	0.988357					
R Square	0.97685					
Adjusted R Square	0.833993					
Standard Error	87.08764					
Observations	8					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	2240191	2240191	295.3738	2.48E-06	
Residual	7	53089.8	7584.258			
Total	8	2293281				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.69051	0.098363	17.18644	5.54E-07	1.457919	1.923102

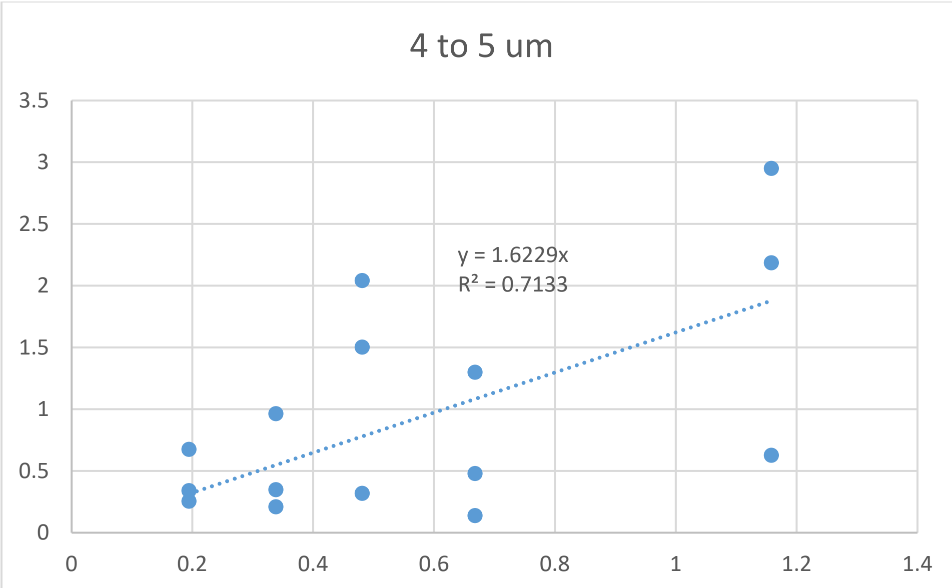
Appendix C2. Removal of Fine Stormwater Particulates by Biofilter Media

The following data are from the pilot-scale long-term tests conducted by Clark and Pitt (1999) showing the observed influent and effluent concentrations for the small particle sizes. These data are for all the granular media combined (except for the GAC-sand mixture which was significantly different).

	1 to 2 um					4 to 5 um		
	influent concentration (mg/L)	effluent concentration (mg/L)	% reduction			influent concentration (mg/L)	effluent concentration (mg/L)	% reduction
	0.511593	1.402735	-174.19			1.15822	2.18469	-88.6248
	0.227548	0.351185	-54.3348			0.338313	0.347963	-2.85239
	0.07032	0.265105	-276.998			0.19447	0.673848	-246.505
	0.137095	0.538535	-292.819			0.481048	1.502463	-212.331
	0.252645	0.539818	-113.666			0.667823	1.298968	-94.5079
	0.511593	0.94185	-84.1016			1.15822	2.94902	-154.617
	0.227548	0.62623	-175.208			0.338313	0.963688	-184.851
	0.07032	0.141883	-101.767			0.19447	0.340083	-74.8766
	0.137095	0.55162	-302.363			0.481048	2.040905	-324.263
	0.252645	0.22239	11.9753			0.667823	0.47878	28.3073
	0.511593	0.233435	54.37091			1.15822	0.626745	45.88722
	0.227548	0.232073	-1.9886			0.338313	0.208625	38.33364
	0.07032	0.110523	-57.1708			0.19447	0.254325	-30.7785
	0.137095	0.116053	15.34885			0.481048	0.31846	33.79864
	0.252645	0.10587	58.09535			0.667823	0.138575	79.24973
mean	0.23984	0.425287	-99.6545			0.567975	0.955142	-79.242
stdev	0.155924	0.361349	122.2567			0.345842	0.860461	122.4831
COV	0.650119	0.84966	-1.22681			0.608905	0.900872	-1.54568



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.862111					
R Square	0.743235					
Adjusted R Square	0.671806					
Standard Error	0.288591					
Observations	15					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	3.375073	3.375073	40.5245	2.47E-05	
Residual	14	1.165987	0.083285			
Total	15	4.541059				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.674822	0.263093	6.365886	1.75E-05	1.110543	2.239101

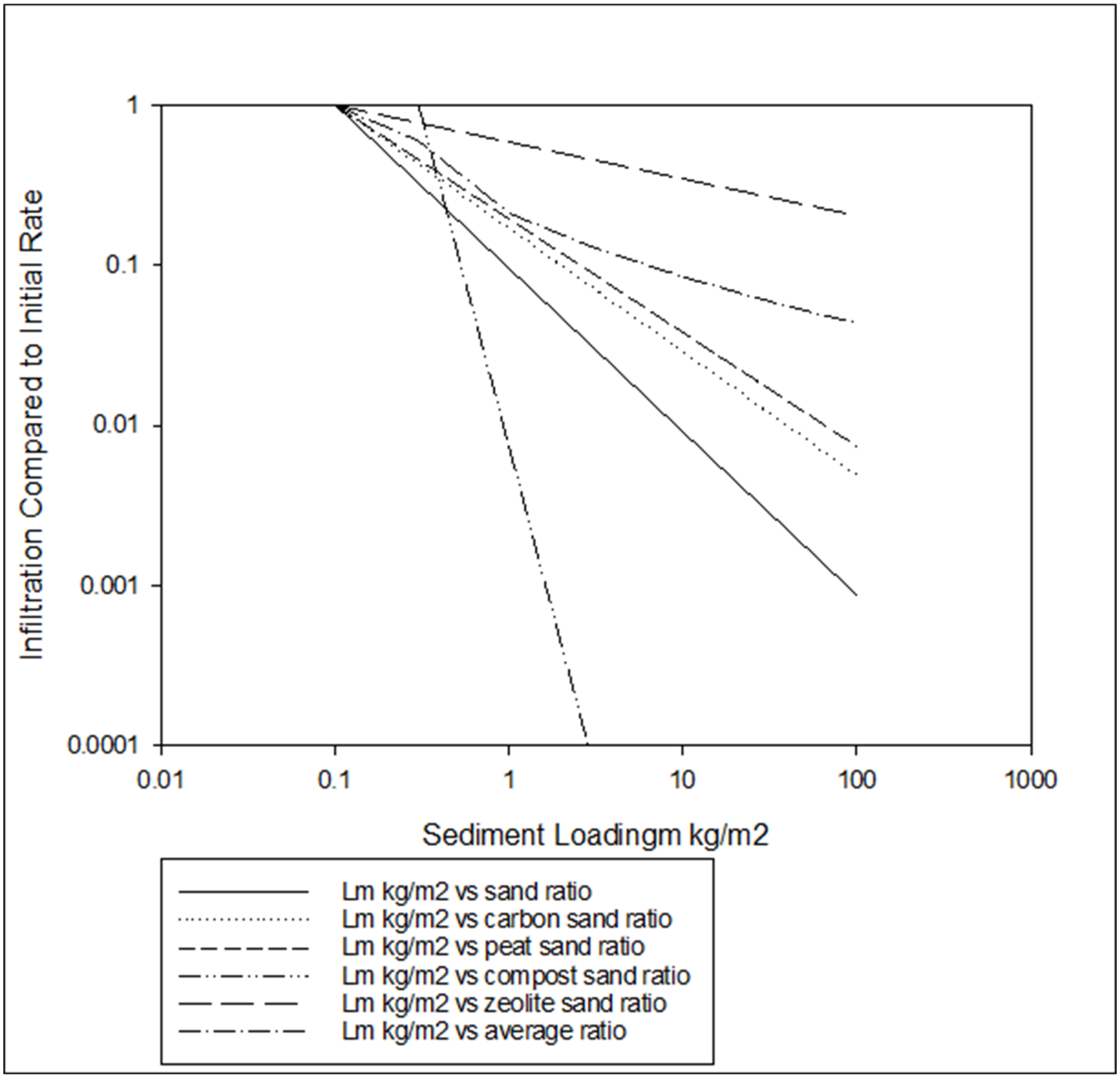


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.844552					
R Square	0.713269					
Adjusted R Square	0.64184					
Standard Error	0.701828					
Observations	15					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	17.15408	17.15408	34.82619	5.22E-05	
Residual	14	6.895876	0.492563			
Total	15	24.04996				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.622853	0.274996	5.901372	3.86E-05	1.033045	2.21266

An average equation was used for the standard 0.45 to 3 µm particle size: y = 1.65 x
The effluent concentrations have substantial variation (even with the highly significant equations and slope factors), so a COV of about 0.85 should be used in Monte Carlo calculations to represent suitable variations in the calculated effluent concentrations.

Appendix C3. Effects of Solids Accumulation on Flow Rate Reductions

As particulates accumulate in biofilter media, the treatment flow rate decreases. Few studies have examined this for extended periods. During her PhD dissertation research, Clark (2000) measured treatment flow rates in large media columns using pre-settled stormwater over extended periods of time, along with monitoring of solids accumulations. She developed clogging equations based on these data for the different media, with the resulting normalized plot shown below.



Model Equations for the Effect of Solids Loading on Flow Rate (Clark 2000)

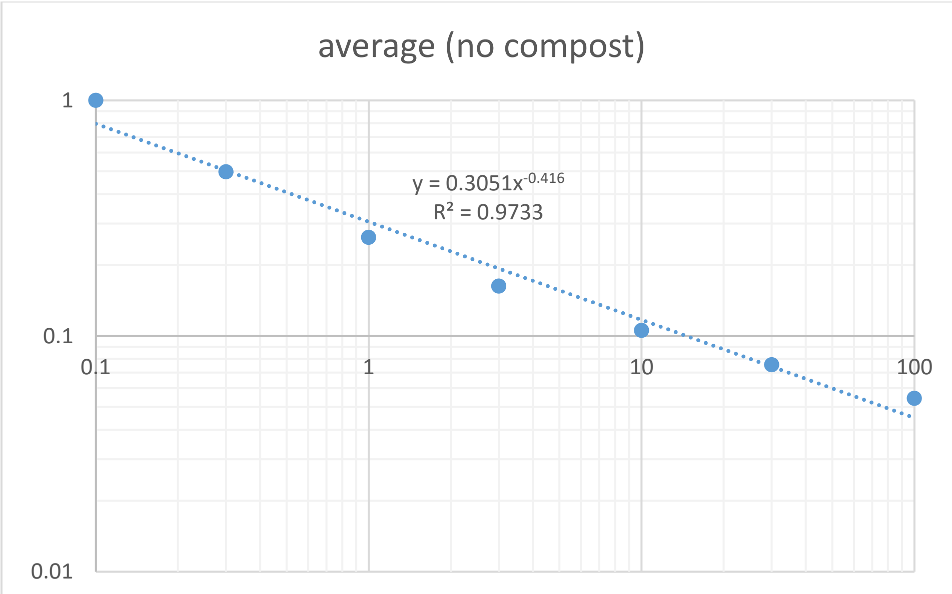
Filtration Media	Equation for Effect of Suspended Solids Loading on Flow Rate*
Sand	$u = 44500 \cdot L_{m,sand}^{-1.02}$
Carbon-Sand	$u = 14800 \cdot L_{m,carbon}^{-0.77}$
Peat-Sand	$u = 2000 \cdot L_{m,peat}^{-0.71}$
Compost-Sand	$u = 1.6 \times 10^{13} \cdot L_{m,compost}^{-4.09}$
Zeolite-Sand	$u = 60 \cdot L_{m,zeolite}^{-0.23}$
Agrofiber-Sand	$u = 205 – 0.09 \cdot L_{m,agrofiber}$
Cotton-Sand	$u = 106 – 0.01 \cdot L_{m,cotton}$
*Statistically significant coefficients (a = 0.05).	

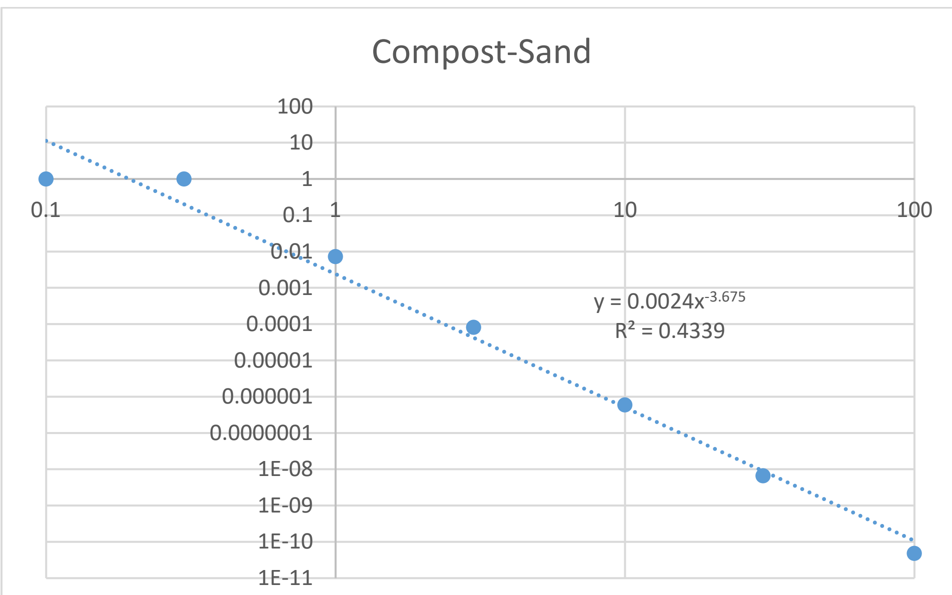
u = unit flow/loading rate (m/day),
Lm = suspended solids loading (g/m^2)

These equations were used to calculate the following treatment flow rates (in/hr) as a function of sediment accumulation (kg/m^2).

Lm (kg/m2)	Sand	Carbon-Sand	Peat-Sand	Compost-Sand	Zeolite-Sand	Agrofiber-Sand	Cotton-Sand
0.1	665.8	700.2	124.7		34.1	321.5	172.2
0.3	217.1	300.5	57.2	1,939.3	26.5	292.0	169.0
1	63.6	118.9	24.3	14.1	20.1	188.6	157.5
3	20.7	51.0	11.1	0.2	15.6		124.7
10	6.1	20.2	4.7	0.0	11.8		9.8
30	2.0	8.7	2.2	0.0	9.2		
100	0.6	3.4	0.9	0.0	7.0		

These values were then plotted in the following figures.



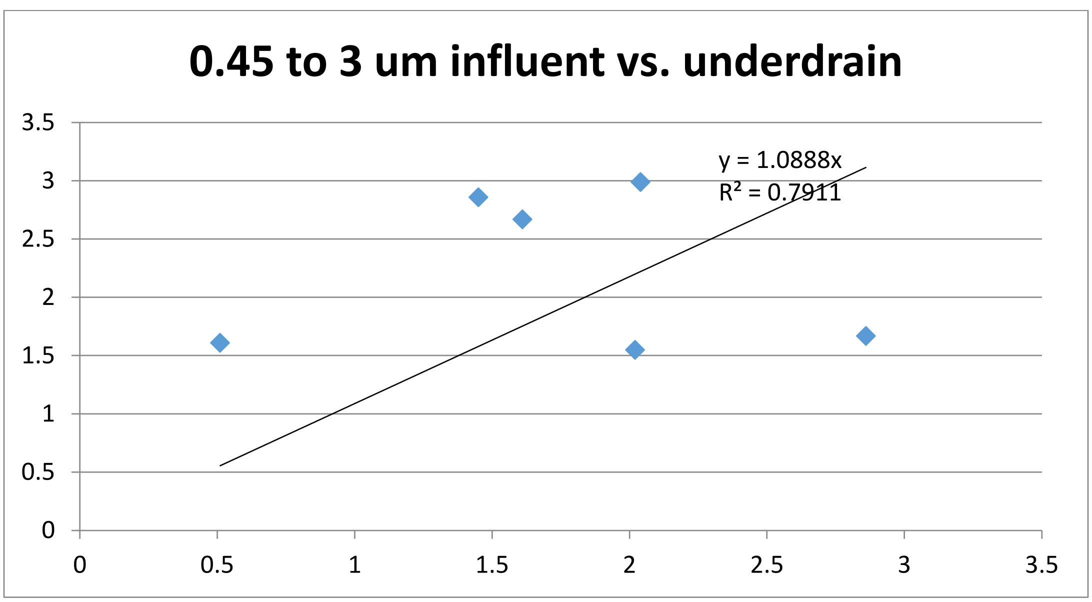


The granular media is seen to lose an order of magnitude of flow capacity after about 8 kg/m^2 acculturation and about 2 orders of flow capacity after about 30 kg/m^2. The compost-sand flow rate losses are much faster, with 1 order of magnitude of flow capacity lost after about 0.5 kg/m^2 of sediment accumulation and 2 orders of magnitude after about 2 kg/m^2, but the initial rates are much larger.

