

Evaluation of the Multi-Chambered Treatment Train, a Retrofit Water-Quality Management Device

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and Robert E. Pitt**

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CONVERSION FACTORS AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To Obtain
centimeter (cm)	0.394	inch
meter (m)	3.28	foot
meters ² (m ²)	10.76	feet ²
meters ³ (m ³)	35.31	feet ³
liter (L)	0.2642	gallon
gram	2.20×10^{-3}	pound
kilogram (kg)	2.20	pound

Abbreviated water-quality units used in this report: Chemical concentrations and water temperature are given in metric units. Chemical concentration is given in milligrams per liter (mg/L) or micrograms per liter ($\mu\text{g/L}$). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Other units of measurement used in this report are microsiemens per centimeter at 25°Celsius ($\mu\text{S/cm}$) and micrometers (μm).

Evaluation of the Multi-Chambered Treatment Train, a Retrofit Water-Quality Management Device

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Abstract

This paper presents the results of an evaluation of the benefits and efficiencies of a device called the Multi-Chambered Treatment Train (MCTT), which was installed below the pavement surface at a municipal maintenance garage and parking facility in Milwaukee, Wisconsin. Flow-weighted water samples were collected at the inlet and outlet of the device during 15 storms, and the efficiency of the device was based on reductions in the loads of 68 chemical constituents and organic compounds. High reduction efficiencies were achieved for all particulate-associated constituents, including total suspended solids (98 percent), total phosphorus (88 percent), and total recoverable zinc (91 percent). Reduction rates for dissolved fractions of the constituents were substantial, but somewhat lower (dissolved solids, 13 percent; dissolved phosphorus, 78 percent; dissolved zinc, 68 percent). The total dissolved solids load, which originated from roadsalt storage, was more than four times the total suspended solids load. No appreciable difference was detected between particle-size distributions in inflow and outflow samples.

INTRODUCTION

The implementation and installation of water-quality best management practices (BMP's) in developed urban areas is problematic. A landscape composed of buildings and pavement presents little opportunity for placement of new BMP's. To overcome this obstacle of limited space, new retrofit BMP technologies are emerging that use underground space, and thus do not disrupt current above-ground land uses. One such device, called the Multi-Chambered Treatment Train (MCTT), uses aeration, settling, filtration, sorption, and ion exchange to provide a high level of treatment of stormwater runoff (Pitt and others, 1997). Underground retrofitted BMP's have two additional advantages. First, they are effective at targeting source areas that generate

large pollutant loads, such as maintenance yards and busy parking lots. Second, they provide a viable alternative where space limitations preclude the use of larger open BMP's such as wet detention ponds.

As part of an ongoing program of urban water-quality research in Wisconsin, the U.S. Geological Survey (USGS), in cooperation with the Wisconsin Department of Natural Resources, evaluated the water-quality benefits of a newly constructed MCTT. The primary objective of this project was to design and install a MCTT at a municipal maintenance yard and measure the pollutant reduction achieved by this device. The purpose of this project was to provide Wisconsin's urban land managers with additional information about the MCTT with which to make decisions on the implementation of BMP's.

Purpose and Scope

This report describes the methods of the Milwaukee MCTT study and presents the results of the USGS and WDNR evaluation. Detailed data on selected water-quality properties and constituents, including concentrations, loads, toxicities, and efficiencies of removal by the MCTT, are listed in appendixes.

Acknowledgments

Additional support for the construction of the MCTT and subsequent evaluation work was provided by the U.S. Environmental Protection Agency (Region V, Section 319 funds), and the City of Milwaukee. The authors thank Timothy Thur of the City of Milwaukee for providing the site and facilities support and Thomas Davenport, USEPA Region V project officer for program support.

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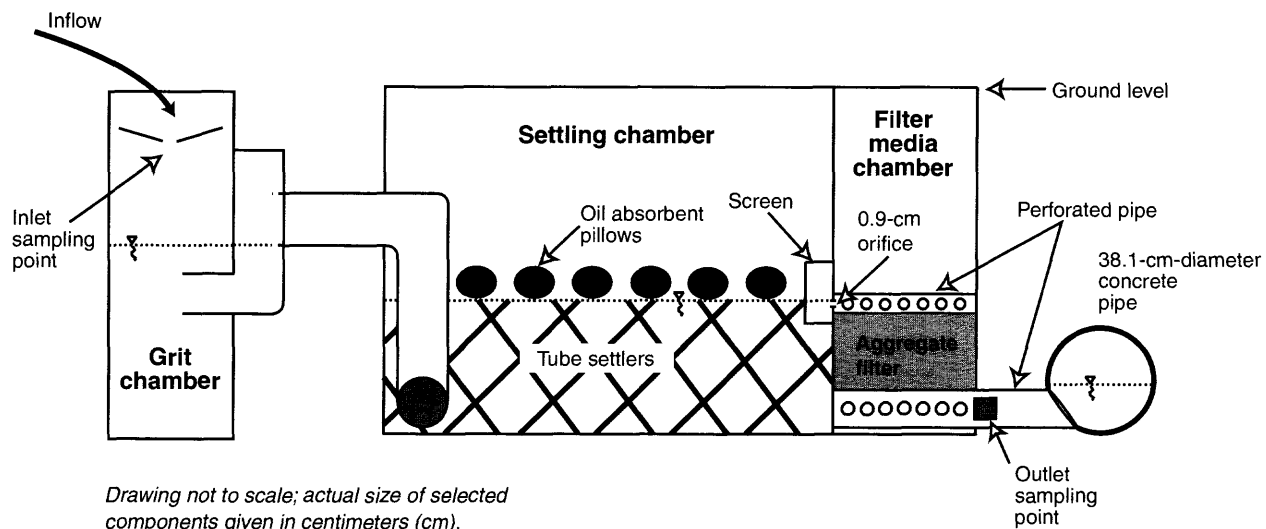


Figure 1. Cross-sectional view of the Multi-Chambered Treatment Train device, showing the two sampling locations in Milwaukee, Wis.

STUDY DESCRIPTION

Design of the Multi-Chambered Treatment Train

The MCTT consists of three components: a grit chamber, a settling chamber, and a filter media chamber (fig. 1). The 1.22-m-diameter grit chamber or catch basin removes the larger sized particles in runoff from the contributing area. In addition, a mesh bag of column packing balls suspended in the grit chamber enhances aeration and removal of highly volatile components (this component was not used for the MCTT in this project). The second chamber, where most of the settling takes place, contains inclined tube settlers that increase removal of solids by reducing the distance that particles must fall. The modular tubes are slanted at 60 degrees, so particles are not required to fall the full depth of the tank. As the water flows through the tubes, particles settle on the tube walls. Eventually, built-up material on the tube walls sloughs off and collects in the bottom of the tank, where it is periodically pumped out. The chamber also contains absorbent pillows that remove floatable hydrocarbons. Stormwater fills the tank and then slowly drains to the final chamber by way of a 0.9-cm orifice. This restricted outlet increases water-retention time in the settling tank (24 hours when filled completely) and enhances the particle settling. The third chamber, called the filter media chamber, con-

tains a mixed media of sand, peat, and activated carbon supported by filter fabric and is designed to remove fine particles, along with some dissolved constituents by means of sorption and ion exchange. Water exits this chamber through a perforated pipe underlying the filter media and flows directly into the existing storm sewer.

The second and third chambers at the study site were constructed from a single partitioned concrete box (3.0 m wide x 4.6 m long x 1.5 m high). The capacity of the settling chamber is 21 m³, although the height of the orifice results in a dead-storage capacity of 10.5 m³, leaving the actual storm-volume capacity at 10.5 m³. Once this capacity is reached, any additional water backs up on the parking-lot surface, eventually spilling over to an adjacent storm-sewer inlet.

Manhole covers were placed in the top of the settling and filter media chambers for access and maintenance purposes. According to design and operation specifications, the unit should be inspected every 6 months to ensure all chambers are operational. The maintenance requirements are somewhat site specific, although the catch basin and settling chambers should be cleaned every 6–12 months and the filter media should be replaced every 3–5 years.

Site Description

The site chosen for this project was a municipal maintenance garage and parking facility in Milwaukee,

Wis. The site is used heavily by garbage trucks, plows, and other large road equipment. The garage, originally built in 1948, is surrounded by a large parking area composed mainly of aged asphalt with some concrete pavement. Given the nature of the parking lot's activities, it is common for oily deposits, yard waste, sand, and salt to accumulate on the pavement surface. Runoff water from the parking area drains into the storm-sewer system through several storm grates/catch-basin inlets. The MCTT device was installed below the pavement surface and placed in line between one of the catch basins and the existing storm-sewer pipe. Because of the finite capacity of the MCTT and the slow draining of the settling chamber, the unit was expected to become surcharged when rainfalls exceeded 1.26 cm, but an overestimation of the runoff area draining to the MCTT led to an overdesign of the device. Consequently, the device can actually hold water from a 2.5 cm rainfall without being surcharged (the surface area draining to this device is approximately 426 m²).

Sampling Design

The evaluation of the installed MCTT device was based on results of chemical analyses of flow-weighted samples collected during 15 storms at two locations, the inlet and outlet of the device.

The 15 storms (events) were monitored as three separate groups. The first group consisted of four consecutive events, the second was five consecutive events, and the third was six consecutive events. This was done for two reasons: first, because the settling tank has some permanent storage, monitoring individual events would not allow for direct comparison of influent and effluent from the same event, and second, technical difficulties two times during the monitoring period prevented the sampling of 15 consecutive events.

Flow into the device was calculated from velocity measurements in the inlet pipe. Flow out of the settling chamber was calculated from water-level measurements in the settling chamber. Outlet flow was assumed to be equal to flow out of the settling chamber. The influent (inlet) sample was collected from a creased flat plate mounted below the storm grate. The effluent (outlet) sample was collected from the perforated pipe draining the filter-media chamber. The 15 flow-weighted samples were collected by automated sampling equipment. Two refrigerated samplers equipped with peristaltic pumps and Teflon-lined sample tubing collected the

influent and effluent samples in four 10-L glass jars. Composite samples were processed for analysis only if at least two subsamples were collected during increasing flow, two subsamples during decreasing flow, and one near the peak flow. Samples were transported to the Wisconsin State Laboratory of Hygiene (WSLH), where they were analyzed for a total of 68 constituents, including solids, nutrients, trace metals, and polycyclic aromatic hydrocarbons (PAH's). All constituents tested at the WSLH, along with their abbreviations, detection limits, and method used, are listed in tables 1 and 2. The Microtox toxicity screening procedure (Azur Environmental Inc., Carlsbad, Calif.) was performed on all 15 influent and effluent samples. This rapid procedure involves a marine bioluminescence bacteria (*Vibrio fischeri*); samples having greater toxicity are indicated by less light output. Particle-size analysis was performed on all samples using a Coulter Counter Multisizer II (Beckman Coulter Inc., Fullerton, Calif.). Both Microtox and particle-size analysis were done at the University of Alabama, Birmingham, Environmental Engineering Laboratory. Loads were computed as the product of the event-mean concentration and total stormflow volume, thus the removal performance of the device was measured by comparing differences in constituent mass into and out of the device. All computations and statistical analyses were done with SAS statistical software (1988).

EVALUATION OF MULTI-CHAMBERED TREATMENT TRAIN EFFICIENCY

Water Quantity

Fifteen storms, occurring from April 29 through September 8, 1996, were monitored and sampled. Rainfall amounts for these storms ranged from 0.45 to 3.48 cm. Calculations based on the delineated drainage area indicate that total stormwater volumes for the storms ranged from 1.96 to 14.9 m³. The actual quantity of water passing through the MCTT was 1.72 to 9.10 m³. None of the storms resulted in surcharge of the MCTT. On average, 87 percent of the rainfall resulted in direct runoff to the MCTT. The remaining rainfall volume may have been lost in interception storage, through cracks in the aged pavement surface, or through joint leaks between the grit chamber and the main settling chamber.

Table 1. Aggregate water-quality characteristics and inorganic constituents analyzed for Multi-Chambered Treatment Train study, Milwaukee, Wis.

[mg/L, milligrams per liter; µg/L, micrograms per liter]

Constituent	Abbreviation	Units	Limit of Detection	Method ¹
Aggregate Characteristics				
Alkalinity, total	Alk.	mg/L as CaCO ₃	5	SM 2320B
Biochemical oxygen demand	BOD	mg/L	3	SM 5210B
Chemical oxygen demand	COD	mg/L	5	EPA 410.4
Color	Color (PU)	Plat.-Cobalt	1	SM 2120B
pH	pH	Standard Units	0.1	SM4500B
Specific conductance	SC	µs/cm	?	SM2510B
Total dissolved solids	TDS	mg/L	5	SM2540C
Total suspended solids	TSS	mg/L	5	SM2540D
Turbidity	Turbid.	NTU	.05	SM3120B
Volatile suspended solids	VSS	mg/L	5	SM2540F
Nutrients				
Ammonium as N	NH ₄	mg/L as N	.027	SM4500H
Nitrate + nitrite as N	NO ₃	mg/L as N	.02	SM4500F
Dissolved phosphorus	DP	mg/L as P	.002	SM4500PF
Total phosphorus	TP	mg/L as P	.008	SM4500PB
Major ions				
Total calcium	Ca	mg/L	1	SM3111B
Dissolved calcium	Ca	mg/L	1	SM3111B
Chloride	Cl	mg/L	1	SM4500CL
Dissolved magnesium	Mg	mg/L	1	SM3111B
Total magnesium	Mg	mg/L	1	SM3120B
Sulfate	SO ₄	mg/L	5	SM4500SO4
Metals				
Dissolved cadmium	Cd	µg/L	.02	SM3113B
Total cadmium	Cd	µg/L	.04	EPA 200.9
Dissolved chromium	Cr	µg/L	.5	SM3113B
Total chromium	Cr	µg/L	1	EPA 200.9
Dissolved copper	Cu	µg/L	.7	SM3113B
Total copper	Cu	µg/L	1	EPA 200.9
Dissolved lead	Pb	µg/L	.4	SM3113B
Total lead	Pb	µg/L	.8	EPA 200.9
Dissolved zinc	Zn	µg/L	8	SM3113B
Total zinc	Zn	µg/L	19	EPA 200.9

¹EPA (1979); and SM, Standard Methods, American Public Health Association and others, 1989.

Table 2. Organic constituents analyzed for Multi-Chambered Treatment Train study, Milwaukee, Wis.

[mg/L, milligrams per liter; µg/L, micrograms per liter; PAH, polycyclic aromatic hydrocarbon; -, none]

Parameter	Abbreviation	Units	Limit of Detection	Method ¹
Dissolved organic carbon	DOC	mg/L as C	1	SM5310
Total organic carbon	TOC	mg/L as C	1	SM5311
Sum of total PAH's ²	TPAH	µg/L	0.47	SW8310
Acenaphthene	N/A	µg/L	.048	SW8310
Acenaphthylene	-	µg/L	.044	SW8310
Anthracene	-	µg/L	.015	SW8310
Benz[a]anthracene	-	µg/L	.059	SW8310
Benzo[a]pyrene	-	µg/L	.041	SW8310
Benzo[b]fluoranthene	-	µg/L	.073	SW8310
Benzo[g,h,i]perylene	-	µg/L	.05	SW8310
Benzo[k]fluoranthene	-	µg/L	.059	SW8310
Chrysene	-	µg/L	.03	SW8310
Dibenz[a,h]anthracene	-	µg/L	.019	SW8310
Fluoranthene	-	µg/L	.098	SW8310
Fluorene	-	µg/L	.12	SW8310
Indeno[1,2,3-c,d]pyrene	-	µg/L	.078	SW8310
Naphthalene	-	µg/L	.054	SW8310
Phenanthrene	-	µg/L	.035	SW8310
Pyrene	-	µg/L	.063	SW8310

¹SM, Standard Methods, American Public Health Association and others, 1989; and U.S. Environmental Protection Agency (1996) solid-waste method.

²Sum of total PAH's includes the sum of all 16 species of total PAH.

Compared to historical precipitation records, the depths of rainfall for these 15 storms were larger than average (fig. 2). This may be due to the short period that the MCTT was monitored, which included mainly warmweather rainstorms. The historical record includes precipitation from the entire year (from intense summer thunderstorms, long duration fall and spring rainfall, and snowfall). Long-term records (National Oceanic and Atmospheric Administration, 1997) show only 20 percent of Milwaukee storms are greater than 1.3 cm in precipitation, whereas during the period of study, approximately half of the storms were greater than 1.3 cm. Therefore, in terms of rainfall amounts, the study-period events may be considered a rigorous test of the system. The fact that none of the storm-runoff amounts exceeded the design capacity, even though the largest amounts were expected to, was due to inaccurate delineation of the drainage area at the design phase and resultant overdesign of the unit.

Concentration Summary Statistics

Summaries of the inorganic and organic concentration data for the inflow and outflow samples are given

in tables 3 and 4 and in appendix 1, and a summary of the load data and removal efficiencies of the MCTT is given in appendix 2. All samples were collected on a volume-weighted basis; hence, the concentrations reported here are event-mean concentrations. The constituent concentrations in the runoff entering the unit were characteristic of stormwater quality found in previous studies (U.S. Environmental Protection Agency, 1983; Ellis, 1986; Bannerman and others, 1983, 1993, 1996). The data sets were tested for normality/ log-normality using the Shapiro-Wilk statistic (SAS, 1988). This procedure produces a test statistic for the null hypothesis that the input data values are a random sample from a normal or transformed-normal distribution. In general, inorganic as well as organic constituent concentrations were found to be log-normally distributed. Of the 68 constituents measured in the influent, 21 were normally distributed and 47 were log-normally distributed ($\alpha < 0.05$). This test should be interpreted with caution, however, because of its low power when applied to the sample size of 10–15 observations. The log-normal distributions are consistent with the findings of others (U.S. Environmental Protection Agency, 1983; DiToro, 1984).

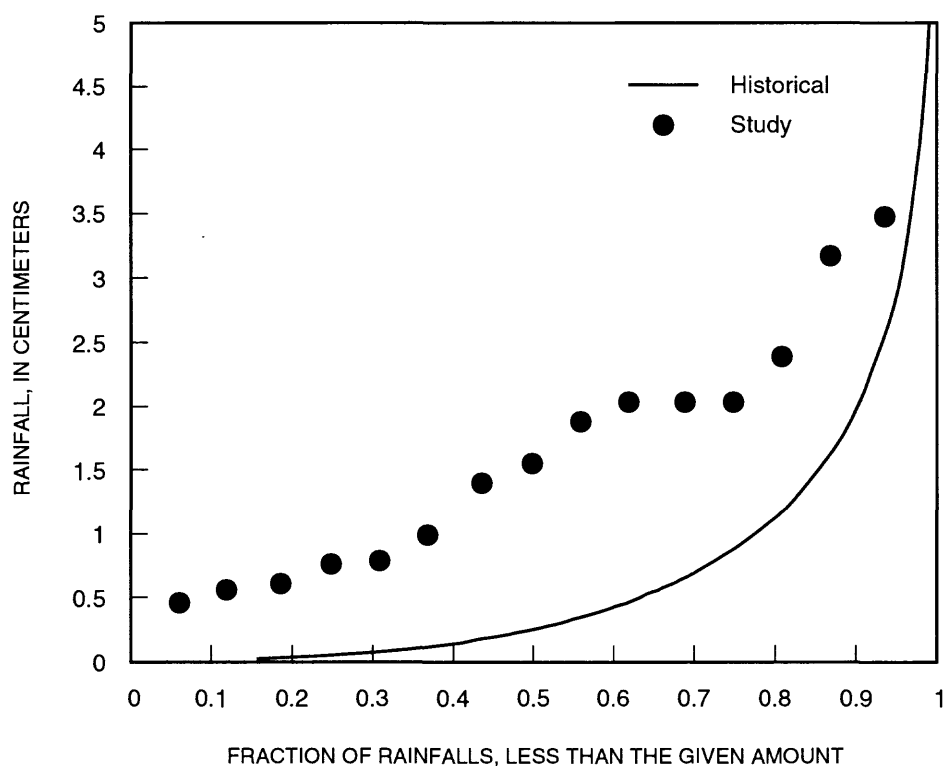


Figure 2. Cumulative rainfall distributions for the study period and historical rainfall records (1948–92) for Milwaukee, Wis.