Appendix C4. Kansas City EPA Demonstration Project Biofilter Performance Data

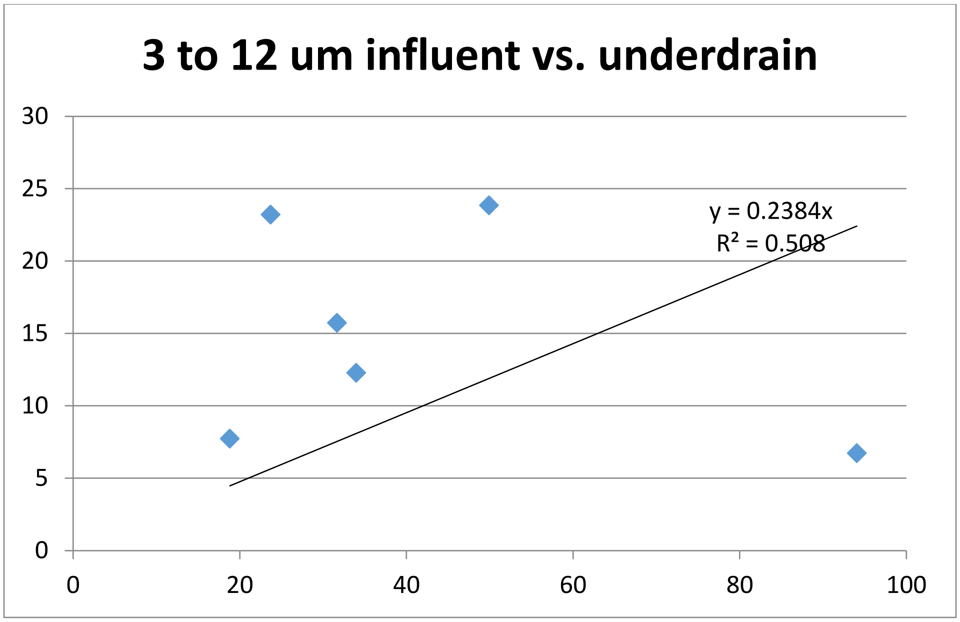
The Kansas City project was an EPA-funded demonstration project to show how green infrastructure can be integrated into areas having combined sewers (Pitt, *et al.* 2014). This was an extensive project and included the construction of several hundred controls in the test area. An adjacent area with no stormwater controls was used for comparison. The monitoring program lasted for about 2 years and included more than 50 storms. However, the monitored biofilters worked very well and only six events produced underdrain flows that could be sampled and analyzed. These monitored underdrain and inflow data are summarized below, for the various stormwater particle size groups.

0.45 to 3	influent	underdrain	% reduc.
4/7/2013	0.51	1.61	-215.686
4/9/2013	2.02	1.55	23.26733
5/2/2013	1.61	2.67	-65.8385
5/27/2013	2.86	1.67	41.60839
6/5/2013	1.45	2.86	-97.2414
6/9/2013	2.04	2.99	-46.5686
min	0.51	1.55	-215.686
max	2.86	2.99	41.60839
median	1.815	2.17	-56.2036
average	1.748333333	2.225	-60.0765
stdev	0.779266749	0.6824	92.84105
COV	0.44571978	0.306697	-1.54538



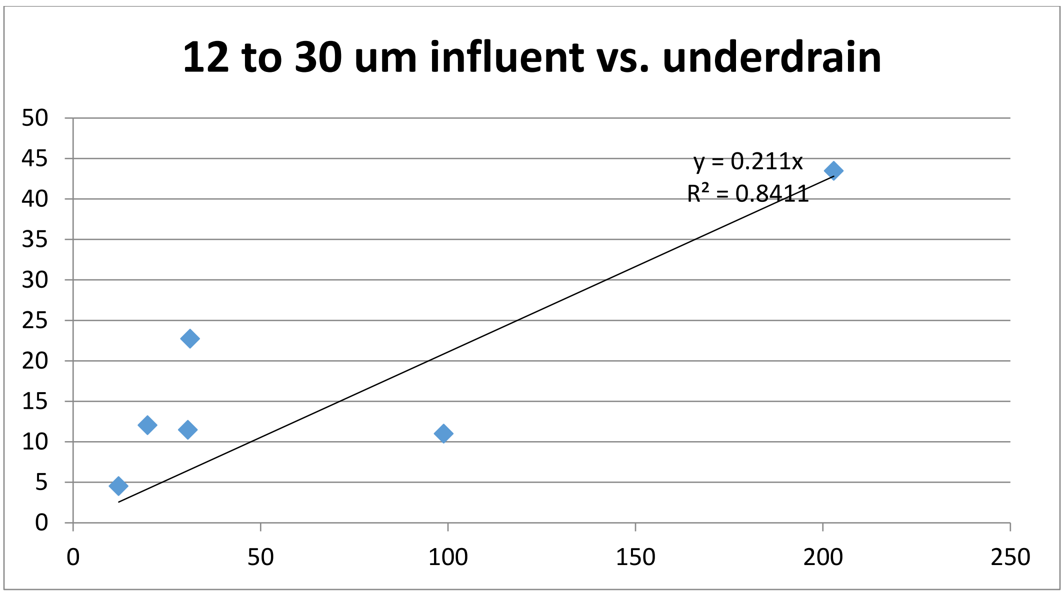
SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.889415					
R Square	0.79106					
Adjusted R Square	0.59106					
Standard Error	1.156962					
Observations	6					
ANOVA						
	df	SS	MS	F	Significance F	
Regression	1	25.3393	25.3393	18.93026	0.012149	
Residual	5	6.692801	1.33856			
Total	6	32.0321				
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.088757	0.250238	4.350892	0.007353	0.445501	1.732014

3 to 12	influent	underdrain	% reduc.
4/7/2013	31.66	15.73	50.31586
4/9/2013	23.69	23.21	2.026171
5/2/2013	18.8	7.74	58.82979
5/27/2013	94.04	6.73	92.84347
6/5/2013	33.96	12.28	63.83981
6/9/2013	49.9	23.85	52.20441
min	18.8	6.73	2.026171
max	94.04	23.85	92.84347
median	32.81	14.005	55.5171
average	42.00833333	14.92333	53.34325
stdev	27.62471532	7.412464	29.47695
COV	0.657600841	0.496703	0.55259



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.71276					
R Square	0.508027					
Adjusted R Square	0.308027					
Standard Error	12.59006					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	818.4109	818.4109	5.163166	0.085514	
Residual	5	792.5475	158.5095			
Total	6	1610.958				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.238367	0.104903	2.27226	0.072234	-0.03129	0.50803

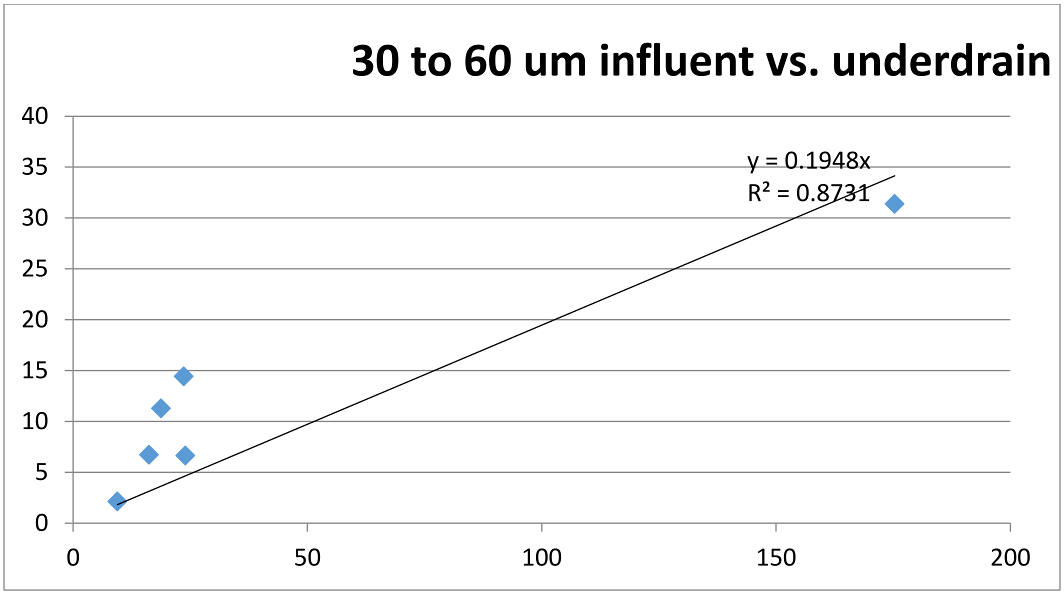
12 to 30	influent	underdrain	% reduc.
4/7/2013	202.88	43.48	78.56861
4/9/2013	19.85	12.05	39.29471
5/2/2013	12.13	4.52	62.73702
5/27/2013	98.83	11.01	88.85966
6/5/2013	30.61	11.48	62.49592
6/9/2013	31.18	22.73	27.10071
min	12.13	4.52	27.10071
max	202.88	43.48	88.85966
median	30.895	11.765	62.61647
average	65.91333333	17.545	59.84277
stdev	73.90613254	13.99174	23.24787
COV	1.121262252	0.797478	0.388483



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.917108					
R Square	0.841087					
Adjusted R Square	0.641087					
Standard Error	9.476892					
Observations	6					
ANOVA						

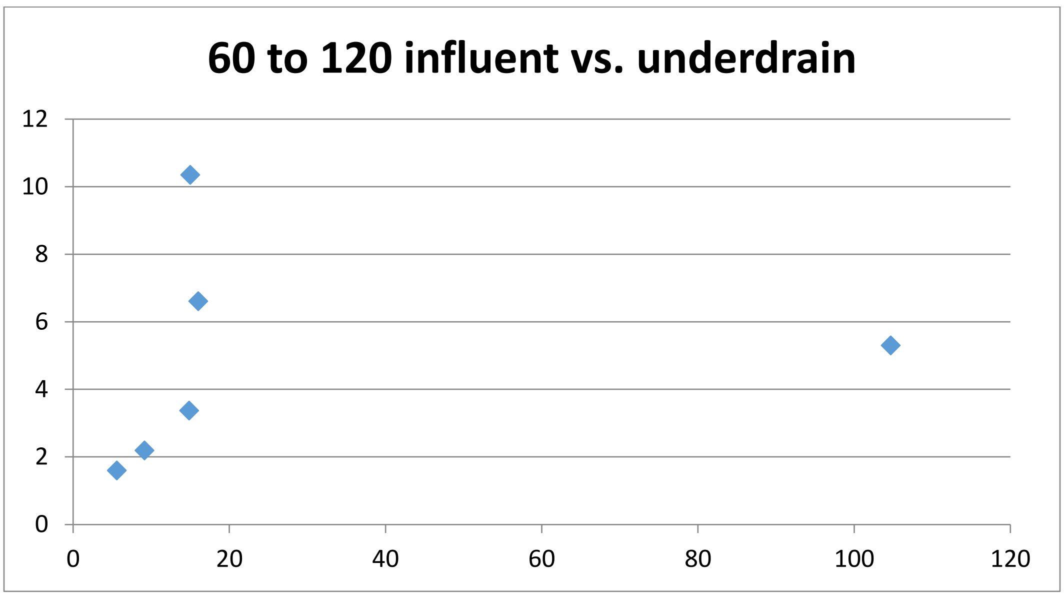
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	2376.749	2376.749	26.46376	0.006771	
Residual	5	449.0574	89.81148			
Total	6	2825.807				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.211014	0.041019	5.144294	0.003632	0.105571	0.316456

30 to 60	influent	underdrain	% reduc.
4/7/2013	175.3	31.39	82.09355
4/9/2013	16.17	6.73	58.37972
5/2/2013	9.44	2.14	77.33051
5/27/2013	18.73	11.29	39.72237
6/5/2013	23.59	14.43	38.83001
6/9/2013	23.93	6.65	72.21061
min	9.44	2.14	38.83001
max	175.3	31.39	82.09355
median	21.16	9.01	65.29516
average	44.52666667	12.105	61.4278
stdev	64.28821686	10.35307	18.90669
COV	1.443813824	0.855272	0.307787



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.934397					
R Square	0.873097					
Adjusted R Square	0.673097					
Standard Error	5.993032					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1235.534	1235.534	34.40024	0.004219	
Residual	5	179.5822	35.91643			
Total	6	1415.116				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.194796	0.033212	5.865172	0.002043	0.109421	0.280172

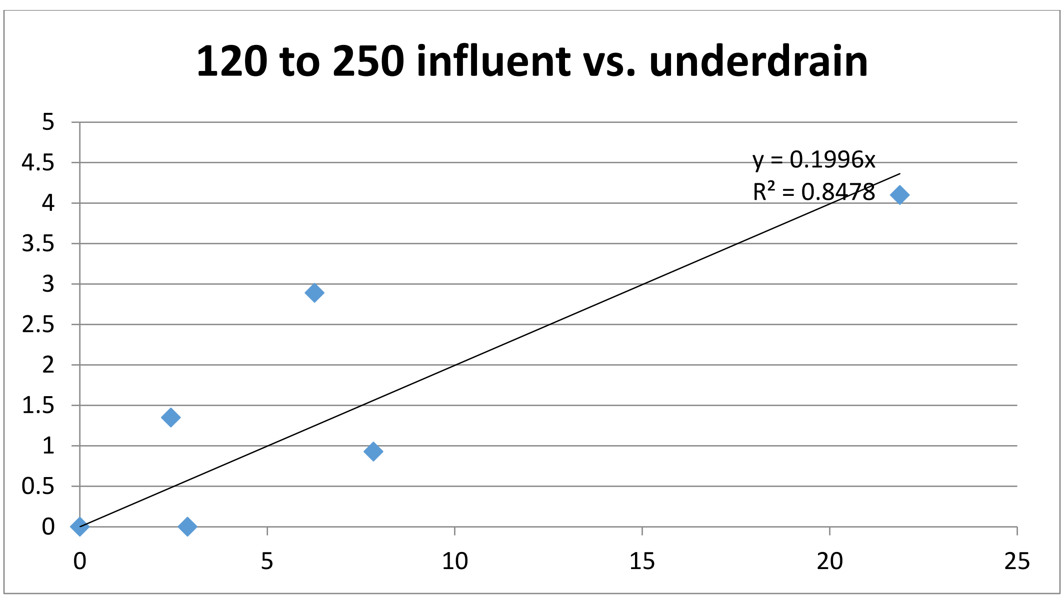
60 to 120	influent	underdrain	% reduc.
4/7/2013	104.67	5.3	94.93647
4/9/2013	9.13	2.19	76.01314
5/2/2013	5.6	1.6	71.42857
5/27/2013	14.85	3.37	77.3064
6/5/2013	15	10.35	31
6/9/2013	16.03	6.61	58.76482
min	5.6	1.6	31
max	104.67	10.35	94.93647
median	14.925	4.335	73.72086
average	27.54666667	4.903333	68.24157
stdev	38.00025298	3.26685	21.64295
COV	1.379486434	0.666251	0.317152