Influent samples generally had detectable concentrations of most constituents tested. The exception was dissolved zinc (Zn) and the dissolved fractions of 15 of the 16 PAH's, which rarely were detectable. The one dissolved PAH that was consistently measurable in the influent was phenanthrene (median = 0.1 µg/L).

In the effluent water, all dissolved and total PAH concentrations were below detection limits. In addition, total suspended solids (TSS), volatile suspended solids (VSS), dissolved cadmium (Cd), dissolved lead (Pb), dissolved Zn and total Zn were generally below detection limits in the effluent samples. The preponderance of nondetectable values in effluent samples made the determination of normality problematic. Having effluent values reported as "less than" for a constituent also made the exact calculation of removal efficiencies impossible. In those cases, removal efficiencies were estimated using one half of the detection limit as the concentration of the effluent.

The nonparametric two-sided Wilcoxon rank-sum test (SAS, 1988) was applied to the influent and effluent concentrations of all constituents, the null hypothesis being that the distributions of the influent and effluent concentrations are the same. Constituents with signifi-

cant differences ($\alpha=0.05$) are noted in tables 3 and 4. A paired statistical test comparing individual storms was not used because, during any given storm, the water exiting the device will not be the same water that entered the device because of the permanent storage volume and hydraulic residence time in the settling tank. Influent and effluent concentrations of constituents that were not found to be significantly different were either soluble constituents that are generally considered conservative (for example, chloride) or constituents that have the potential to be generated within the tank (for example, ammonia). Because influent and effluent concentrations of some constituents (for example, dissolved PAH's) frequently were below detection limits, significant changes in concentrations were indeterminable.

Water-Quality Characteristics

Concentrations of total suspended solids (TSS) in influent ranged widely, from 79 to 1,050 mg/L; median concentration was 232 mg/L (table 3, appendix 1). As stated previously, most of the effluent TSS concentra-

Table 3. Inorganic influent and effluent minimum, maximum, and median event-mean concentration values for the monitored storms (n=15) at the Multi-Chambered Treatment Train in Milwaukee, Wis.

[BOD, biochemical oxygen demand; COD, chemical oxygen demand; TDS, total dissolved solids; TSS, total suspended solids; VSS, volatile suspended solids; NH₄⁺, ammonium, as N; NO₃⁻, nitrate plus nitrite; Ca, calcium; Mg, magnesium; Cl, chloride; SO₄²⁻, sulfate; Cd, cadmium; Cr, chromium; Cu, copper; Pb, lead; Zn, zinc; TOC, All units in milligrams per liter unless otherwise noted. **Bold** font identifies constituents for which influent concentrations are significantly different ($\alpha=0.05$) from effluent concentrations using a nonparametric two-sided Wilcoxon rank-sum test.]

Characteristic or constituent	Influent			Effluent		
	Minimum	Maximum	Median	Minimum	Maximum	Median
<u>Aggregate characteristic</u>						
Turbidity (NTU)	9.3	100	41	0.7	10	2.6
Color (PU)	10	70	30	5.0	25	15
BOD	8.8	51	15	<3.0	9.2	<3
COD	52	260	115	<5.0	33	13
pH (SIC)	6.8	8.1	7.2	7.5	8.1	7.8
Alkalinity	20	58	40	51	122	82
TDS	164	5,930	634	320	3,070	885
TSS	79	1,050	232	<5.0	18	<5.0
VSS	17	154	52	<5.0	12	<5.0
<u>Nutrients</u>						
NH ₄ as N	<.027	.258	.051	<.027	.115	.062
NO ₂ + NO ₃ as N	.180	1.36	.353	.074	.463	.273
Phosphorus, total	.101	.440	.262	.014	.088	.023
Phosphorus, dissolved	<.002	.040	.0025	.002	.0016	.002
<u>Major Ions</u>						
Ca, total	18	210	43	19	66	32
Ca, dissolved	8.3	45	16	18	68	31
Mg, total	4.0	100	14	2.1	13	3.4
Mg, dissolved	.4	1.2	.82	2.0	13	3.4
Cl	57	3,560	302	100	1820	427
SO ₄	10	58	19	16	47	27
<u>Metals</u>						
Cd,dissolved (µg/L)	.03	1.1	.22	<.02	.97	.05
Cr, dissolved (µg/L)	<.5	2.0	.8	<.5	3.4	.8
Cu, dissolved (µg/L)	1.7	12	4.4	<.7	5.7	1.4
Pb, dissolved (µg/L)	<.4	7.6	.9	<.4	1.3	<.4
Zn, dissolved (µg/L)	<8	38	<8	<8	22	<8
Cd-total (µg/L)	.48	3.7	1.5	<.04	1.0	.10
Cr, total (µg/L)	3	14	6	<1	18	<1
Cu, total (µg/L)	11	58	32	2	8	3
Pb, total (µg/L)	16	72	48	<.8	3.9	1.8
Zn, total (µg/L)	55	250	150	<19	53	<19
<u>Organics</u>						
Total organic carbon	2.2	20	7.9	2.1	11	4.4
Dissolved organic carbon	2.1	17	6.8	2.0	9.5	4.1
Sum of total polycycli aromatic hydrocarbon	2.9	23	8.3	<.47	<.89	<.89

Table 4. Dissolved and total influent minimum, maximum, and median event-mean concentrations of polycyclic aromatic hydrocarbons for the monitored storms (n=15) at the Multi-Chambered Treatment Train in Milwaukee, Wis.

[Concentrations in micrograms per liter. All effluent concentrations were below detection limits.]

Constituent	Minimum ¹	Maximum	Median
Dissolved PAH species			
Acenaphthene	<0.048	<0.048	<0.048
Acenaphthylene	<.044	<.044	<.044
Anthracene	<.015	.026	<.015
Benz[a]anthracene	<.059	.23	<.059
Benzo[a]pyrene	<.041	.38	<.041
Benzo[b]fluoranthene	<.073	.54	<.073
Benzo[g,h,i]perylene	<.05	.38	<.05
Benzo[k]fluoranthene	<.059	.24	<.059
Chrysene	<.03	.52	<.03
Dibenz[a,h]anthracene	<.019	.038	<.019
Fluoranthene	<.098	1.1	<.098
Fluorene	<.12	<.12	<.12
Indeno[1,2,3-c,d]pyrene	<.078	.39	<.078
Naphthalene	<.054	<.054	<.054
Phenanthrene	<.035	.35	.105
Pyrene	<.063	.79	<.063
Total PAH species			
Acenaphthene	<.048	.23	<.048
Acenaphthylene	<.044	<.044	<.044
Anthracene	<.015	.34	.101
Benz[a]anthracene	<.24	1.4	.5
Benzo[a]pyrene	<.4	1.6	.55
Benzo[b]fluoranthene	<.23	2	.77
Benzo[g,h,i]perylene	<.64	1.4	.53
Benzo[k]fluoranthene	<.46	1	.31
Chrysene	<.26	2.1	.8
Dibenz[a,h]anthracene	<.24	1.4	.5
Fluoranthene	.51	5.1	1.75
Fluorene	<.12	.38	<.12
Indeno[1,2,3-c,d]pyrene	<.8	1.4	.48
Naphthalene	<.054	<.054	<.054
Phenanthrene	.12	2.8	.71
Pyrene	.47	3.2	1.3

¹Digestion of samples for total analysis resulted in higher detection limits. In addition, detection limits varied during the period of study. Bold font identifies constituents in which influent concentrations are significantly different ($\alpha=0.05$) from effluent concentrations using a nonparametric two-sided Wilcoxon rank-sum test.

tions were below detection limit (8 out of 14). The highest concentration of TSS observed in the effluent was only 18 mg/L. Because most effluent TSS values were below detection limit, it was difficult to determine if any discernible relation existed between influent and effluent concentrations. The influent TSS concentrations from all 15 storms exceeded Wisconsin's discharge limit of 30 mg/L (Wisconsin Administrative Code NR 210, 1997). The cumulative load of TSS to the unit for the 15 consecutive storms was 18.3 kg (appendix 2). The amount of TSS in the effluent was estimated to be only 0.30 kg, making the overall removal efficiency greater than 98 percent. Pitt and others (1997) reported a lower overall TSS removal of 83 percent in their pilot-scale testing. In examining concentrations at intermediate points, they found that most of the TSS was removed in the settling chamber.

Influent volatile suspended solids (VSS) ranged from 17 to 154 mg/L; median concentration was 52 mg/L. The VSS concentrations averaged 21 percent of TSS in the influent, an indication that most of the particulate material entering the unit was inorganic. On a cumulative mass basis, the VSS influent load was 17 percent of the influent TSS load. Effluent VSS concentrations ranged from less than 5 to 12 mg/L; 58 percent of the samples were below the detection limit. The overall load reduction of VSS (> 94 percent) was similar to that for TSS. The influent biochemical oxygen demand (BOD) concentrations ranged from 8.8 to 51 mg/L. Only one sample had a BOD concentration that would exceed the Wisconsin discharge limit of 30 mg/L (Wisconsin Administrative Code NR 210, 1997). Again, most BOD in effluent samples (58 percent) was below the detection limit. The estimate of overall removal efficiency for BOD was 82 percent or greater. The chemical oxygen demand (COD) influent and effluent concentrations (median = 115 and 13, respectively) were considerably greater than the BOD concentrations. Influent VSS concentrations were well correlated with both BOD and COD concentrations ($r = 0.62$ and 0.82 , respectively), confirming the organic nature of this solid material. The average ratio of BOD to COD was 0.15 in the influent, suggesting that this organic material was highly refractory. The unit removed 86 percent of the total COD load.

Total dissolved solids (TDS) in influent samples had a median concentration of 634 mg/L and a range of 164 to 5,930 mg/L. The source of the high dissolved solids in samples collected during the middle of the study period was road salt stored within the drainage

area. This salt resulted in a load of dissolved solids to the unit that was more than 4.5 times the particulate (suspended solids) load for the period of study. The relative loads of the three aggregate solids characteristics are illustrated in figure 3. (Note that the y-axis is plotted on a log scale.)

Major Ions

Total calcium (Ca) had the greatest influent concentrations (median = 43 mg/L) of the reported cations (table 3, appendix 1). Though not directly measured, the ionic balance and high chloride concentrations suggest that sodium and/or potassium were most likely the dominant cations. Dissolved Ca concentrations generally made up half of the total Ca in the influent. Total magnesium (Mg) concentrations followed a similar storm-to-storm pattern as total calcium concentrations, but at about one-third the concentration (median = 14 mg/L). Dissolved Mg generally made up only 10 percent of the total Mg in the influent.

In effluent, total Ca concentrations were always less than those in the influent, although the median values differed by only 4.5 mg/L. Somewhat surprisingly, the dissolved Ca concentrations in the effluent were consistently greater than the influent concentrations, suggesting either dissolution of some of the influent particulate Ca and (or) addition of Ca ions to the stormwater from the unit itself (that is, concrete walls of the catch basin and main tank). Magnesium behaved similarly, with dissolved Mg concentrations in effluent greater than those in influent. On a load basis, the unit removed 55 and 85 percent of the total Ca and Mg, respectively (appendix 2). The increase in dissolved Ca and Mg concentrations resulted in negative efficiencies for these analytes (-62 and -340, respectively). The effluent loads of both dissolved Ca and Mg were equal to their respective total loads, implying that the Ca and Mg leaving the unit was virtually all in the dissolved phase.

Chloride (Cl) was by far the dominant anion in all the samples (median influent and effluent = 302 and 427 mg/L, respectively). Again, this was a result of road salt being stored within the drainage area during the study period. Both influent and effluent concentrations during the 15 storms are shown in figure 4. Placement of the road salt onsite occurred between the fourth and fifth storms, and this is clearly evident in the sharp increase in Cl concentrations in figure 4. Peak effluent

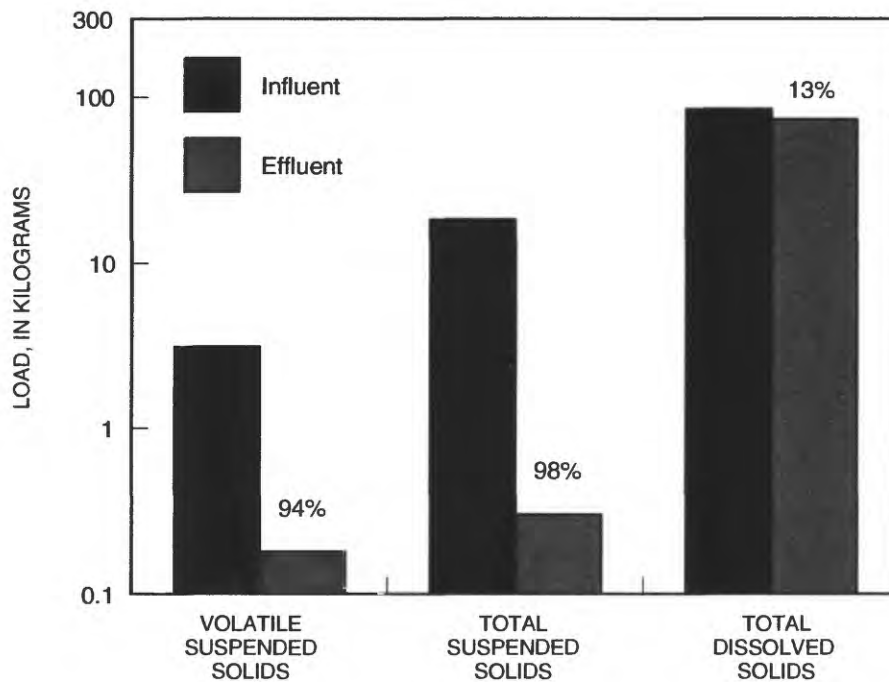


Figure 3. Total influent and effluent loads for volatile suspended solids, total suspended solids, and total dissolved solids accumulated over the entire rating period at the Multi-Chambered Treatment Train in Milwaukee, Wis. (Removal efficiencies, in percent, are noted above the effluent load bars.)

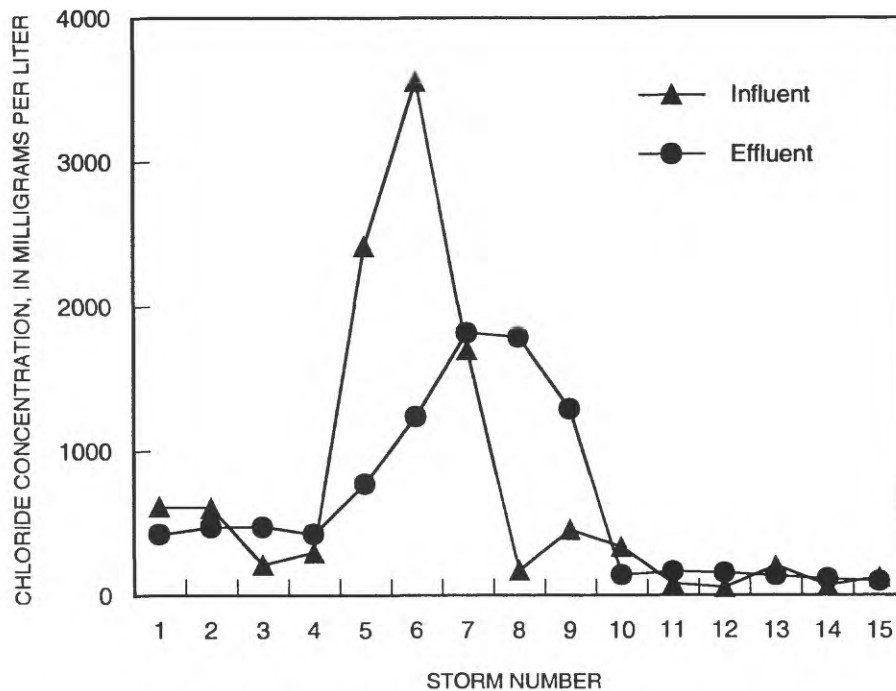


Figure 4. Event-mean concentrations of chloride in influent and effluent for the 15 monitored storms, Multi-Chambered Treatment Train study, in Milwaukee, Wis.

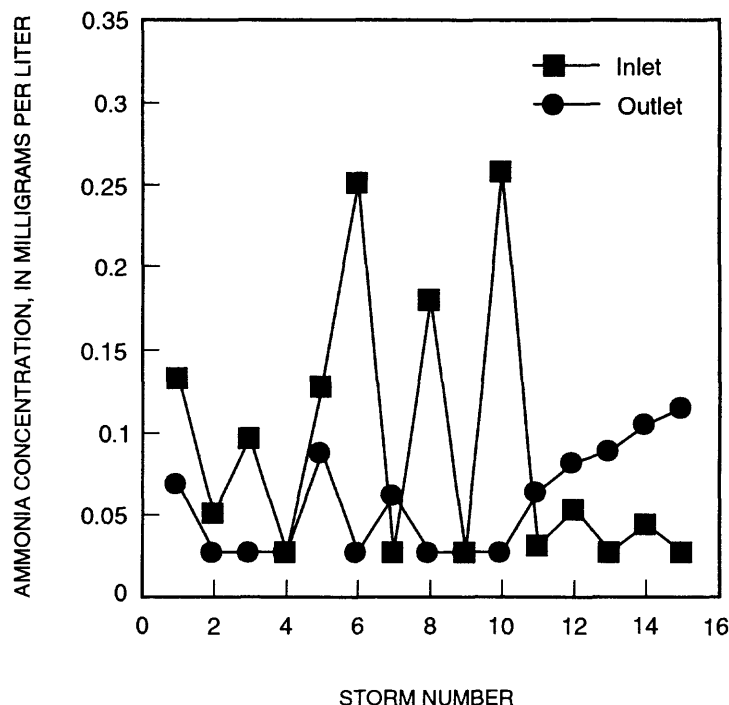


Figure 5. Event-mean concentrations of ammonium in influent and effluent for the 15 monitored storms, Multi-Chambered Treatment Train study, in Milwaukee, Wis.

concentration, however, was substantially less than the peak influent concentration. This attenuation of maximum effluent concentrations was due to dilution of the influent waters with previously stored water in the settling tank. Although Cl is generally considered to be a conservative constituent, the difference between influent and effluent loads of 20 percent suggests that the unit did remove a portion of the Cl.