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.586741					
R Square	0.344265					
Adjusted R Square	0.144265					
Standard Error	5.09087					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	

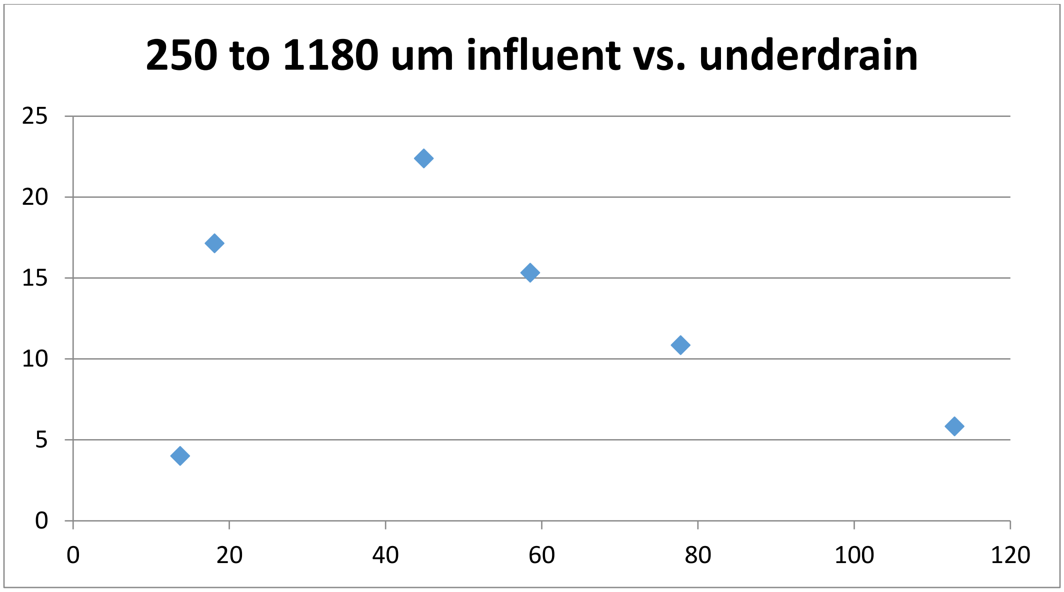
Regression	1	68.03279	68.03279	2.62503	0.180506	
Residual	5	129.5848	25.91696			
Total	6	197.6176				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.076018	0.046919	1.620194	0.166116	-0.04459	0.196627

120 to 250	influent	underdrain	% reduc.
4/7/2013	21.87	4.1	81.25286
4/9/2013	2.87	0	100
5/2/2013	0	0	n/a
5/27/2013	7.83	0.93	88.12261
6/5/2013	6.26	2.89	53.83387
6/9/2013	2.43	1.35	44.44444
min	0	0	44.44444
max	21.87	4.1	100
median	4.565	1.14	81.25286
average	6.876666667	1.545	73.53075
stdev	7.863891318	1.644831	23.49018
COV	1.14356151	1.064616	0.319461



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.920765					
R Square	0.847808					
Adjusted R Square	0.647808					
Standard Error	0.920703					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	23.61103	23.61103	27.85326	0.00618	
Residual	5	4.238468	0.847694			
Total	6	27.8495				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.199551	0.037811	5.277619	0.003251	0.102355	0.296747

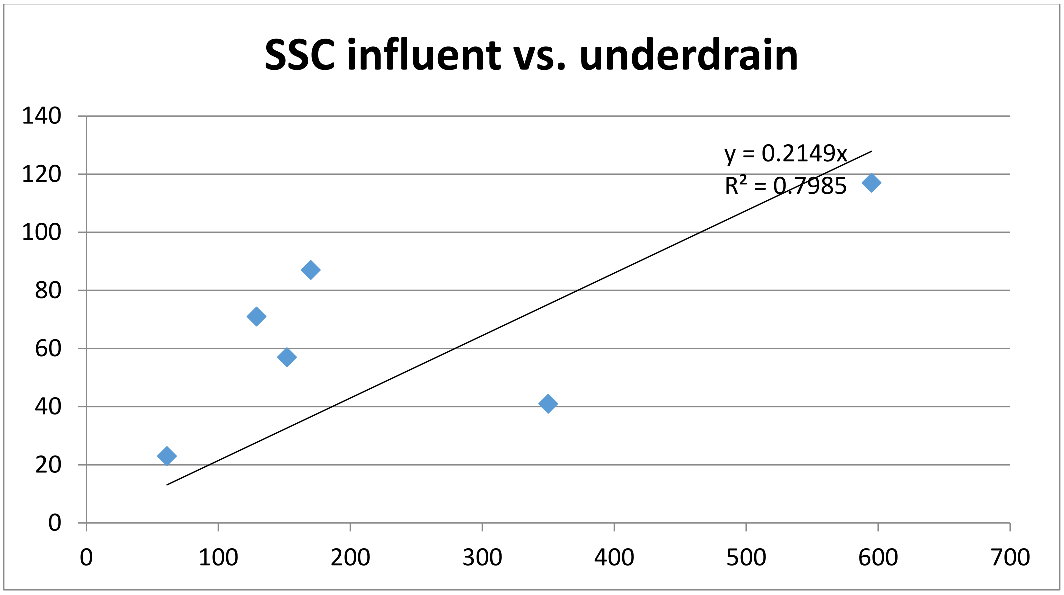
250 to 1180	influent	underdrain	% reduc.
4/7/2013	58.52	15.32	73.82092
4/9/2013	77.78	10.85	86.0504
5/2/2013	13.71	4	70.82422
5/27/2013	112.86	5.83	94.83431
6/5/2013	18.12	17.14	5.408389
6/9/2013	44.9	22.39	50.13363
min	13.71	4	5.408389
max	112.86	22.39	94.83431
median	51.71	13.085	72.32257
average	54.315	12.58833	63.51198
stdev	37.53209706	7.024367	32.26087
COV	0.691007955	0.558006	0.507949



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.692418					
R Square	0.479443					
Adjusted R Square	0.279443					
Standard Error	11.16575					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	574.1359	574.1359	4.605101	0.098428	
Residual	5	623.3696	124.6739			
Total	6	1197.506				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.152325	0.070983	2.14595	0.084678	-0.03014	0.334792

>1180	influent	underdrain	% reduc.
4/7/2013	0	0	n/a
4/9/2013	0	0	n/a
5/2/2013	0	0	n/a
5/27/2013	0	0	n/a
6/5/2013	0	0	n/a
6/9/2013	0	0	n/a
min	0	0	0
max	0	0	0
median	0	0	#NUM!
average	0	0	#DIV/0!
stdev	0	0	#DIV/0!
COV	#DIV/0!	#DIV/0!	#DIV/0!

total SSC	influent	underdrain	% reduc.
4/7/2013	595	117	80.33613
4/9/2013	152	57	62.5
5/2/2013	61	23	62.29508
5/27/2013	350	41	88.28571
6/5/2013	129	71	44.96124
6/9/2013	170	87	48.82353
min	61	23	44.96124
max	595	117	88.28571
median	161	64	62.39754
average	242.8333333	66	64.53362
stdev	197.5261164	33.53207	17.04648
COV	0.81342258	0.508062	0.264149



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.893599					
R Square	0.798518					
Adjusted R Square	0.598518					
Standard Error	35.77333					
Observations	6					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	25359.35	25359.35	19.81615	0.011233	
Residual	5	6398.655	1279.731			
Total	6	31758				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.214944	0.048285	4.451534	0.006693	0.090823	0.339066

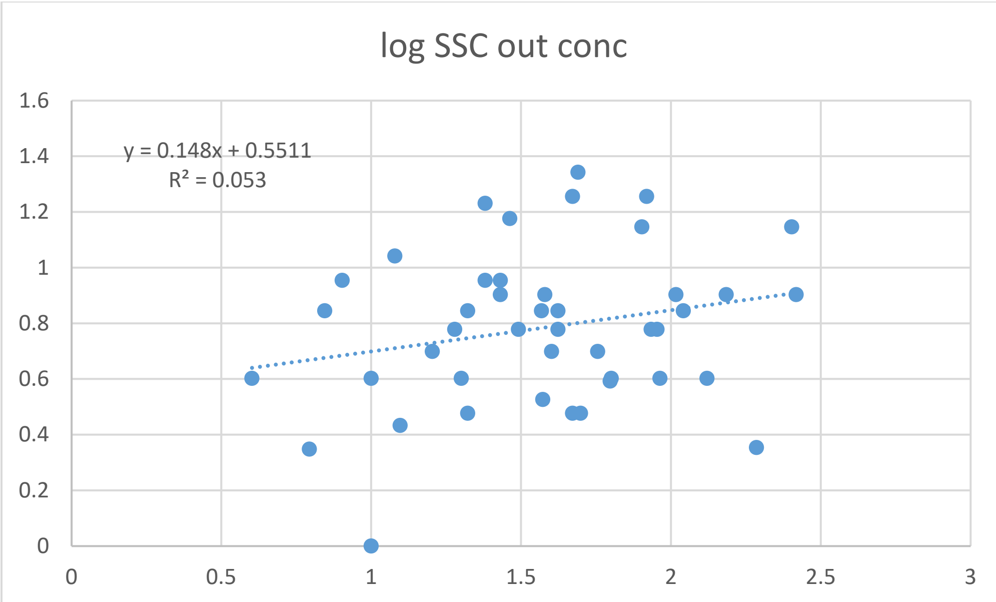
Appendix C5. Fill-Scale Biofilter Tests in Neenah WI

The Wisconsin full-scale biofilter tests were conducted in Neenah, WI (Bannerman, personal communication). These were especially constructed biofilters to compare different test mixtures and biofilter designs. The data shown below are for the mix-2, which was comprised of 86% sand, 11% peat moss, and 3% Imbrium phosphorus removal material. The biofilters were sealed and all of the treated effluent was collected by underdrains and analyzed, resulting in 44 sets of data. The following show the data and statistical analyses for the particulate retention data and for the retention of filtered pollutants.

Particulate Retention

The following show the statistical summaries for the data sets having complete data (observed influent and effluent concentrations), along with the scatterplots, regression equations, and ANOVA analyses indicating the significance of the overall equations and the equation coefficients.

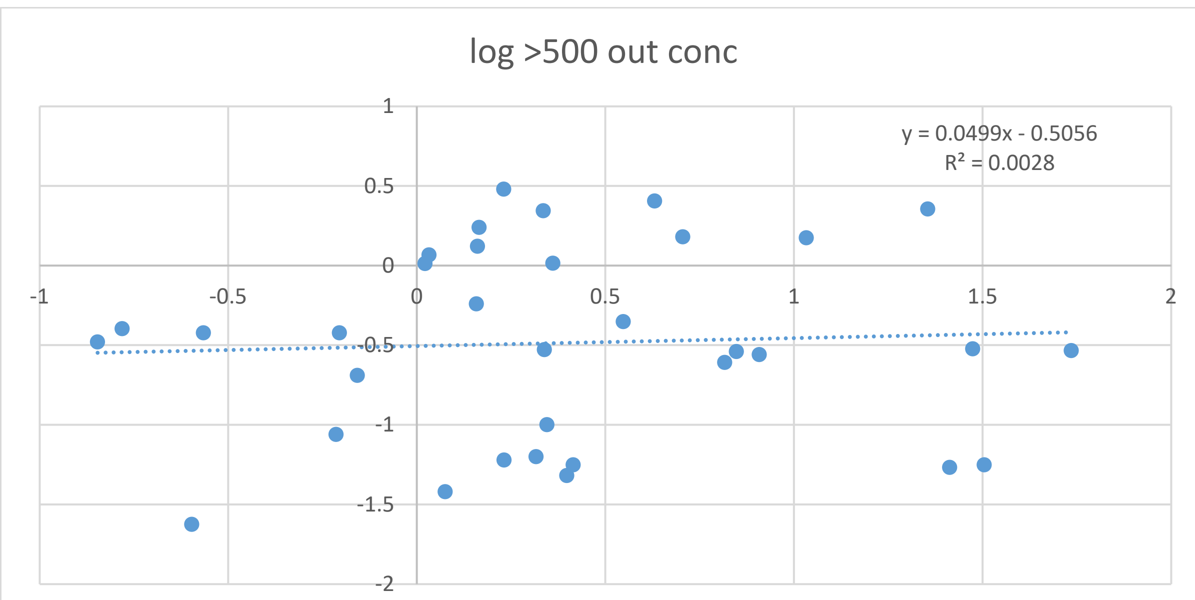
	Inlet conc	log inlet SSC conc	Outlet conc	log SSC out conc	% reduc
mean	58.616	1.571	7.374	0.784	73.112
stdev	60.337	0.433	4.816	0.278	28.184
COV	1.029	0.276	0.653	0.355	0.385
min	4.000	0.602	1.000	0.000	-12.500
max	262.000	2.418	22.000	1.342	98.829
median	39.000	1.591	6.000	0.778	81.791
count	44	44	44	44	44



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.230195629					
R Square	0.052990028					
Adjusted R Square	0.030442171					
Standard Error	0.274131546					
Observations	44					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.176607	0.176607	2.35011376	0.132773	
Residual	42	3.15622	0.075148			
Total	43	3.332827				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.551149001	0.157215	3.505709	0.00109754	0.233877	0.868421
X Variable 1	0.14800871	0.096548	1.533008	0.13277274	-0.04683	0.34285

Only the intercept is significant, not the overall equation or the slope. Therefore use a constant effluent concentration (and COV) for the effluent values.

	In conc	log >500 inlet conc	Out conc	log >500 out conc	% reduc
mean	7.056	0.388	0.715	-0.486	50.675
stdev	11.987	0.648	0.827	0.607	67.008
COV	1.699	1.669	1.157	-1.248	1.322
min	0.142	-0.846	0.024	-1.626	-142.240
max	54.384	1.735	3.017	0.480	99.825
median	2.173	0.337	0.315	-0.502	86.288
count	34	34	34	34	34

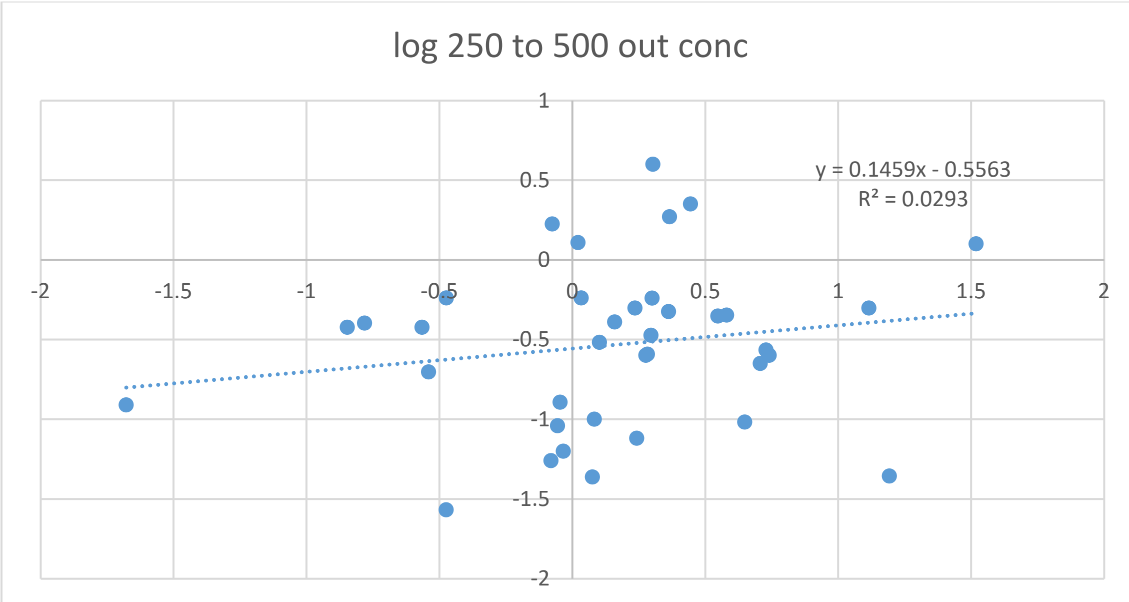


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.053273998					
R Square	0.002838119					

Adjusted R Square	-0.02832319					
Standard Error	0.615528447					
Observations	34					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.034507313	0.034507313	0.091078294	0.764763	
Residual	32	12.1240086	0.378875269			
Total	33	12.15851592				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.50559343	0.123542503	-4.092465508	0.00026991	-0.75724	-0.25394559
X Variable 1	0.049916708	0.165401138	0.301791806	0.764763458	-0.28699	0.386827801

Only the intercept is significant, not the overall equation or the slope. Therefore use a constant effluent concentration (and COV) for the effluent values.