Alkalinity concentrations were considerably less than Cl concentrations (median influent and effluent concentrations = 40 and 82 mg/L, respectively). On an equivalence basis, alkalinity (as bicarbonate) closely tracked Ca concentrations and increased as the water passed through the unit, again pointing to an addition/dissolution of calcium carbonate in the unit.

Nutrients

The median nitrate (NO_3) concentrations in the influent and effluent were 0.35 and 0.27 mg/L, respectively (table 3). Removal efficiency of this mobile nitrogen species was 32 percent (appendix 2). Ammonium (NH_4) concentrations were often considerably less than NO_3 concentrations in the influent and the effluent (appendix 1). The removal rate for ammonium (47 per-

cent) was somewhat greater than that for NO_3 , although the rate decreased over the study period because of a steady rise in effluent concentrations over the last five storms (fig. 5). This rise of ammonium concentrations in effluent indicates that the settling-chamber contents may become anaerobic as sediments begin to accumulate and reduced species are subsequently released within the unit.

Influent total phosphorus (P) ranged from 0.10 to 0.44 mg/L; the median was 0.26 mg/L. Effluent concentrations were generally an order of magnitude less than influent concentrations (median = 0.02 mg/L), resulting in a high overall removal efficiency of 88 percent. Dissolved P was consistently less than 10 percent of the total P in the influent and the effluent samples. Dissolved P removal efficiency (78 percent), although somewhat less than total P removal, was still substantial.

Metals

Influent metals concentrations were characteristic of values previously observed in stormwater runoff in Wisconsin (Bannerman and others, 1996). Median total recoverable metal concentrations, in increasing order,

were Cd (1.5 µg/L), Cr (6 µg/L), Cu (32 µg/L), Pb (48 µg/L), and Zn (150 µg/L) (table 3). The total recoverable metal concentrations in effluent followed a similar order of increasing concentration, except that lead and copper were reversed (appendix 1). Concentrations of all total recoverable metals in effluent were generally an order of magnitude less than concentrations in influent. A comparison of total recoverable metals concentrations in influent to Wisconsin acute toxicity criteria for warmwater sport fisheries (Wisconsin Administrative Code, NR105, 1997) showed that Cu exceeded the criteria in 15 of 15 samples, Pb in 7 of 15 samples, and Zn in 14 of 15 samples. In contrast, no total recoverable metal concentrations in effluent exceeded metal-toxicity criteria.

Removal efficiencies of the MCTT were substantial for all the total recoverable metals, ranging from 78 percent for Cr to 96 percent for Pb (appendix 2). Because most of the total recoverable metal concentrations were in the particulate form, the physical removal of particulates may be occurring in all three chambers of the unit, although the bulk of the particulates (associated with the suspended solids) was most likely being removed in the settling chamber. MCTT performance data collected by Pitt and others (1997) for TSS and unfiltered metals also suggests this, although for Cd and Cu, efficiencies were substantially less than those for the unit used in this study. This difference may have been due to several factors, such as a different mixture of filter media, the different concentration ranges of Cd and Cu, and differences in the proportion of these metals in the dissolved form, which are less effectively removed than those in particulate form.

Concentrations of dissolved metals in the influent to the MCTT followed the order of Cd < Cr < Pb < Cu < Zn. The concentrations in effluent appeared to follow a similar order, although a full characterization of metals concentrations is again difficult because of many below detection limit. With the exception of Cr, removal efficiencies of dissolved metals ranged from 66 to 78 percent, somewhat less than their respective total metal removals efficiencies (appendix 2). Because concentrations in effluent were generally found below detection limits, actual removals may have been greater, especially for Cd, Pb, and Zn. The order of removal efficiencies of dissolved metals was Cr < Cd < Zn < Cu < Pb. The removal of the dissolved phase of these metals most likely occurred in the sand/peat/carbon filter chamber. A similar order of “affinity” in peat materials was noted by Pakarinen and others (1981) for Cu, Pb,

and Zn. They did not describe Cd and Cr affinities. Dissolved chromium, which has a higher valence and requires time to reach exchange equilibrium, had virtually no removal efficiency (-3.3 percent) (Aho and Tummavuori, 1984).

Although the concentrations of metals generally were greatly reduced by the treatment of the MCTT, the proportion of metal in the dissolved phase generally increased. In the influent samples, the average ratio of dissolved metal to total metal concentrations ranged from 3 percent for Pb to 19 percent for Cu. In the effluent samples, the proportion of the dissolved phase in the total recoverable metal was higher ranging from 20 percent for Cd to 80 percent for Cr.

Polycyclic Aromatic Hydrocarbons

Detectable concentrations of 12 of the 16 total polycyclic aromatic hydrocarbon (PAH) species were typically found in influent samples to the MCTT (table 4, appendix 1). The four species that were below detection limits in more than 50 percent of the samples were total acenaphthylene, acenaphthene, fluorene, and naphthalene. Concentrations of total fluoranthene and pyrene were consistently double or more than the concentrations of other PAH species, with median concentrations of 1.8 and 1.4 µg/L, respectively. The sum of total PAH concentrations for all 16 species (Σ total PAH) in the influent samples ranged from 2.9 to 23 µg/L. The median Σ total PAH concentration was 8.3 µg/L, considerably less than what was reported by Steuer and others (1997) for parking lots. All of the 15 influent samples exceeded the Wisconsin human cancer criterion of 0.1 µg/L (Wisconsin Administrative Code, NR105, 1997) for the class of streams draining this area. This criterion is based on dermal contact and the consumption of warmwater sport fish taken from these waters.

In the influent, the Σ dissolved PAH averaged 14 percent of the Σ total PAH. The average percentage may be less because the dissolved fractions were commonly reported as less than detection limits, and actual concentrations are unknown. The only dissolved PAH species in the influent that was consistently reported above the detection limit was phenanthrene (median=0.1 µg/L). The dissolved PAH concentrations were also consistently above the Wisconsin human cancer criterion of 0.1 µg/L.

Little interpretation can be made from the effluent PAH data because, without exception, all values were reported as less than the detection limit. Consequently, all PAH removal efficiencies are conservative estimates of actual removal rates. Efficiencies of individual total PAH's ranged from >53 percent for total fluorene to >98 percent for total phenanthrene, and for 11 of the total PAH's, efficiencies were 90 percent (appendix 2). The removal efficiencies of the dissolved PAH fractions ranged from >22 percent (dibenzanthracene) to >86 percent (phenanthrene) and were consistently lower than the removal efficiencies for total PAH's. This finding does not necessarily suggest a lower removal efficiency of dissolved PAH fractions; the lower efficiencies may be an artifact due to a preponderance of "less-than" values or concentrations approaching the detection limit.

Because most of the PAH's were found in the particulate fraction, most of the removal probably occurred in the settling chamber, consistent with the findings of Pitt and others (1997). In addition, peat materials, such as those found in the filter chamber, have been shown to be effective in removing oily material (Mathavan and Viraraghavan, 1989).

Microtox Results

Microtox-assay results, reported as gamma values, are computed as the amount of light lost from exposed fluorescent bacteria (as compared to a laboratory control) divided by the amount of light remaining. The larger the value of gamma, the greater the detrimental effect the sample has on the test microbes. Influent-sample gamma values from 15-minute assays ranged from 0.02 to 0.49; the median was 0.12 (appendix 3). In contrast, all effluent samples yielded negative gamma values (median = -0.17), suggesting that the effluent water was a better medium for microbial growth than the laboratory control water. Without exception, Microtox gamma values were less in effluent samples than influent samples, a strong indication that toxicity was reduced by MCTT treatment. There was however, little indication of any simple relation (linear regression) between Microtox gamma values for influent and concentrations of any single constituent.

Particle-Size Distribution

The particle-size data were summarized by averaging the 15 influent and effluent cumulative distributions of those data (fig. 6). Each trace on this plot represents the average percentage of particles less than the given size for each measured particle-size fraction. Most influent and effluent particles were in the silt-size fraction. Somewhat surprising was the fact that no appreciable shift in the particle-size distribution was observed between the influent and effluent particle sizes. One might expect a selective removal of the larger particles and subsequent decrease in the average particle size as the water passed through the filter media. The findings here, however, suggest that the mean particle size, or D_{50} , actually increased from 18 μm in the influent water to 28 μm in the treated effluent water; thus, the unit may not have been selective in the size of particles it removed. Another possibility is that large particulate materials were indeed removed in the settling chamber, but escaped sand fines from the filter media were later reintroduced. Because no samples were collected between the settling and filter chambers, the proportion of the suspended-solids treatment that can be attributed to each section of the unit cannot be determined. Another indication that the filter chamber can potentially lose particles is reported by Pitt and others (1997), who noted a slight increase in TSS concentrations as the water passed through the filter tank of their pilot-scale unit. Therefore, the unit may be selectively removing larger particles but, coincidentally, may be adding similar particles from the filter-media material, resulting in little change in the distributions. It is emphasized, however, that even though the particle-size distribution influent remained similar, the overall removal rate of the particulate material by the unit was 98 percent of the influent suspended-solids load.