	In conc	log 250 to 500 inlet conc	Out conc	log 250 to 500 out conc	% reduc
mean	3.331	0.154	0.565	-0.534	32.653
stdev	5.968	0.601	0.781	0.512	114.591
COV	1.792	3.890	1.382	-0.959	3.509
min	0.021	-1.678	0.027	-1.568	-485.714
max	33.034	1.519	3.982	0.600	99.718
median	1.722	0.236	0.336	-0.474	85.778
count	37	37	37	37	37

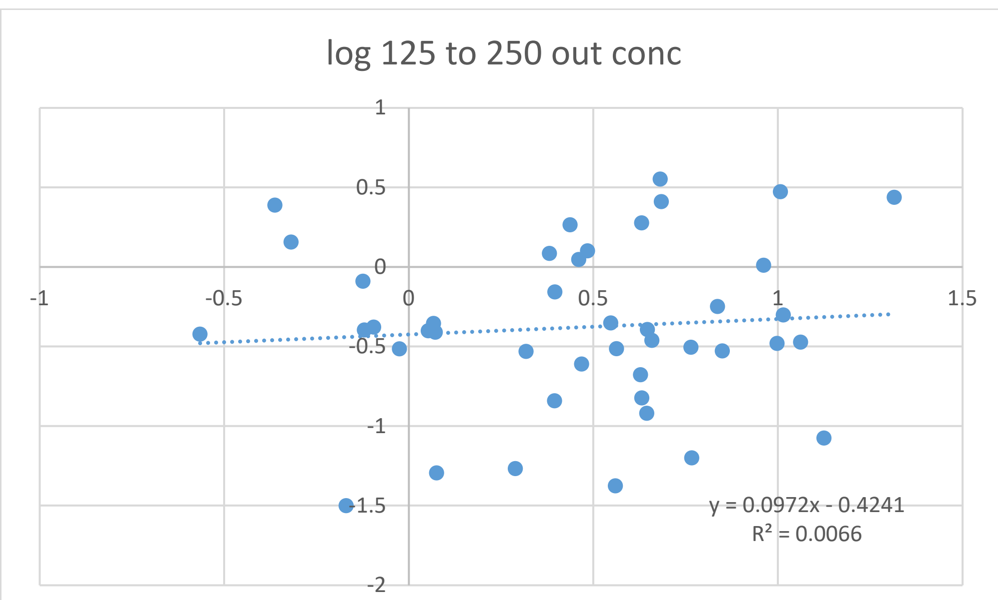


log 250 to 500						
only intercept sign						
SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.171294701					
R Square	0.029341875					
Adjusted R Square	0.001608785					
Standard Error	0.51148569					
Observations	37					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.276793944	0.276793944	1.05801	0.31072589	
Residual	35	9.156616401	0.261617611			
Total	36	9.433410346				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*

Intercept	-0.55633582	0.086896065	-6.402313226	2.29E-07	-0.732744215	-0.37993
X Variable 1	0.145904076	0.141847805	1.028595935	0.310726	-0.142062278	0.43387

Only the intercept is significant, not the overall equation or the slope. Therefore use a constant effluent concentration (and COV) for the effluent values.

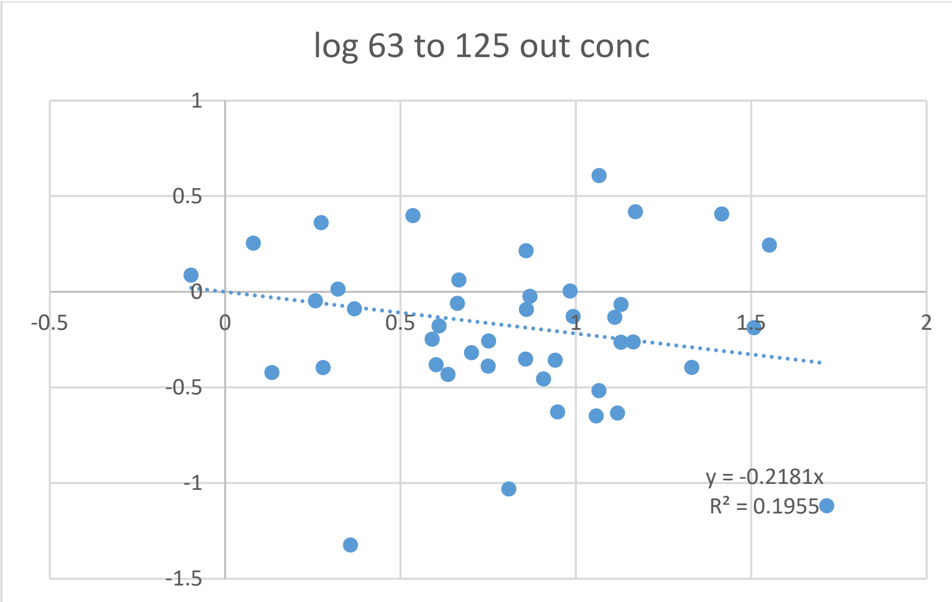
	In conc	log 150 to 250 inlet conc	Out conc	log 125 to 250 out conc	% reduc
mean	4.423	0.458	0.782	-0.380	55.308
stdev	4.151	0.440	0.895	0.524	95.677
COV	0.938	0.960	1.146	-1.382	1.730
min	0.272	-0.565	0.032	-1.501	-462.903
max	20.667	1.315	3.564	0.552	99.370
median	3.528	0.548	0.396	-0.402	87.411
count	43	43	43	43	43



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.081493					
R Square	0.006641					
Adjusted R Square	-0.01759					
Standard Error	0.52905					
Observations	43					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.07672	0.07672	0.274103	0.603411	
Residual	41	11.47566	0.279894			
Total	42	11.55238				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.4241	0.117219	-3.61799	0.000807	-0.66083	-0.18737
X Variable 1	0.097197	0.185651	0.523548	0.603411	-0.27773	0.472127

Only the intercept is significant, not the overall equation or the slope. Therefore use a constant effluent concentration (and COV) for the effluent values.

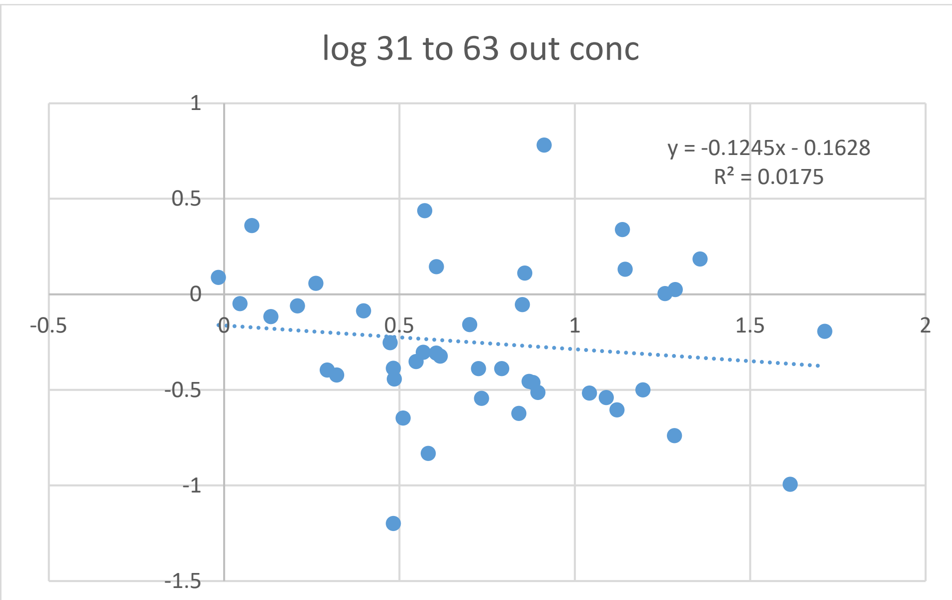
	In conc	log 63 to 150 inlet conc	Out conc	log 63 to 125 out conc	% reduc
mean	9.909	0.815	0.909	-0.204	77.163
stdev	10.193	0.410	0.834	0.405	36.244
COV	1.029	0.503	0.918	-1.979	0.470
min	0.800	-0.097	0.047	-1.325	-52.500
max	51.938	1.715	4.050	0.607	99.854
median	7.221	0.859	0.648	-0.188	90.230
count	43	43	43	43	43



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.442165					
R Square	0.19551					
Adjusted R Square	0.1717					
Standard Error	0.407647					
Observations	43					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1.696153	1.696153	10.20698	0.002691	
Residual	42	6.97938	0.166176			
Total	43	8.675533				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	-0.21814	0.068278	-3.19484	0.002655	-0.35593	-0.08035

The overall equation and the slope term are significant, but not the intercept.

	In conc	log 31 to 63 inlet conc	Out conc	log 31 to 63 out conc	% reduc
mean	8.708	0.740	0.841	-0.255	75.807
stdev	10.083	0.413	0.999	0.388	37.218
COV	1.158	0.558	1.188	-1.523	0.491
min	0.964	-0.016	0.063	-1.200	-90.500
max	51.614	1.713	6.030	0.780	99.754
median	5.169	0.713	0.483	-0.316	88.386
count	44	44	44	44	44

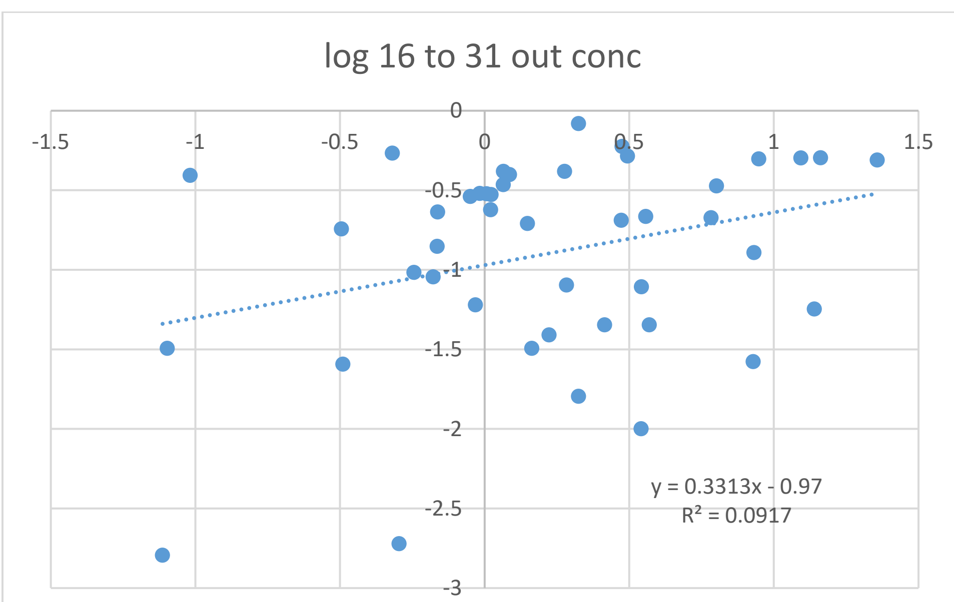


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.537758					
R Square	0.289183					
Adjusted R Square	0.265927					
Standard Error	0.392862					
Observations	44					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	

Regression	1	2.699996	2.699996	17.49378	0.000143	
Residual	43	6.636634	0.15434			
Total	44	9.33663				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	-0.29317	0.070094	-4.18256	0.000139	-0.43453	- 0.15181

The overall equation and the slope term are significant, but not the intercept.

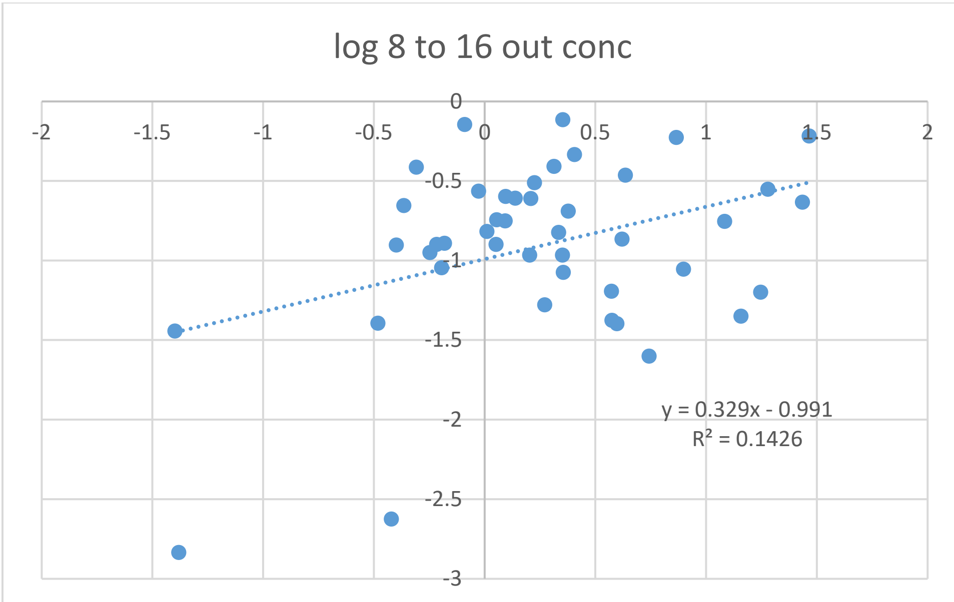
	In conc	log 16 to 31 inlet conc	Out conc	log 16 to 31 out conc	% reduc
mean	3.508	0.217	0.237	-0.898	74.461
stdev	4.714	0.578	0.202	0.633	62.350
COV	1.344	2.663	0.851	-0.704	0.837
min	0.077	-1.114	0.002	-2.795	- 307.292
max	22.794	1.358	0.828	-0.082	99.712
median	1.564	0.193	0.208	-0.682	92.637
count	44	44	44	44	44



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.302838					
R Square	0.091711					
Adjusted R Square	0.070085					
Standard Error	0.610037					
Observations	44					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1.578192	1.578192	4.240794	0.045698	
Residual	42	15.63011	0.372146			
Total	43	17.2083				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.96998	0.09838	-9.85951	1.71E-12	-1.16852	-0.77144
X Variable 1	0.331344	0.1609	2.059319	0.045698	0.006635	0.656053

The overall equation and both terms are significant.