SUMMARY

The MCTT treated all the stormwater that drained to the unit for the 15 storms monitored. The actual quantity of water passing through the MCTT ranged from 1.7 to 8.9 m^3 for individual storms and was, on average, 87 percent of the rainfall volume. High reduction efficiencies were found for all particulate-associated constituents, such as TSS (98 percent), total P (88 percent), and total Zn (91 percent). Dissolved fractions were removed at substantial but somewhat lower rates (TDS, 13 percent; dissolved P, 78 percent; dissolved Zn,

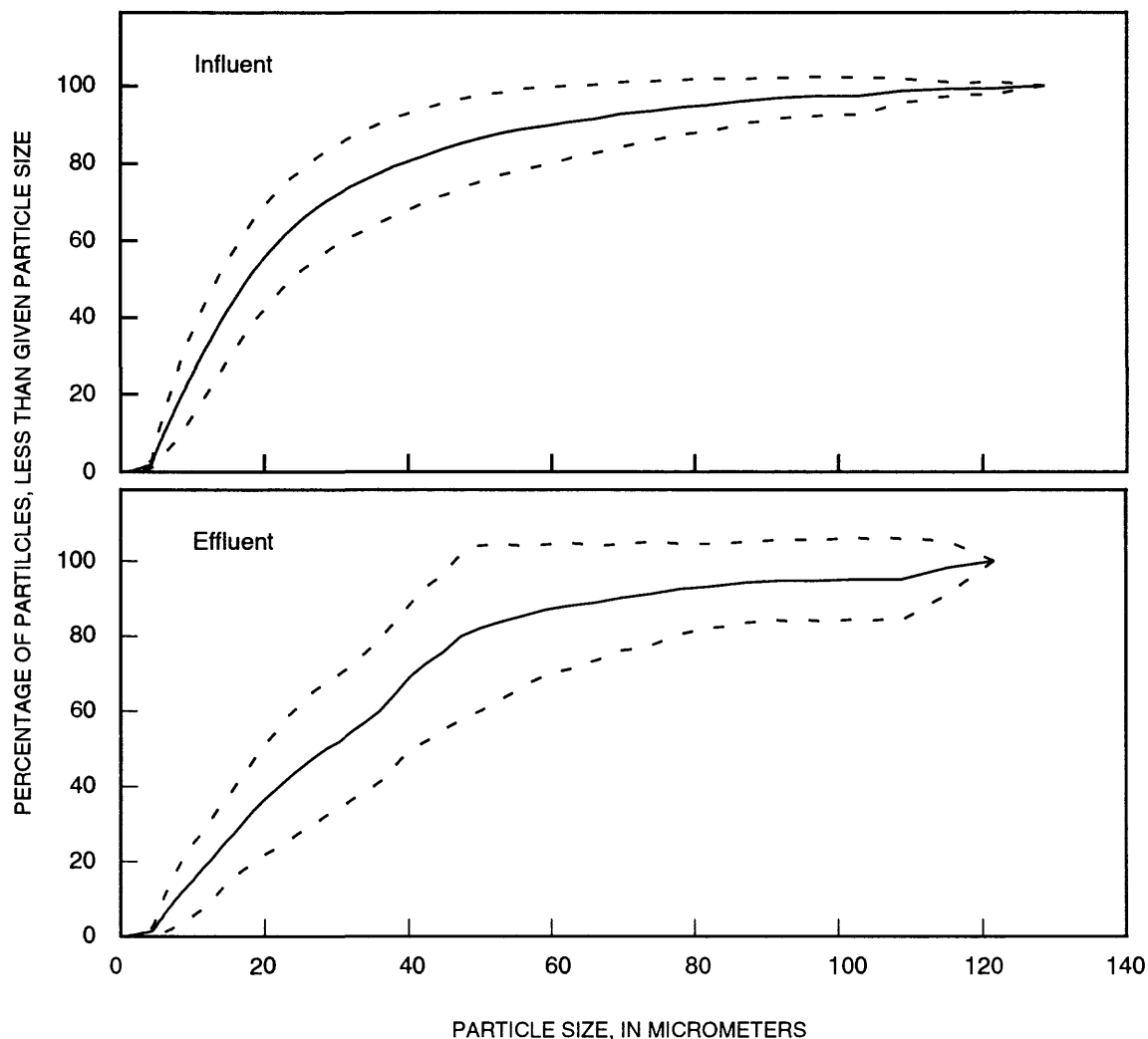


Figure 6. Average influent and effluent particle-size distributions for the 15 monitored storms in the Multi-Chambered Treatment Train, in Milwaukee, Wisconsin. (The dotted lines represent ± 1 standard deviation.)

68 percent). The TDS load, which was composed mainly of road salt, was four times the load of TSS. Increases of Ca, Mg, and alkalinity were attributed to dissolution or leaching of the cement from the MCTT tanks. In addition, NH_4 began to rise slowly over the latter part of the study, presumably because of anaerobic sediment buildup in the settling chamber. No appreciable shift was seen between influent and effluent particle-size distribution.

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APPENDIXES 1–3

Appendix 1. Concentrations and other measurements of monitored water-quality characteristics in influent and effluent to the Multi-Chambered Treatment Train at Ruby Street Garage, Milwaukee, Wis.

[mm, millimeter; m³, meter³; mg/L, milligrams per liter; µg/L, micrograms per liter; µs/cm, microsiemens per centimeter; --, no data; NTU, National turbidity units; PU, platinum cobalt units; DOC, dissolved organic carbon; TOC, total organic carbon]

Storm no.	Aggregate Parameters															
	Beginning sample date	Beginning sample time	Ending sample date	Ending sample time	Rainfall (mm)	Flow volume (m³)	Turbidity (NTU)	Color (PCU)	Biochemical oxygen demand (mg/L)	Chemical oxygen demand (mg/L)	pH (SIC)	Alkalinity (mg/L)	Total dissolved solids (mg/L)	Total suspended solids (mg/L)	Volatile suspended solids (mg/L)	Specific conductance (µs/cm)
Influent																
Group 1																
1	4/29/96	7:18	4/29/96	13:13	20.3	3.18	87	45	15.3	120	7.47	40	1,130	422	72	2,160
2	5/9/96	7:10	5/10/96	4:57	34.8	3.43	39.8	20	13.8	140	7.65	40	1,120	296	68	2,150
3	5/14/96	18:58	5/15/96	6:51	14	5.14	37	10	13.3	100	7.38	35	440	136	36	827
4	5/20/96	13:04	5/20/96	17:16	7.87	2.69	78	30	51.2	260	7.32	58	634	560	96	1,190
Group 2																
5	6/1/96	16:26	6/2/96	3:29	31.8	2.2	98	70	11.8	--	7.85	53.6	3,890	340	51	7,300
6	6/2/96	18:08	6/2/96	21:44	15.5	6.61	93	15	18.8	100	8.07	53	5,930	1050	154	10,500
7	6/5/96	22:14	6/6/96	1:13	9.91	3.91	43	10	10.7	60	7.1	35	2,900	206	47	5,320
8	6/7/96	1:47	6/7/96	3:44	6.1	1.71	28	15	8.8	52	7.13	27	370	79	17	693
9	6/7/96	14:11	6/8/96	5:10	20.3	8.07	51	30	11	78	7.25	38	860	172	40	1,650
Group 3																
10	7/18/96	21:50	7/18/96	22:50	20.3	8.56	--	--	34.8	137	6.85	48	670	232	52	1,270
11	7/24/96	14:41	7/24/96	14:52	4.57	1.71	39.4	50	18	164	7.17	42	246	220	58	404
12	7/29/96	1:13	7/29/96	1:35	7.62	2.94	9.3	25	10.3	86	6.97	20	164	182	34	268
13	8/5/96	21:30	8/6/96	7:28	18.8	6.36	31	30	15.5	110	7.23	36	432	278	57	813
14	8/20/96	1:03	8/20/96	1:23	5.59	1.96	100	30	14.8	140	7.34	42	190	338	62	347
15	9/8/96	13:51	9/8/96	22:28	23.9	9.05	32	35	28.1	130	6.85	31	<7.01	188	45	526
Effluent																
Group 1																
1	4/29/96	13:21	4/30/96	1:44	--	3.18	10	25	9	20	8.03	86	--	--	--	1,660
2	5/10/96	5:46	5/10/96	18:25	--	3.43	5.3	10	--	11	7.85	68	928	<4.88	12	1,760
3	5/14/96	20:07	5/15/96	13:18	--	5.14	4	5	4.1	<5	7.87	59	918	<4.88	<4.88	1,750
4	5/20/96	14:36	5/21/96	9:00	--	2.69	2.6	15	7.1	5	8.03	79	852	<4.88	<4.88	1,620
Group 2																
5	6/2/96	4:03	6/2/96	11:47	--	2.2	2.3	10	<3	9	8	85	1,540	<4.88	<4.88	2,780
6	6/2/96	19:11	6/3/96	13:39	--	6.61	2.1	10	<3	14	7.77	51	2,230	18	6	4,280
7	6/5/96	23:22	6/6/96	12:26	--	3.91	1.2	10	<3	11	--	--	3,070	<4.88	<4.88	--
8	6/7/96	2:54	6/7/96	9:25	--	1.71	0.7	10	<3	12	--	--	2,980	<4.88	<4.88	--
9	6/7/96	14:36	6/8/96	15:07	--	8.07	2.3	10	<3	13	7.75	52	2,080	<4.88	--	4,130
Group 3																
10	7/18/96	22:13	7/19/96	23:52	--	8.56	6	25	<3	20	7.73	70	358	--	--	661
11	7/24/96	15:13	7/24/96	22:21	--	1.71	1.5	15	<3	15.8	8.08	122	472	5	5	827
12	7/29/96	1:43	7/29/96	11:13	--	2.94	3.3	15	<3	14	7.94	104	434	8	<4.88	763
13	8/5/96	22:00	8/6/96	15:09	--	6.36	2.3	20	1.6	13	7.93	92	374	<4.88	<4	686
14	8/20/96	1:39	8/20/96	9:19	--	1.96	3.1	20	4.4	19	7.82	100	344	<4.88	<4.88	632
15	9/8/96	14:15	9/9/96	15:52	--	9.05	3.7	25	9.2	33	7.46	82	320	7	3	547

Appendix 1. Concentrations and other measurements of monitored water-quality characteristics in influent and effluent to the Multi-Chambered Treatment Train at Ruby Street Garage, Milwaukee, Wis.—Continued

Storm no.	Nutrients				Major Ions								Metals			
	NH ₄ as N	NO ₂ + NO ₃ as N	Phosphorus, dissolved (mg/L)	Phosphorus, total (mg/L)	Calcium, dissolved (mg/L)	Calcium, total (mg/L)	Magnesium, dissolved (mg/L)	Magnesium, total (mg/L)	Chloride, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Hardness, dissolved (mg/L)	Hardness, total (mg/L)	Cadmium, dissolved (µg/L)	Cadmium, total (µg/L)	Chromium, dissolved (µg/L)	Chromium, total (µg/L)
Influent																
Group 1																
1	0.133	0.192	0.04	0.255	14	36	0.5	10	619	21	36	130	1.1	1.7	1.1	7
2	0.051	.301	--	.229	13	37	.46	10	613	18	34	130	.03	1.2	.9	6
3	.097	.281	.025	.205	13	34	.52	10	215	16	34	130	.03	1	.8	6
4	<.027	.363	<.002	.308	22	90	.96	31	302	30	60	350	.15	1.9	1.4	9
Group 2																
5	.128	.347	.001	.215	35	65	.98	17	2,420	42	91	230	.51	1.4	<.5	5
6	.251	.18	<.002	.44	45	150	1.1	46	3,560	58	120	560	.74	3.7	.6	12
7	<.027	.404	.002	.234	31	79	.82	25	1,700	41	80	300	.33	1.2	<.5	4
8	.18	1.36	.012	.101	11	18	.4	4	177	18	30	61	.05	.48	<.5	3
9	<.027	.363	0	.188	16	34	.52	11	458	19	41	130	.1	.99	.5	5
Group 3																
10	.258	.273	.031	.388	16	45	1.2	14	342	19	45	170	.63	2	1.4	8
11	.031	.276	<.002	.31	17	35	1.1	10	849	15	47	130	.22	1.7	1.7	7
12	.053	.4	.04	.262	8.3	57	.51	21	57.2	10	23	230	.11	1.3	.6	6
13	<.027	.426	<.002	.311	17	210	.98	100	208	22	47	950	.31	3	2	14
14	.044	.353	.003	.33	14	43	.75	15	68.4	16	37	170	.13	1.9	.6	8
15	<.027	.393	.026	.288	13	31	.89	9.8	127	17	37	120	.41	1.5	.8	4
Effluent																
Group 1																
1	.069	.273	.016	.046	18	19	3.4	3.6	427	39	60	61	.97	1	1.5	2
2	<.027	.294	--	.03	22	22	3.7	3.7	476	24	70	70	.4	.12	.8	<1
3	<.027	.281	.007	.018	21	20	2.6	2.6	478	27	64	61	.02	.09	1.9	1
4	<.027	.27	.004	.016	26	27	2.7	2.8	427	28	76	79	.05	.06	1	<1
Group 2																
5	.088	.456	.002	.017	68	66	13	13	777	36	220	220	.02	<.04	1	<1
6	<.027	.463	.002	.014	38	39	5.6	6.4	1,240	33	120	120	<.02	.04	.8	<1
7	.062	.328	.001	.022	47	46	4.6	4.7	1,820	44	140	130	.02	.04	1	<1
8	<.027	.353	.001	.019	42	42	3.3	3.3	1,790	47	120	120	<.02	<.04	.8	<1
9	<.027	.317	.001	.018	30	29	2	2.1	1,290	38	82	82	<.02	<.04	.7	<1
Group 3																
10	<.027	.074	.001	.043	23	25	2.4	2.9	144	22	68	74	.14	.2	1.2	2
11	.064	.127	<.002	.023	43	44	4.6	4.8	167	25	130	130	.05	.1	<.5	<1
12	.082	.126	.003	.037	37	39	3.8	4.3	158	22	110	120	.07	.12	3.4	18
13	.089	.11	<.002	.033	31	32	3.4	3.4	139	20	92	94	.05	.01	<.5	<1
14	.105	.166	.01	.051	34	33	3.3	3.4	116	19	99	97	.1	.1	.7	2
15	.115	.139	.004	.088	28	28	2.9	3.1	100	16	83	83	.15	.26	<.5	<1

Appendix 1. Concentrations and other measurements of monitored water-quality characteristics in influent and effluent to the Multi-Chambered Treatment Train at Ruby Street Garage, Milwaukee, Wis.—Continued

Storm no.	Metals						Carbon			Dissolved PAH						
	Copper, dissolved (µg/L)	Copper, total (µg/L)	Lead, dissolved (µg/L)	Lead, total (µg/L)	Zinc, dissolved (µg/L)	Zinc, total (µg/L)	DOC, (mg/L)	TOC, (mg/L)	Acenaph-thene (µg/L)	Acenaph-ylene (µg/L)	Anthracene (µg/L)	Benzo [a] anthracene (µg/L)	Chrysene (µg/L)	Dibenzo [a,h] anthracene (µg/L)	Fluoran-thene (µg/L)	Benzo [b] fluoranthene (µg/L)
Influent																
Group 1																
1	8	31	1.5	48	26	160	6.8	7.9	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
2	1.7	24	<.4	46	<8	150	3.9	4.3	--	--	<.015	<.059	<.03	<.019	<.098	<.073
3	2.6	32	<.4	44	<8	140	4.6	5.2	--	<.044	<.015	<.059	<.03	<.019	.099	<.073
4	7.3	48	1.3	71	9	220	12	16	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
Group 2																
5	2.5	19	.6	23	<8	90	2.1	2.2	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
6	3.8	58	1	72	<8	250	5.6	5.7	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
7	3.5	22	<.4	33	<8	110	5.3	6.3	--	<.044	<.015	--	<.03	<.019	<.098	<.073
8	3.2	11	<.4	16	<8	55	5.2	5.9	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
9	3.3	26	.5	38	13	130	4.3	4.6	--	<.044	.015	--	<.03	<.019	<.098	<.073
Group 3																
10	12	41	7.6	56	38	210	15	18	<.048	<.044	<.015	<.059	<.03	--	<.098	<.073
11	10	37	.9	55	19	200	16	20	<.048	<.044	<.015	<.059	.18	<.019	.32	.19
12	4.4	23	.5	62	<8	150	8.3	8.6	<.048	<.044	.026	.23	.52	.038	1.1	.54
13	12	39	1.5	48	18	250	11	12	--	--	--	--	--	--	--	--
14	4.4	34	1.5	62	<8	200	8.2	8.8	--	--	--	--	--	--	--	--
15	10	34	5.8	46	26	150	17	20	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
Effluent																
Group 1																
1	5.7	8	1.2	2.9	22	29	5.7	5.8	--	--	--	--	--	--	--	--
2	1.8	3	<.4	1.8	<8	<19	--	--	--	--	--	--	--	--	--	--
3	1.6	2	<.4	1.3	<8	<19	2.1	2.1	--	--	--	--	--	--	--	--
4	1.2	3	.9	.9	<8	<19	2.1	2.3	--	--	--	--	--	--	--	--
Group 2																
5	.7	4	.5	1.3	<8	<19	--	--	--	--	--	--	--	--	--	--
6	<.7	3	<.4	2	<8	<19	4.1	4.4	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
7	1.3	3	<.4	2.3	<8	53	2.3	2.6	--	<.044	<.015	--	<.03	<.019	<.098	<.073
8	.8	2	<.4	<.8	<8	<19	--	--	--	--	--	--	--	--	--	--
9	1.2	2	<.4	.9	<8	<19	2	2.4	--	<.044	<.015	--	<.03	<.019	<.098	<.073
Group 3																
10	2.3	4	1.3	3	<8	25	4	4.3	<.048	<.044	<.015	<.059	<.03	--	<.098	<.073
11	1.4	2	<.4	1	<8	<19	4.2	4.4	--	--	--	--	--	--	--	--
12	<.7	3	<.4	2.3	<8	<19	4.4	4.8	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
13	2	3	<.4	3.9	<8	<19	4.9	5.1	--	--	--	--	--	--	--	--
14	1.9	3	<.4	1.5	<8	<19	5.8	6.9	--	--	--	--	--	--	--	--
15	3.1	6	.9	2.3	<8	<19	9.5	11	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073

Appendix 1. Concentrations and other measurements of monitored water-quality characteristics in influent and effluent to the Multi-Chambered Treatment Train at Ruby Street Garage, Milwaukee, Wis.—Continued