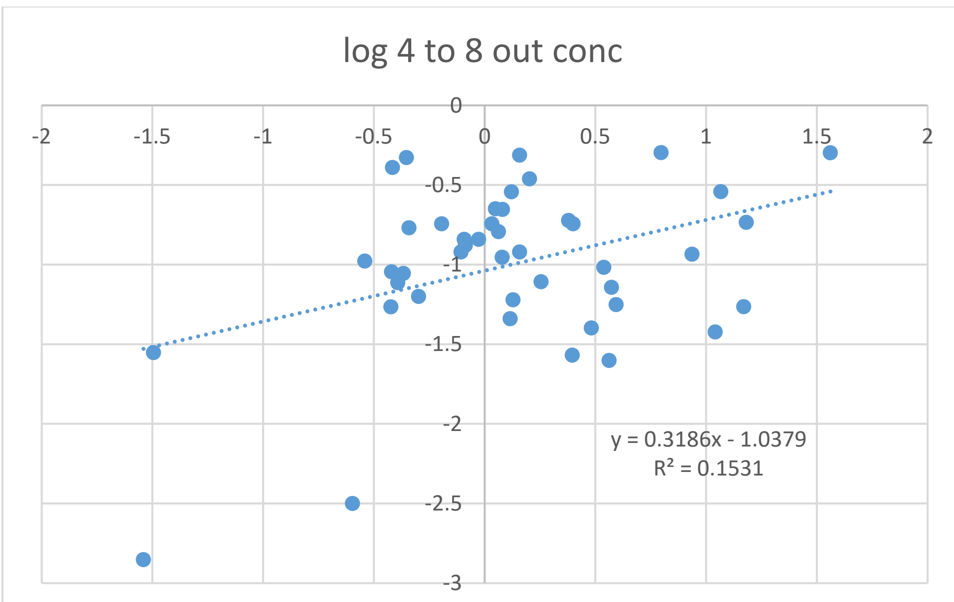
	In conc	log 8 to 16 inlet conc	Out conc	log 8 to 16 out conc	% reduc
mean	4.469	0.257	0.204	-0.906	83.614
stdev	6.877	0.627	0.186	0.546	21.774
COV	1.539	2.436	0.908	-0.603	0.260
min	0.040	-1.398	0.001	-2.836	10.000
max	29.233	1.466	0.765	-0.116	99.690
median	1.775	0.249	0.143	-0.845	90.142
count	44	44	44	44	44



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.377649					
R Square	0.142619					
Adjusted R Square	0.122205					
Standard Error	0.511705					
Observations	44					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1.829327	1.829327	6.986373	0.011495	
Residual	42	10.99737	0.261842			
Total	43	12.82669				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.99101	0.083528	-11.8643	5.37E-15	-1.15957	-0.82244
X Variable 1	0.328962	0.124457	2.643175	0.011495	0.077797	0.580126

The overall equation and both terms are significant.

	In conc	log 4 to 8 inlet conc	Out conc	log 4 to 8 out conc	% reduc
mean	3.480	0.124	0.158	-0.999	82.342
stdev	6.325	0.628	0.138	0.511	24.736
COV	1.817	5.075	0.873	-0.512	0.300
min	0.029	-1.540	0.001	-2.853	-5.990
max	36.383	1.561	0.504	-0.298	99.657
median	1.255	0.098	0.118	-0.928	89.125
count	44	44	44	44	44

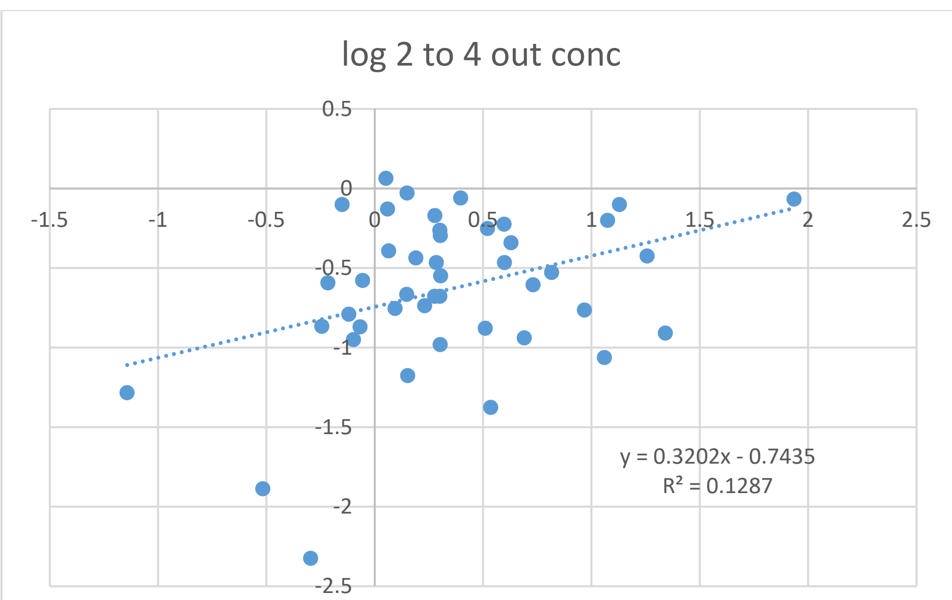


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.39124					
R Square	0.153068					
Adjusted R Square	0.132903					
Standard Error	0.475831					
Observations	44					
ANOVA						

	df	SS	MS	F	Significance F	
Regression	1	1.718665	1.718665	7.590779	0.008638	
Residual	42	9.509422	0.226415			
Total	43	11.22809				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.03794	0.073145	-14.1902	1.27E-17	-1.18556	-0.89033
X Variable 1	0.318597	0.115638	2.755137	0.008638	0.085231	0.551964

The overall equation and both terms are significant.

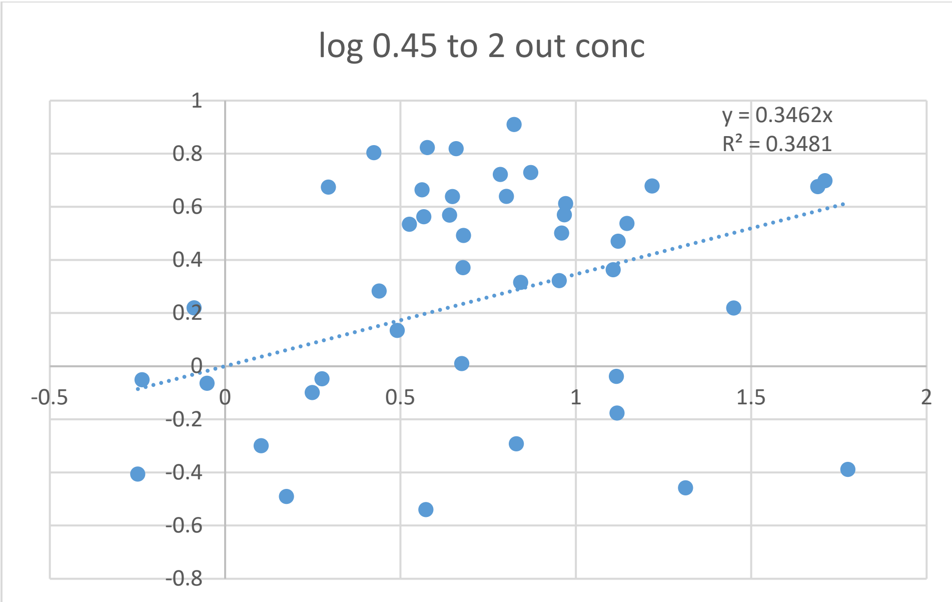
	In conc	log 2 to 4 inlet conc	Out conc	log 2 to 4 out conc	% reduc
mean	5.632	0.350	0.358	-0.632	78.632
stdev	13.316	0.543	0.288	0.485	25.834
COV	2.364	1.554	0.806	-0.768	0.329
min	0.072	-1.143	0.005	-2.325	-11.864
max	86.226	1.936	1.156	0.063	99.438
median	1.964	0.293	0.260	-0.586	85.988
count	44	44	44	44	44



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.358682					
R Square	0.128653					
Adjusted R Square	0.107906					
Standard Error	0.45804					
Observations	44					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1.301023	1.301023	6.201221	0.016807	
Residual	42	8.811645	0.209801			
Total	43	10.11267				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.74354	0.082387	-9.0249	2.19E-11	-0.9098	-0.57727
X Variable 1	0.320159	0.128566	2.490225	0.016807	0.060702	0.579617

The overall equation and both terms are significant.

	In conc	log 0.45 to 2 inlet conc	Out conc	log 0.45 to 2 out conc	% reduc
mean	9.865	0.731	2.869	0.300	34.040
stdev	13.230	0.483	2.076	0.421	62.450
COV	1.341	0.660	0.723	1.403	1.835
min	0.564	-0.249	0.288	-0.541	-139.269
max	59.670	1.776	8.115	0.909	99.316
median	4.777	0.679	2.649	0.420	55.576
count	44	44	44	44	44



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.589999					
R Square	0.348099					
Adjusted R Square	0.324843					
Standard Error	0.418571					
Observations	44					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	4.022801	4.022801	22.96096	2.09E-05	
Residual	43	7.533675	0.175202			
Total	44	11.55648				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.346181	0.072245	4.79176	2E-05	0.200485	0.491877

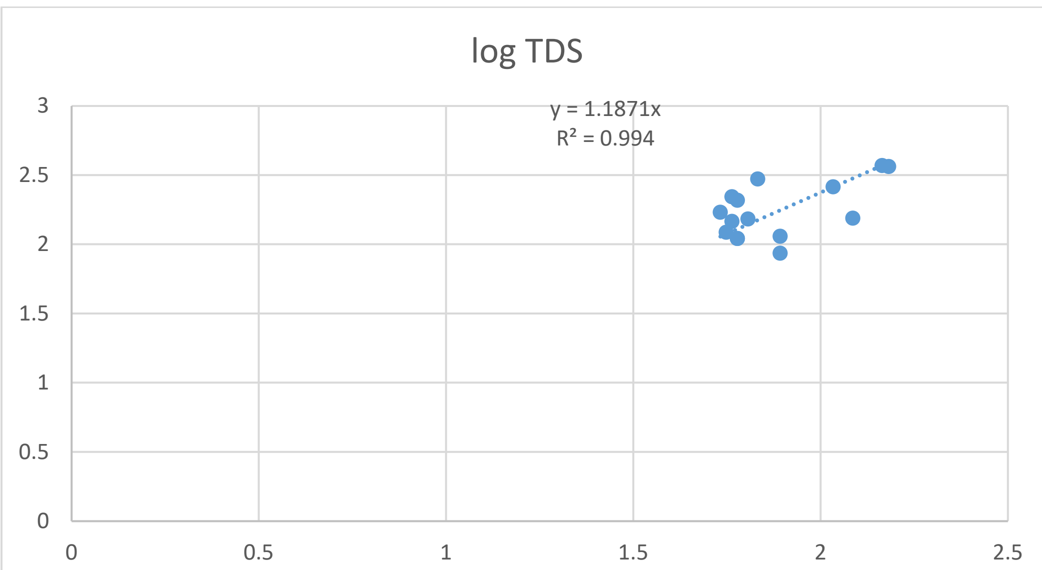
The overall equation and the slope term are significant, but not the intercept.

Filtered Pollutant Retention

These calculations deleted pairs that either influent or effluent as non-detected.

TDS, mg/L

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	15	15	15	15	15.0
min	54	1.732394	86	1.934498	-335.3
max	152	2.181844	370	2.568202	-10.3
mean	81.46667	1.88205	192.1333333	2.240051	-144.4
median	64	1.80618	154	2.187521	-139.5
stdev	33.68312	0.156635	92.21858092	0.198713	92.6
COV	0.413459	0.083226	0.479971795	0.088709	-0.6



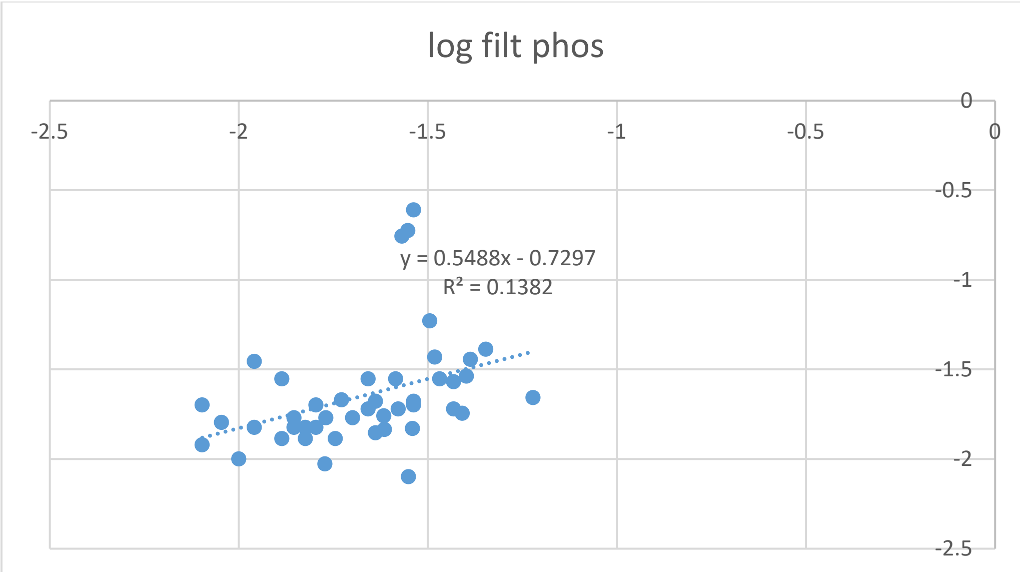
SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.462137					
R Square	0.21357					
Adjusted R Square	0.196474					
Standard Error	0.156918					
Observations	48					

ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.307597	0.307597093	12.4922	0.000944	
Residual	46	1.132664	0.024623133			
Total	47	1.440261				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.629698	0.148063	11.00680815	1.76E-14	1.331663	1.927733
X Variable 1	0.333818	0.094447	3.534430574	0.000944	0.143705	0.52393

Sign test indicated highly significant differences between influent and effluent (all increases). The sign test considers non-detected influent observations. ANOVA showed significant regression equation and coefficients.

filtered phosphorus, mg/L

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	44	44	44	44	44.0
min	0.008	-2.09691	0.00796	-2.0990869	-744.8
max	0.06	-1.22185	0.245	-0.6108339	71.7
mean	0.023895	-1.66984	0.0334218	-1.6461582	-45.7
median	0.023	-1.63827	0.019	-1.7212464	7.5
stdev	0.0112392	0.2118826	0.047956097	0.312803254	168.5
COV	0.47035	-0.12689	1.434874	-0.1900202	-3.7

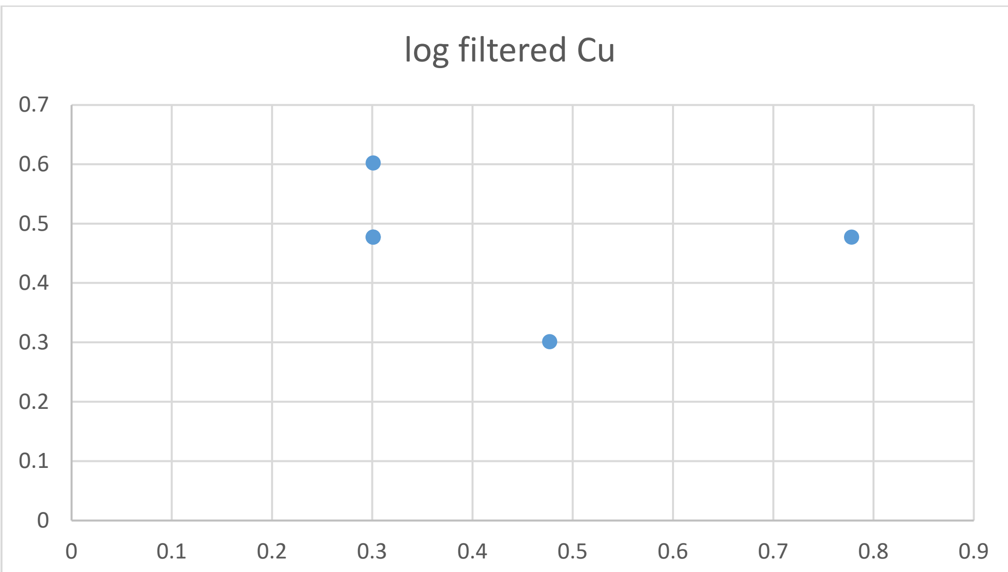


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.371741					
R Square	0.138191					
Adjusted R Square	0.117672					
Standard Error	0.293823					
Observations	44					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.5814224	0.58142237	6.734714	0.012969	
Residual	42	3.6259503	0.08633215			
Total	43	4.2073727				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.72975	0.3558943	-2.0504599	0.046594	-1.44797	-0.01152
X Variable 1	0.548803	0.2114739	2.59513282	0.012969	0.122031	0.975575

The sign test did not indicate any significant difference between influent and effluent filtered phosphorus concentrations. The ANOVA however indicated a significant regression and coefficients.

filtered Cu, ug/L

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	5	5	5	5	5.0
min	2	0.30103	2	0.30103	-100.0
max	6	0.778151	4	0.60206	50.0
mean	3	0.431672	3	0.466891	-23.3
median	2	0.30103	3	0.477121	-50.0
stdev	1.732051	0.208156	0.707107	0.107348	63.0
COV	0.57735	0.482208	0.235702	0.229921	-2.7

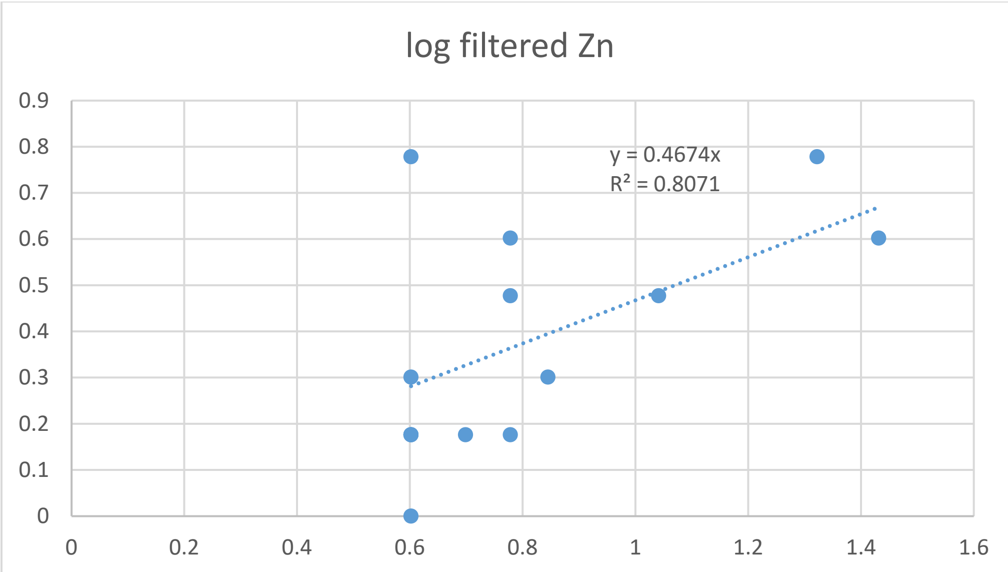


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.272156					
R Square	0.074069					
Adjusted R Square	-0.23458					
Standard Error	0.119276					
Observations	5					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.003414	0.003414	0.239981	0.65780717	
Residual	3	0.04268	0.014227			
Total	4	0.046095				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.527477	0.13469	3.916237	0.029599	0.09883423	0.956121
X Variable 1	-0.14035	0.286507	-0.48988	0.657807	-1.05214534	0.771438

Regression not significant due to few data with both influent and effluent detectable. The sign test that does consider non-detectable values indicated significant differences (7% influent were non-detected, while 57% of effluent values were non-detected). Therefore, use median effluent concentration (with COV) to represent expected effluent filtered copper concentrations (median effluent Cu = 3 µg/L and COV = 0.24).

filtered Zn, ug/L

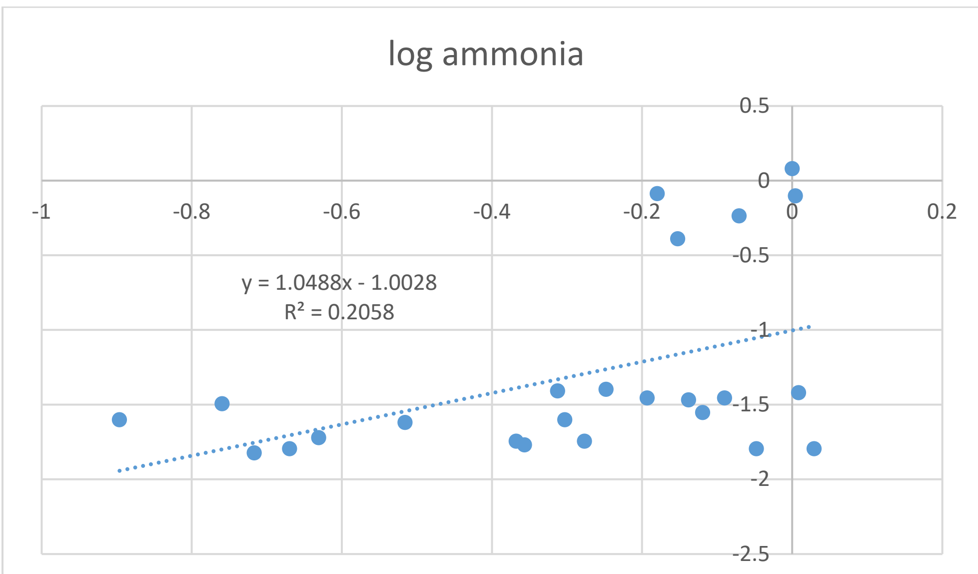
	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	14	14	14	14	14.0
min	4	0.60206	1	0	-50.0
max	27	1.431364	6	0.778151	85.2
mean	8.07142857	0.806133	2.75	0.371227	56.5
median	5.5	0.738561	2	0.30103	66.3
stdev	7.10865438	0.274259	1.672745	0.247794	33.4
COV	0.88071824	0.340215	0.608271	0.667499	0.6



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.898374					
R Square	0.807075					
Adjusted R Square	0.730152					
Standard Error	0.201191					
Observations	14					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	2.201346	2.201346	54.38384	8.56E-06	
Residual	13	0.526213	0.040478			
Total	14	2.727559				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.467418	0.063383	7.37454	5.39E-06	0.330488	0.604349

Significant regression and slope term (intercept not significant) ammonia, mg/L

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	24	24	24	24	24.0
min	0.127	-0.8962	0.015	-1.82391	-23.4
max	1.07	0.029384	1.2	0.079181	98.5
mean	0.597792	-0.29169	0.178417	-1.30875	76.1
median	0.603	-0.22055	0.03	-1.52385	92.7
stdev	0.295245	0.271521	0.328405	0.627797	36.9
COV	0.493892	-0.93086	1.840662	-0.47969	0.5

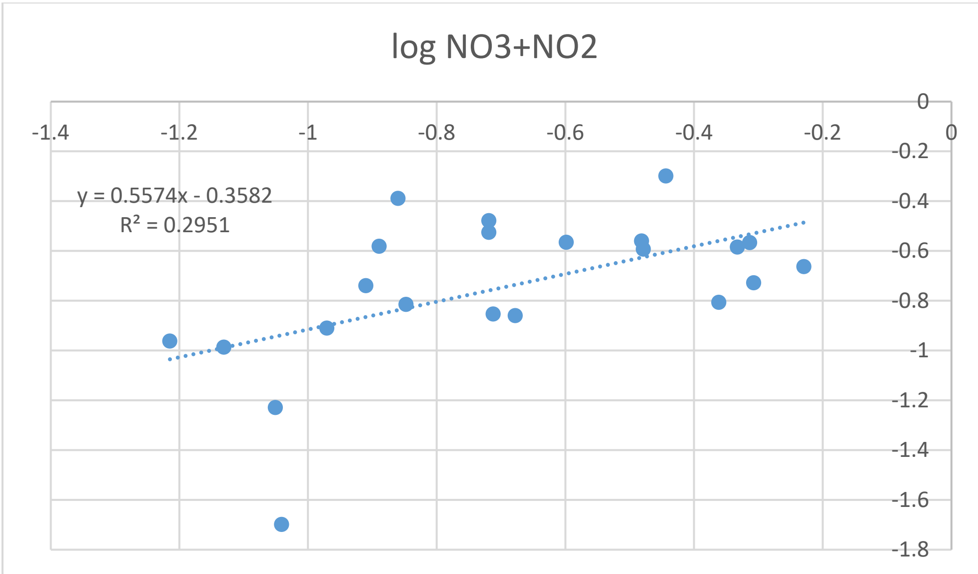


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.453607					
R Square	0.20576					
Adjusted R Square	0.169658					
Standard Error	0.572068					
Observations	24					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	1.865206	1.865206	5.699422	0.025993	
Residual	22	7.199771	0.327262			
Total	23	9.064977				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.00282	0.17337	-5.78428	8.08E-06	-1.36237	-0.64327
X Variable 1	1.048809	0.43932	2.387346	0.025993	0.137715	1.959903

Regression and all equation coefficients significant.

NO3+NO3, mg/L

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	22	22	22	22	22.0
min	0.061	-1.21467	0.02	-1.69897	-195.7
max	0.59	-0.22915	0.502	-0.2993	78.0
mean	0.249227	-0.69497	0.214636	-0.74556	-7.9
median	0.1925	-0.71558	0.202	-0.69585	4.5
stdev	0.16051	0.295915	0.113677	0.303602	66.9
COV	0.644031	-0.4258	0.529627	-0.40721	-8.5

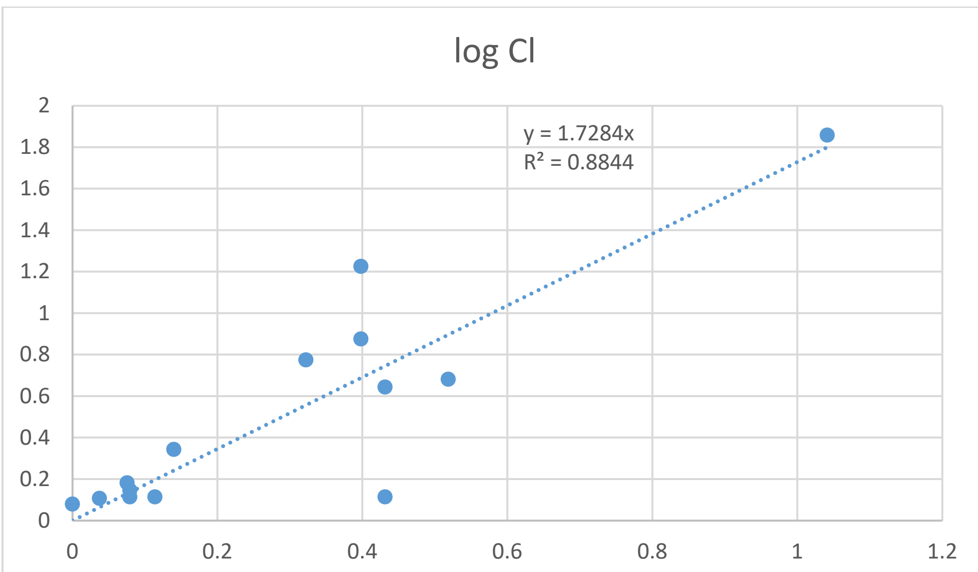


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.543241					
R Square	0.29511					
Adjusted R Square	0.259866					
Standard Error	0.261192					
Observations	22					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.571234	0.571234	8.373233	0.00898	
Residual	20	1.364428	0.068221			
Total	21	1.935662				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.35822	0.14498	-2.47082	0.022596	-0.66064	-0.0558
X Variable 1	0.557354	0.192612	2.893654	0.00898	0.155571	0.959136

Regression and all equation coefficients significant.

Cl, mg/L

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	14	14	14	14	14.0
min	1	0	1.2	0.079181	-572.0
max	11	1.041393	72.1	1.857935	51.9
mean	2.511429	0.290421	8.789286	0.518295	-122.6
median	1.74	0.231049	1.86	0.262133	-36.6
stdev	2.559399	0.279755	18.70919	0.530936	198.6
COV	1.019101	0.963276	2.128636	1.024389	-1.6

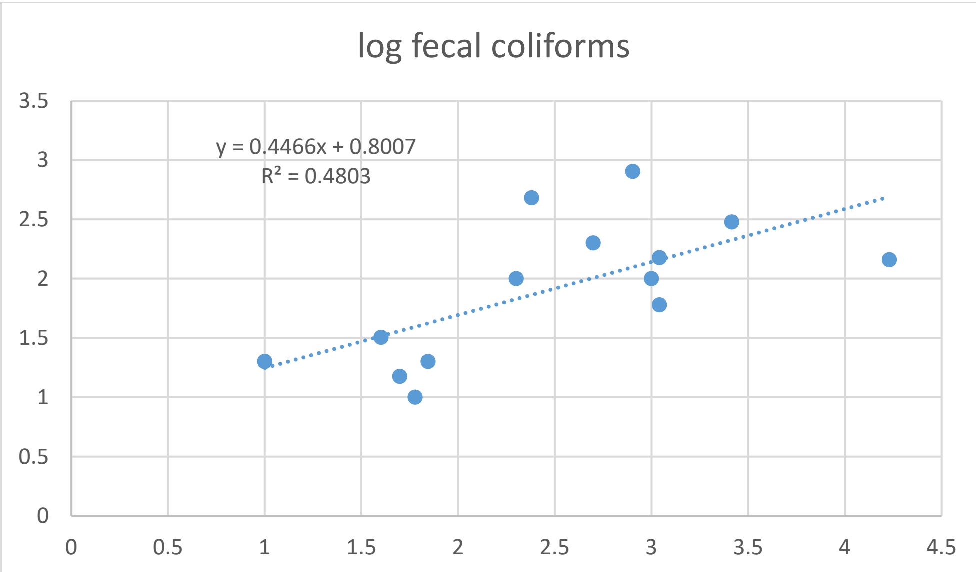


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.940408					
R Square	0.884368					
Adjusted R Square	0.807445					
Standard Error	0.256997					
Observations	14					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	6.566806	6.566806	99.4256	3.69E-07	
Residual	13	0.858617	0.066047			
Total	14	7.425423				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.728382	0.173337	9.971239	1.86E-07	1.35391	2.102853

Regression equation and slope term significant. Intercept not significant.

fecal coliforms, #/100 mL

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	15	15	15	15	15.0
min	10	1	10	1	-100.0
max	17000	4.230449	800	2.90309	99.2
mean	1652	2.395719	163.4	1.870628	34.2
median	240	2.380211	100	2	70.0
stdev	4303.187	0.912557	218.6471	0.588069	74.7
COV	2.604835	0.380911	1.338109	0.31437	2.2

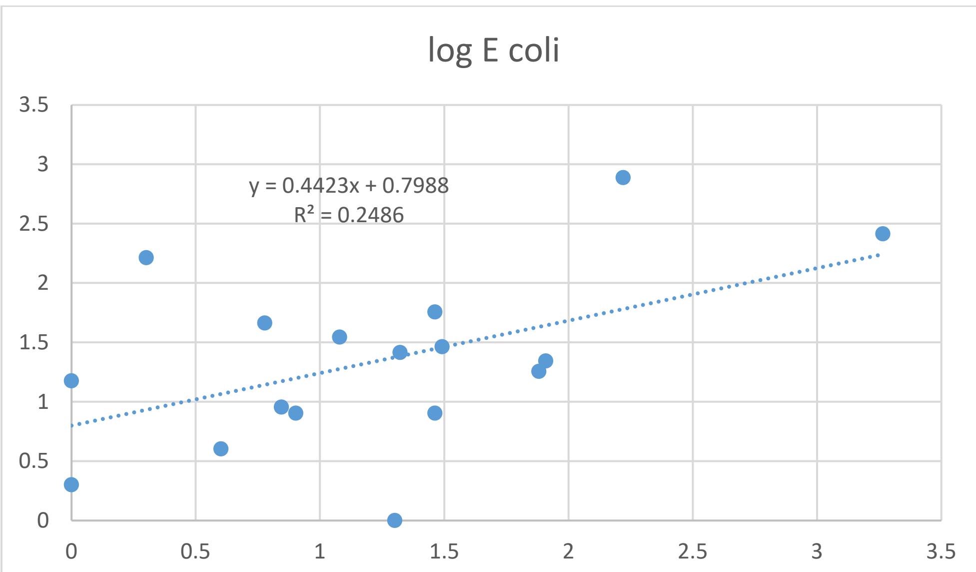


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.693009					
R Square	0.480261					
Adjusted R Square	0.440281					
Standard Error	0.43996					
Observations	15					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	2.325208	2.325208	12.01255	0.004179	
Residual	13	2.516343	0.193565			
Total	14	4.841551				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.800729	0.32893	2.434343	0.030085	0.090119	1.511339
X Variable 1	0.446588	0.128851	3.465913	0.004179	0.168221	0.724954

Regression and both coefficients significant.