Total PAH																
Storm no.	Dissolved PAH										Total PAH					
	Benzo[k]fluoranthene (µg/L)	Fluorene (µg/L)	Naphthalene (µg/L)	Benzo [g,h,i] perylene (µg/L)	Phenanthrene (µg/L)	Pyrene (µg/L)	Benzo [a] pyrene (µg/L)	Indeno [1,2,3-c,d] pyrene (µg/L)	Acenaphthene (µg/L)	Acenaphthylene (µg/L)	Anthracene (µg/L)	Benzo[a] anthracene (µg/L)	Chrysene (µg/L)	Dibenzo [a,h] anthracene (µg/L)	Fluoranthene (µg/L)	Benzo (b) fluoranthene (µg/L)
Influent																
Group 1																
1	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078	<.048	<.044	.34	1.1	1.3	.14	3.5	1.3
2	<.059	--	--	<.05	--	<.063	<.041	<.078	--	<.11	.17	.54	.92	.12	2.1	.96
3	<.059	<.12	--	<.05	.12	.063	<.041	<.078	<.12	<.044	.21	.6	1	.084	2.6	1
4	<.059	<.12	<.054	<.05	.1	.082	<.041	<.078	<.048	<.044	.19	.98	1.3	<.14	3.2	1.3
Group 2																
5	<.059	<.12	<.054	<.05	.12	<.063	<.041	<.078	<.048	<.044	<.015	.16	.35	.029	.78	.36
6	<.059	<.12	<.054	<.05	.2	<.063	<.041	<.078	.17	<.044	.32	1.4	2.1	.16	5.1	2
7	<.059	--	--	<.05	.097	--	--	<.078	<.1	<.044	.093	.37	.58	.046	1.7	.6
8	<.059	<.12	<.054	<.05	.16	<.063	<.041	<.078	<.048	<.044	<.2	<.24	<.26	.02	.51	<.23
9	<.059	--	--	<.05	.1	--	--	<.078	<.1	<.044	.11	.54	.71	.068	1.8	.71
Group 3																
10	<.059	<.12	<.054	<.05	.11	<.063	<.041	<.078	<.048	<.044	.034	<.32	.69	.042	1.6	<.65
11	.072	<.12	<.054	.13	.051	.27	.075	.14	<.048	<.044	<.015	.18	.5	.03	.9	.46
12	.24	<.12	<.054	.38	.35	.79	.38	.39	--	--	--	--	--	--	--	--
13	--	--	--	--	--	--	--	--	.23	<.044	.26	1	1.5	.13	3.9	1.7
14	--	--	--	--	--	--	--	--	<.048	<.044	.041	.46	.89	.065	1.7	.84
15	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078	<.048	<.044	.026	<.34	.55	<.044	1	<.44
Effluent																
Group 1																
1	--	--	--	--	--	--	--	--	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
2	--	--	--	--	--	--	--	--	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
3	--	--	--	--	--	--	--	--	--	<.044	<.015	<.059	<.03	<.019	<.098	<.073
4	--	--	--	--	--	--	--	--	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
Group 2																
5	--	--	--	--	--	--	--	--	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
6	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
7	<.059	--	--	<.05	--	--	--	<.078	--	<.044	<.015	--	<.03	<.019	<.098	<.073
8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
9	<.059	--	--	<.05	--	--	--	<.078	--	<.044	<.015	--	<.03	<.019	<.098	<.073
Group 3																
10	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078	<.048	<.044	<.015	<.059	<.03	--	<.098	<.073
11	--	--	--	--	--	--	--	--	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
12	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
13	--	--	--	--	--	--	--	--	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
14	--	--	--	--	--	--	--	--	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073
15	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078	<.048	<.044	<.015	<.059	<.03	<.019	<.098	<.073

Appendix 1. Concentrations and other measurements of monitored water-quality characteristics in influent and effluent to the Multi-Chambered Treatment Train at Ruby Street Garage, Milwaukee, Wis.—Continued

Total PAH										
Storm no.	Benzo[k]fluoranthene (µg/L)	Fluorene (µg/L)	Naphthalene (µg/L)	Benzo [g,h,i]perylene (µg/L)	Phenanthrene (µg/L)	Pyrene (µg/L)	Benzo [a]pyrene (µg/L)	Indeno [1,2,3-c,d]pyrene (µg/L)		
Influent										
Group 1										
1	0.79	<0.25	<0.054	1	1.5	2.4	1.2	1		
2	.51	<.15	<.14	<.64	1.3	1.6	<.62	<.8		
3	.48	<.17	<.054	.77	1.4	1.8	.85	.74		
4	<.46	<.12	<.054	1	2	2.4	1	1		
Group 2										
5	.16	<.12	<.054	.24	.28	.47	.21	.23		
6	1	.38	<.054	1.4	2.8	3.2	1.6	1.4		
7	.27		<.06	.4	.86	1.1	<.4	.41		
8	.098	<.12	<.054	.15	.12	.55	.14	.16		
9	.34		<.08	.61	.56	1.4	.73	.52		
Group 3										
10	.29	<.12	<.054	.45	.56	1.2	.41	.44		
11	.19	<.12	<.054	.34	.15	.75	.28	.32		
12	--	--	--	--	--	--	--	--		
13	.79	.21	<.095	1.3	1.6	2.8	1.5	1.2		
14	.4	<.12	<.054	.64	.53	1.2	.7	.6		
15	.19	<.12	<.054	.44	.28	.72	.39	.38		
Effluent										
Group 1										
1	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
2	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
3	<.059	<.12		<.05	<.035	<.063	<.041	<.078		
4	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
Group 2										
5	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
6	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
7	<.059	--	--	<.05	--	--	--	<.078		
8	--	--	--	--	--	--	--	--		
9	<.059	--	--	<.05	--	--	--	<.078		
Group 3										
10	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
11	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
12	--	--	--	--	--	--	--	--		
13	<.059	<.12	<.054		<.035	<.063	<.041	<.078		
14	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		
15	<.059	<.12	<.054	<.05	<.035	<.063	<.041	<.078		

Appendix 2. Loads and removal efficiencies of monitored constituents in the influent and effluent to the Multi-Chambered Treatment Train at Ruby Street Garage in Milwaukee, Wis.

[mg, milligram; ND, not detected; PAH, polycyclic aromatic hydrocarbons]

Aggregate characteristics													Nutrients				Major ions			
Group	Biochemical oxygen demand (grams)	Chemical oxygen demand (grams)	Alkalinity (grams)	Total dissolved solids (grams)	Total solids (grams)	Volatile suspended solids (grams)	NH ₄ as N (grams)	NO ₂ + NO ₃ (grams)	Phosphorus		Calcium, dissolved (grams)	Calcium, total (grams)	Magnesium, dissolved (grams)	Magnesium, total (grams)	Chloride, dissolved (grams)					
									dissolved (grams)	total (grams)										
Loads																				
Influent																				
1	255	2,070	600	7,800	3,220	676	1.13	4.06	0.258	3.48	215	658	8.42	201	5990					
2	296	1,610	775	66,700	10,000	1,340	2.41	8.8	.037	5.99	644	1,750	17.5	535	39,500					
3	741	3,860	1,130	9,790	5,040	1,090	2.71	10.9	.632	9.85	444	2,310	29.4	953	5850					
Total	1,290	7,550	2,510	84,300	18,300	3,110	6.26	23.8	.928	19.3	1,300	4,720	55.4	1,690	51,300					
Effluent																				
1	68.8	128	1,020	10,200	ND	60.2	.371	4.05	.098	.385	311	311	44.1	45	6590					
2	ND	261	944	52,000	158	58.7	0.658	8.51	0.023	0.394	899	889	105	112	30,500					
3	122	658	2,640	11,100	116	60.4	2.28	3.5	0.081	1.62	897	926	93.9	102	4000					
Total	224	1,050	4,600	73,300	301	179	3.31	16.1	0.202	2.4	2,110	2,130	243	259	41,100					
Removal efficiency as a percentage of influent load																				
1	77	94	-70	-31	99	93	67	0	62	89	-44	53	-424	78	-10					
2	89	84	-22	22	98	96	73	3	38	93	-40	49	-502	79	23					
3	84	83	-133	-13	98	94	16	68	87	84	-102	60	-219	89	32					
Total	83	86	-83	13	98	94	47	33	78	88	-62	55	-340	85	20					
Organics																				
Metals																				
Loads																				
Influent																				
1	291	567	2470	4.16	19.8	14.5	97.9	64.3	474	9.98	727	141	2330	94.9	182					
2	820	1,690	6,530	8.2	41	9.96	151	76.4	740	13.1	990	163	3420	99.5	216					
3	543	1,240	9,820	12	60.2	37.8	239	308	1,100	133	1,600	727	5920	488	201					
Total	1,650	3,500	18,800	24.4	121	62.2	488	449	2,320	156	3,320	1,030	11,700	683	599					
Effluent																				
1	420	964	960	4.69	4.22	20	14.6	35.7	54.1	7.95	24.5	115	199	34.6	605					
2	857	2,690	2,650	.286	.661	18.4	ND	20	59.9	5.16	33	ND	384	52.2	67					
3	605	2,660	2,750	3.36	5.42	25.9	82.5	67.6	126	21.9	82.7	ND	423	183	117					
Total	1,880	6,320	6,360	8.34	10.3	64.3	108	123	240	35	140	327	1,010	270	244					
Removal efficiency as a percentage of influent load																				
1	-44	-70	61	-13	79	-38	85	44	89	20	97	19	91	62	97					
2	-4	-59	59	97	98	-85	93	74	92	61	97	45	89	44	97					
3	-11	-114	72	72	91	31	66	78	89	84	95	83	93	56	94					
Total	-14	-81	66	66	91	-3	78	73	90	78	96	68	91	54	96					

Appendix 3. Results from Microtox analyses of influent and effluent samples at the Multi-Chambered Treatment Train at Ruby St. Garage, Milwaukee, Wis.

Storm no.	Microtox Gamma values			
	Influent		Effluent	
	5 minute	15 minute	5 minute	15 minute
1	0.26	0.34	-0.12	-0.14
2	.09	.1	-.23	-.28
3	.11	.15	-.16	-.24
4	.32	.41	-.06	-.09
5	.05	.03	-.23	-.27
6	.01	.02	-.19	-.23
7	.12	.04	-.15	-.22
8	.25	.34	-.23	-.25
9	-.04	.02	-.25	-.26
10	.09	.09	-.05	-.04
11	.5	.49	-.07	-.17
12	.24	.31	-.02	-.05
13	.15	.17	-.12	-.13
14	.12	.23	-.12	-.12
15	.26	.3	-.1	-.13