E coli, #/100 mL

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	17	17	17	17	17.0
min	1	0	1	0	-8050.0
max	1842	3.26529	770	2.886491	95.0
mean	137.4118	1.224866	86.58824	1.34055	-618.4
median	20	1.30103	22	1.342423	-23.8
stdev	441.281	0.827688	188.4911	0.734334	1951.4
COV	3.211377	0.675738	2.176867	0.547785	-3.2

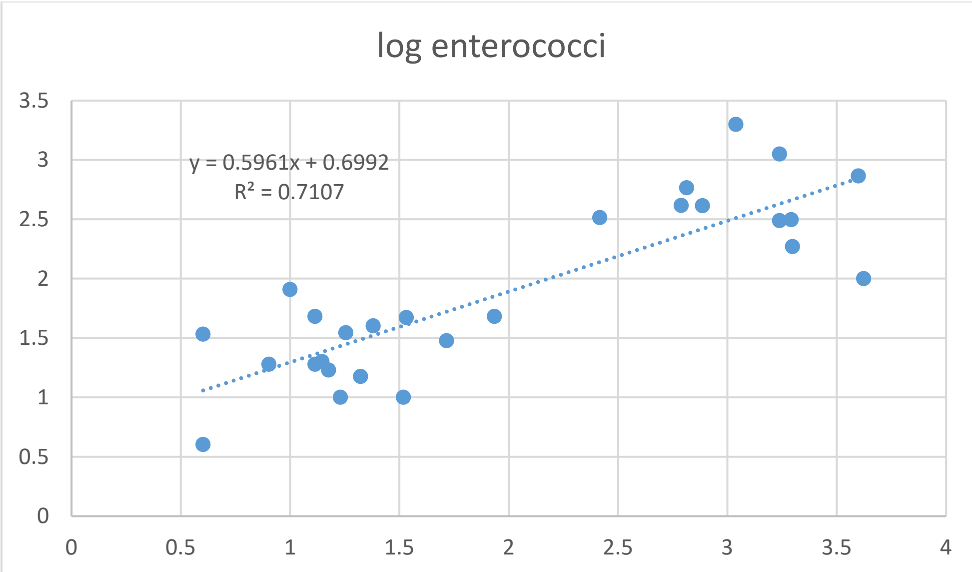


SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.498565					
R Square	0.248567					
Adjusted R Square	0.198471					
Standard Error	0.657435					
Observations	17					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	2.144618	2.144618	4.961854	0.041645	
Residual	15	6.483318	0.432221			
Total	16	8.627937				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.798753	0.290835	2.746412	0.014994	0.178852	1.418653
X Variable 1	0.442332	0.198576	2.227522	0.041645	0.019078	0.865587

Regression and both coefficients significant.

enterococci, #/100 mL

	Inlet conc	log inlet conc	Outlet conc	log outlet conc	% reduc
count	27	27	27	27	27.0
min	4	0.60206	4	0.60206	-750.0
max	4200	3.623249	1986	3.297979	97.6
mean	716.4444	1.991903	257.5185	1.886577	-55.1
median	34	1.531479	48	1.681241	10.6
stdev	1177.336	1.010623	437.847	0.714645	210.9
COV	1.643304	0.507366	1.700255	0.378805	-3.8



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.843013					
R Square	0.710671					
Adjusted R Square	0.699098					
Standard Error	0.392015					
Observations	27					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	9.436772	9.436772	61.40697	3.42E-08	
Residual	25	3.841898	0.153676			
Total	26	13.27867				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.699158	0.169271	4.13041	0.000354	0.350538	1.047779
X Variable 1	0.596123	0.076072	7.83626	3.42E-08	0.439449	0.752797

Regression and both coefficients significant.

Appendix D1. Filterable Pollutant Retention in Soils beneath Millburn, NJ, Dry Wells

Summary of Mann-Whitney Test for Paired Data

Constituent	Significant (at p = 0.05)	135 Shallow vs. 135 Deep	18 Shallow vs. 18 Deep	139 Shallow vs. 139 Deep
Total Coliforms	p-value	0.4	0.16	0.72
	Significant Difference Observed?	No	No	No
E. coli	p-value	0.6	0.69	1
	Significant Difference Observed?	No	No	No
Total Nitrogen as N	p-value	0.5	0.42	0.64
	Significant Difference Observed?	No	No	No
NO_3 plus NO_2 -N	p-value	0.24	0.15	0.77
	Significant Difference Observed?	No	No	No
Total Phosphorus as P	p-value	0.94	0.1	0.27
	Significant Difference Observed?	No	No	No
COD	p-value	0.14	0.4	0.83
	Significant Difference Observed?	No	No	No
Lead	p-value	> 0.06	0.18	> 0.06
	Significant Difference Observed?	No	No	No
Copper	p-value	all ND	>0.06	all ND
	Significant Difference Observed?	all ND	No	all ND
Zinc	p-value	0.45	>0.06	>0.06
	Significant Difference Observed?	No	No	No

None of these initial analyses using the non-parametric Mann-Whitney test for paired data indicated any significant differences between the shallow and deep sample concentrations.

Detected pesticides

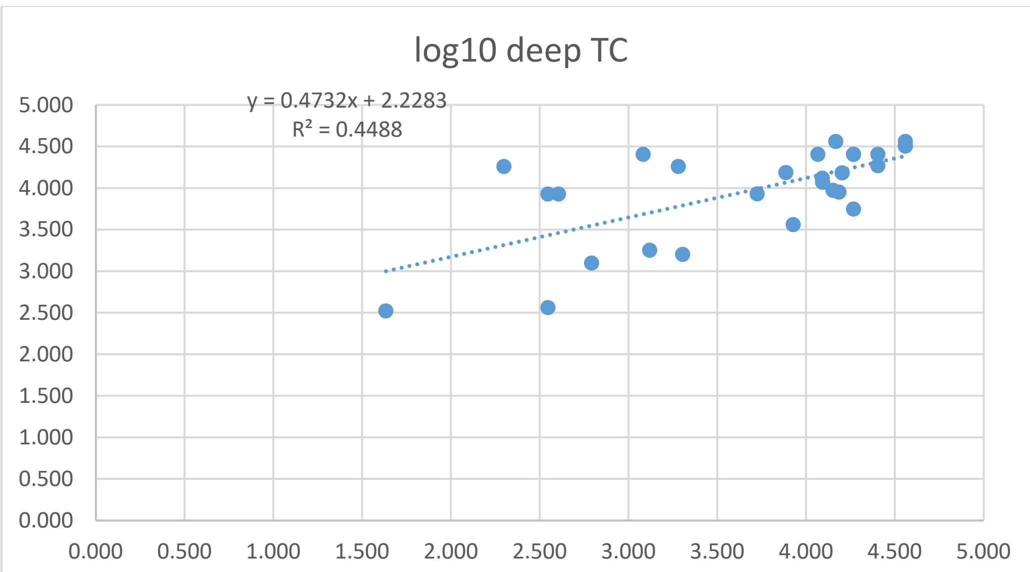
µg/L	135 Shallow	135 Deep
alpha-Chlordane	0.030	0.030
gamma-Chlordane	0.020	0.024
Endosulfan-I	0.032	0.034

There were no obvious differences in the shallow and deep concentrations for these few pesticide analyses.

The following regressions indicate significant differences and relationships between shallow and deep concentrations for some pollutants. As always, the predicted deep concentrations still have a lot of variability so the effluent COV value should be used with a Monte Carlo process to incorporate the uncertainty.

Total Coliforms

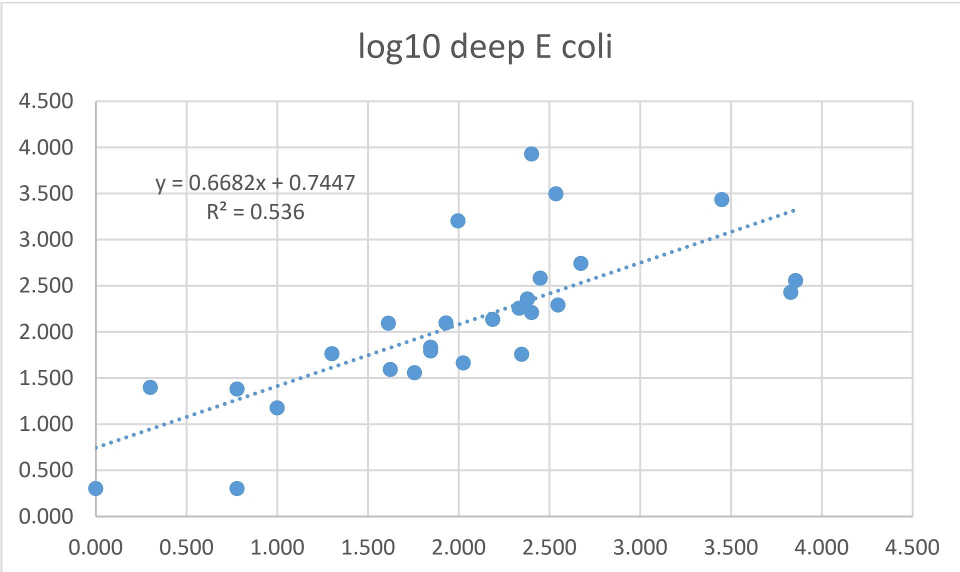
	TC Shallow, #/100mL	log10 shallow TC	TC Deep, #/100mL	log10 deep TC	% TC reduction
count	28	28	28	28	28
min	43	1.633	332	2.521	-9,019
max	36,294	4.560	36,294	4.560	70
mean	11,790	4.518	14,894	4.798	-592
median	12,012	4.079	14,148	4.150	-21
stdev	11581.95368	0.807	11309.58224	0.570	1777.729021
COV	0.98	0.18	0.76	0.12	-3.00



total coliforms sign regression						
SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.669890534					
R Square	0.448753328					
Adjusted R Square	0.427551533					
Standard Error	0.431184769					
Observations	28					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	3.93515528	3.93515528	21.16581764	9.64614E-05	
Residual	26	4.833927941	0.185920305			
Total	27	8.76908322				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.228281272	0.387060879	5.756927126	4.6191E-06	1.432666241	3.023896303
X Variable 1	0.473192829	0.102853868	4.600632308	9.64614E-05	0.261773675	0.684611984

Significant regression equation and coefficients.

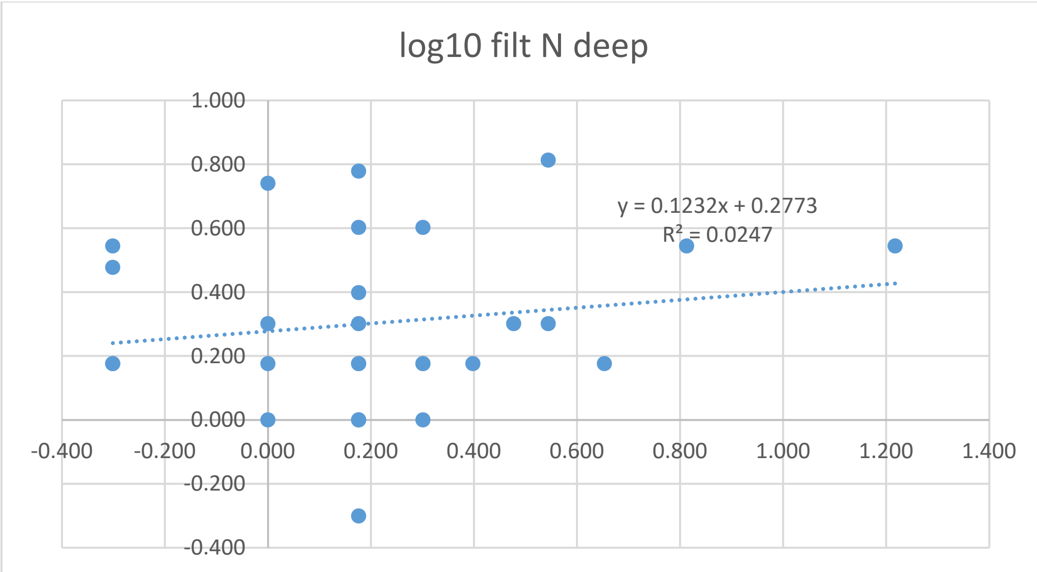
	E coli Shallow, #/100mL	log10 shallow Ecoli	E coli Deep, #/100mL	log10 deep E coli	% E coli reduction
count	27	27	27	27	27
min	1	0.000	2	0.301	-3,261
max	7,183	3.856	8,469	3.928	96
mean	721	2.899	681	2.975	-253
median	106	2.025	125	2.097	4
stdev	1870.58854	0.933	1741.494349	0.852	713.5819014
COV	2.60	0.32	2.56	0.29	-2.82


log10 deep E coli
y = 0.6682x + 0.7447
R² = 0.536
4.500
4.000
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0.000
0.500
1.000
1.500
2.000
2.500
3.000
3.500
4.000
4.500

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.73212408					
R Square	0.536005668					
Adjusted R Square	0.517445895					
Standard Error	0.591536026					
Observations	27					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	10.10553044	10.1055304	28.87996854	1.42048E-05	
Residual	25	8.747871753	0.34991487			
Total	26	18.8534022				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.744681701	0.274256464	2.71527493	0.011831939	0.179839941	1.309523461
X Variable 1	0.668247184	0.124347993	5.37400861	1.42048E-05	0.412147699	0.924346669

Significant regression and coefficients.

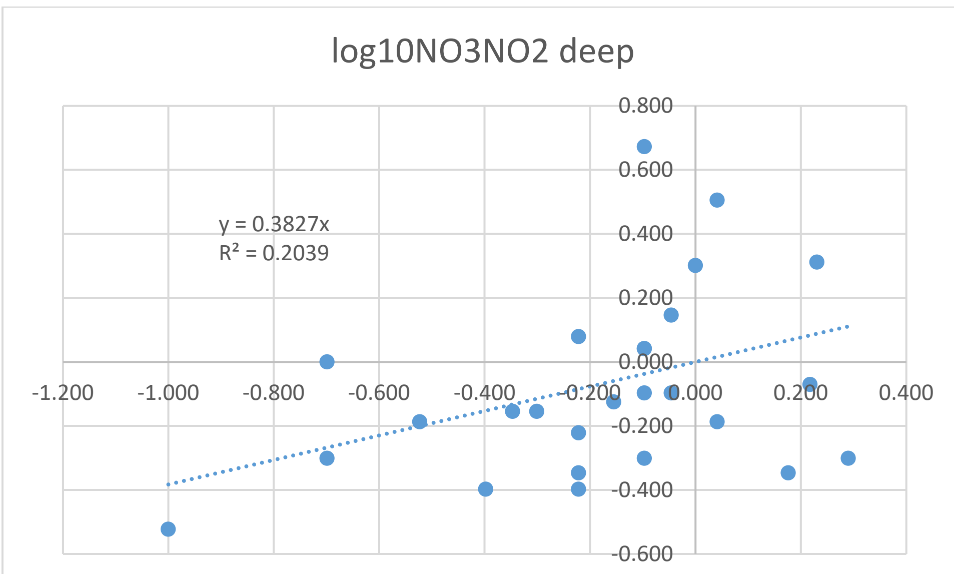
	filtered N, mg/L shallow	log10 filtN shallow	filtered N, mg/L deep	log10 filt N deep	% filt N reduction
count	28	28	28	28	28
min	1	-0.301	0.500	-0.301	-600
max	17	1.217	6.500	0.813	79
mean	3	1.180	3.310	1.260	-79
median	2	0.176	1.750	0.239	0
stdev	3.061268109	0.342	1.585316219	0.269	180.8053831
COV	0.93	0.29	0.48	0.21	-2.30



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.157061422					
R Square	0.02466829					
Adjusted R Square	-0.012844468					
Standard Error	0.270225874					
Observations	28					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.048019089	0.048019089	0.657597354	0.424770732	
Residual	26	1.898572602	0.073022023			
Total	27	1.946591691				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.27725496	0.061243344	4.527103583	0.00011712	0.151367464	0.403142456
X Variable 1	0.123175686	0.151895519	0.810923766	0.424770732	-0.189050024	0.435401396

Regression and no terms significant.

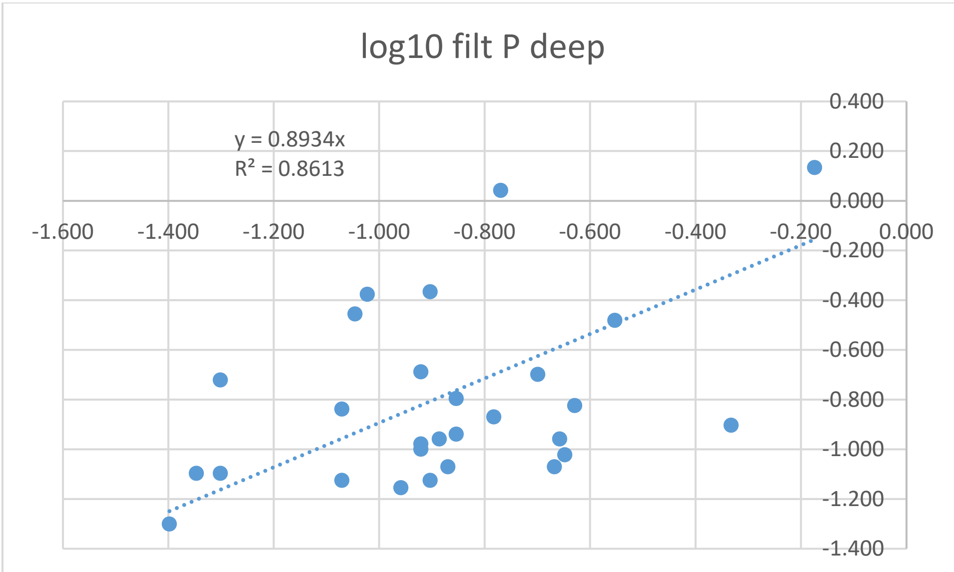
	NO3+NO2 shallow mg/L	log10 NO3NO2 shallow	NO3+NO2 deep mg/L	log10NO3NO2 deep	% NO3+NO2 reduction
count	26	26	26	26	26
min	0.10	-1.000	0	-0.523	-488
max	1.95	0.290	5	0.672	74
mean	1.74	0.793	2	0.885	-60
median	0.80	-0.097	1	-0.140	-29
stdev	0.472656161	0.303	0.980810105	0.287	134.645574
COV	0.27	0.38	0.49	0.32	-2.23



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.451511073					
R Square	0.203862249					
Adjusted R Square	0.163862249					
Standard Error	0.266775734					
Observations	26					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.455597413	0.455597413	6.401600994	0.018375883	
Residual	25	1.779232311	0.071169292			
Total	26	2.234829724				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.382701167	0.151257001	2.530138533	0.018074551	0.071181542	0.694220792

Significant regression and slope term (intercept not significant).

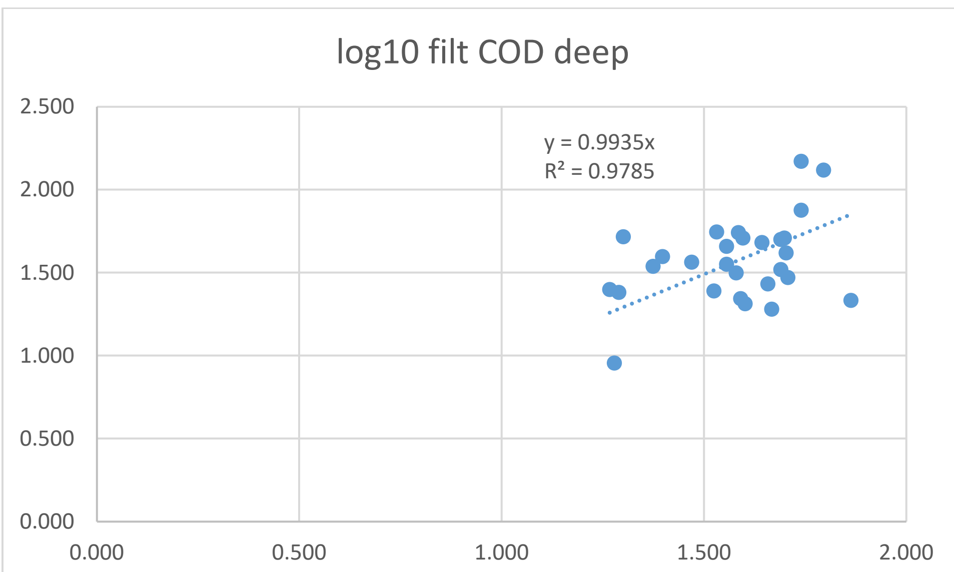
	filtered P shallow, mg/L	log10 filt P shallow	filtered P, deep, mg/L	log10 filt P deep	% filt P reduction
count	28	28	28	28	28
min	0.040	-1.398	0	-1.301	-547
max	0.670	-0.174	1	0.134	73
mean	1.126	0.122	1	0.181	-56
median	0.128	-0.895	0	-0.921	6
stdev	0.131792184	0.282	0.301941414	0.350	148.1764039
COV	0.12	2.31	0.25	1.93	-2.64



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.928077099					
R Square	0.861327102					
Adjusted R Square	0.824290065					
Standard Error	0.334496173					
Observations	28					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	18.76387758	18.76387758	167.7027884	7.60482E-13	
Residual	27	3.020967627	0.11188769			
Total	28	21.78484521				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.893365663	0.068985706	12.95001113	4.25755E-13	0.751818686	1.03491264

Significant regression and slope term (intercept not significant).

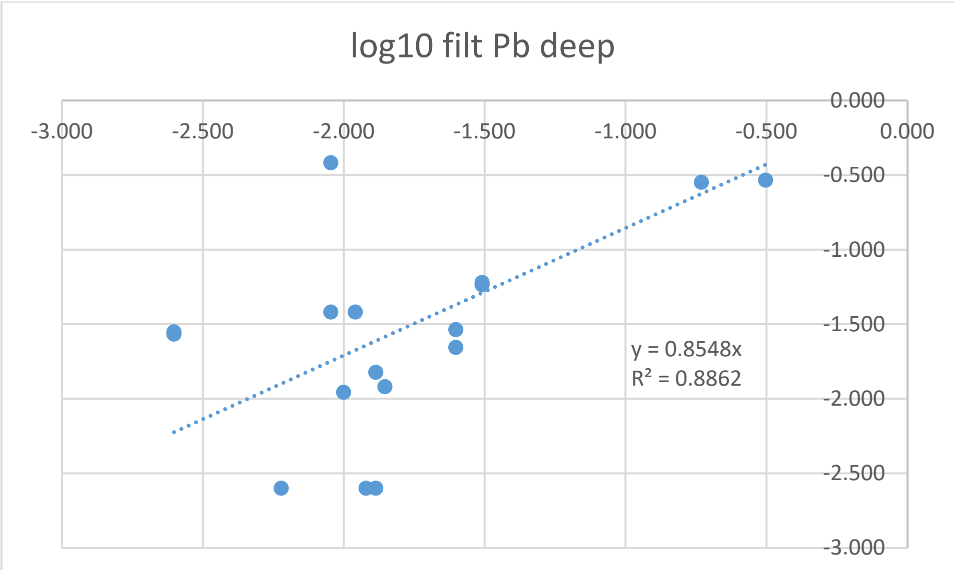
	filtered COD, shallow, mg/L	log10 filt COD shallow	filtered COD, deep, mg/L	log10 filt COD deep	% filt COD reduction
count	28	28	28	28	28
min	19	1.267	9	0.954	-169
max	73	1.863	148	2.170	71
mean	40	2.486	44	2.482	-12
median	39	1.594	36	1.556	-6
stdev	13.70208486	0.162	30.65363767	0.250	60.52479729
COV	0.35	0.07	0.70	0.10	-4.96



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.9891844					
R Square	0.978485778					
Adjusted R Square	0.941448741					
Standard Error	0.237497629					
Observations	28					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	69.26457752	69.26457752	1227.983789	2.04814E-23	
Residual	27	1.522938339	0.056405124			
Total	28	70.78751586				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.993481105	0.028350668	35.04259964	4.76901E-24	0.93531034	1.051651871

Significant regression and slope term (intercept not significant), but slope term is 0.99 indicating only a 1% reduction! Therefore, ignore the regression and y = x.

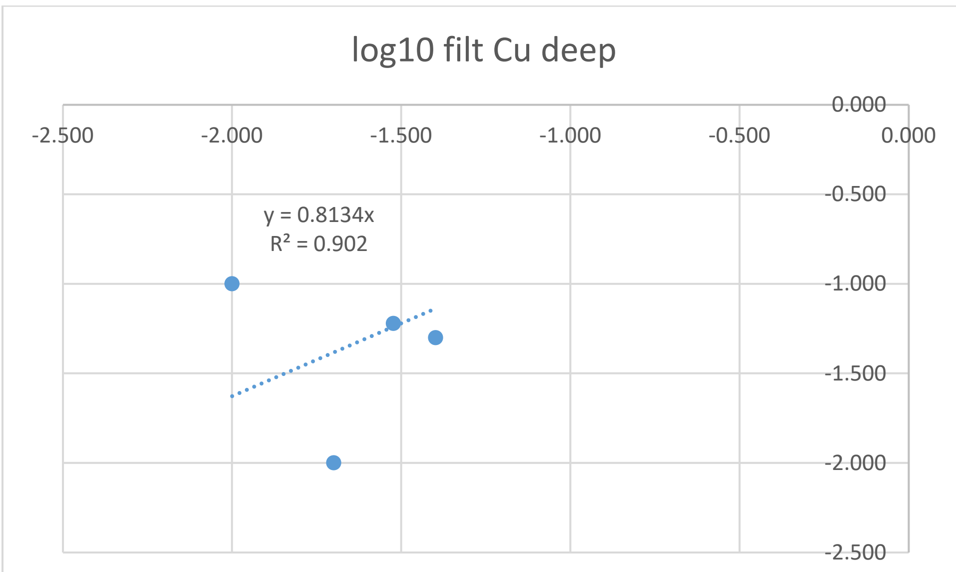
	filtered Pb, shallow, mg/L	log10 filt Pb shallow	filtered Pb, deep, mg/L	log10 filt Pb deep	% filt Pb reduction
count	17	17	17	17	17
min	0.003	-2.602	0	-2.602	-4,133
max	0.314	-0.503	0	-0.419	81
mean	0.984	-0.749	1	-0.535	-373
median	0.013	-1.886	0	-1.553	-16
stdev	0.081962453	0.545	0.118117908	0.673	1019.403612
COV	0.08	-0.73	0.12	-1.26	-2.74



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.941390397					
R Square	0.886215879					
Adjusted R Square	0.823715879					
Standard Error	0.590124621					
Observations	17					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	43.39756081	43.39756081	124.6171606	1.15334E-08	
Residual	16	5.571953091	0.348247068			
Total	17	48.9695139				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.854771496	0.076570433	11.16320566	5.82012E-09	0.692449428	1.017093563

Significant regression and slope term (intercept not significant).

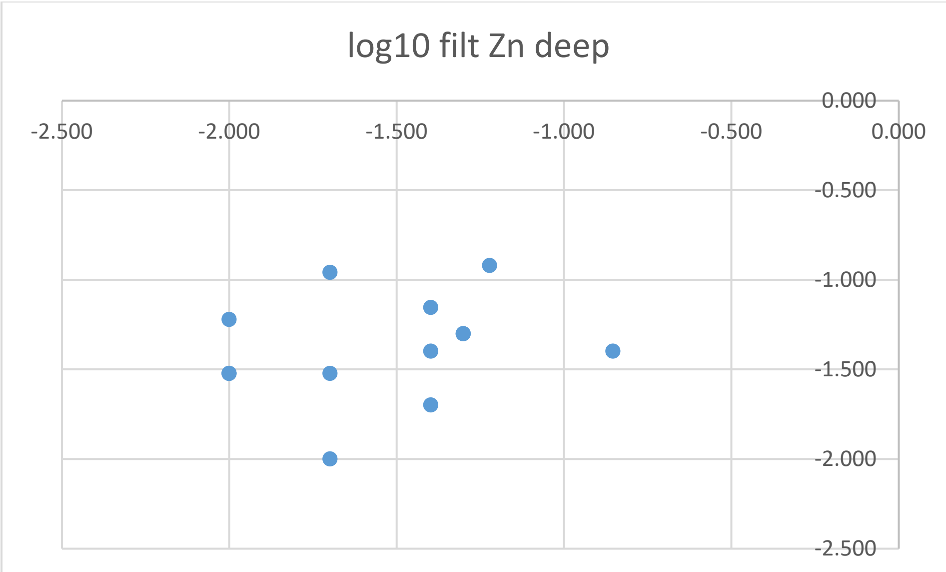
	filtered Cu, shallow, mg/L	log10 filt Cu shallow	filtered Cu, deep, mg/L	log10 filt Cu deep	% filt Cu reduction
count	4	4	4	4	4
min	0.010	-2.000	0	-2.000	-900
max	0.040	-1.398	0	-1.000	50
mean	0.820	-0.524	1	-0.305	-194
median	0.025	-1.611	0	-1.261	-63
stdev	0.012909944	0.261	0.036968455	0.432	441.7649262
COV	0.02	-0.50	0.04	-1.42	-2.27



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.949746583					
R Square	0.902018573					
Adjusted R Square	0.568685239					
Standard Error	0.517054519					
Observations	4					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	7.383557729	7.38355729	27.61804753	0.034353272	
Residual	3	0.802036127	0.267345376			
Total	4	8.185593417				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	0.813397381	0.15477695	5.255287578	0.013420886	0.32082805	1.305966713

Regression and slope term both significant (intercept not significant), but only 4 pairs of detected data, so uncertain how consistent this regression is.

	filtered Zn, shallow, mg/L	log10 filt Zn shallow	filtered Zn, deep, mg/L	log10 filt Zn deep	% filt Zn reduction
count	13	13	13	13	13
min	0.010	-2.000	0.010	-2.000	-500
max	0.140	-0.854	0.120	-0.921	71
mean	0.965	-0.498	0.976	-0.352	-99
median	0.040	-1.398	0.040	-1.398	-50
stdev	0.034751868	0.348	0.032777416	0.292	184.6590548
COV	0.04	-0.70	0.03	-0.83	-1.86



SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.219786978					
R Square	0.048306316					
Adjusted R Square	-0.038211292					
Standard Error	0.297731129					
Observations	13					
ANOVA						
	df	*SS*	*MS*	*F*	*Significance F*	
Regression	1	0.04949347	0.04949347	0.558340863	0.470601	
Residual	11	0.975082074	0.088643825			
Total	12	1.024575544				
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.095505185	0.387749835	-2.825288591	0.016510727	-1.94894	-0.24207
X Variable 1	0.184297952	0.24664414	0.747222098	0.47060086	-0.35856	0.727158

Regression equation and coefficients are not significant.