

Highway Stormwater Runoff Study

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CH2MHILL

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Executive Summary

The Michigan Department of Transportation (MDOT) has undertaken a study to evaluate the characteristics and significance of stormwater runoff quality from highways in Michigan. The object of the study was: (1) to provide monitoring as required by the Michigan Department of Environmental Quality (DEQ) to satisfy requirements of the National Pollutant Discharge Elimination System (NPDES) stormwater permitting program; (2) to analyze highway runoff for specific metals to determine their source, fate, and potential effects; and (3) to conduct a literature search on mitigation measures for controlling metals.

The study was conducted in two phases. Phase I consisted of wet-weather monitoring for NPDES requirements (Part A) and an evaluation of the source, fate, and potential effects of metals (Part B). Phase II consisted of a nationwide survey and a literature search of mitigative measures.

Highway runoff sampling was conducted between June 1995 and October 1997 by McNamee, Porter, and Seeley, under subcontract to CH2M HILL. Three events were sampled at each of three sites during both Part A and Part B. The sites differed between Part A and Part B because the sampling objectives and requirements for each part differed. Part A was designed to document runoff quality from highway pavement. All sites had to be within one of the five regulated communities: Ann Arbor, Flint, Grand Rapids, Sterling Heights, and Warren. Samples were analyzed for a wide range of constituents to document fully the quality of highway runoff. The number of events and constituents to be sampled were agreed upon with Michigan DEQ at the project's inception.

The results of Part A sampling indicated that concentrations of conventional constituents, such as biochemical oxygen demand (BOD), total suspended solids (TSS), and phosphorus, are comparable to the concentrations collected in the Federal Highway Administration (FHWA) studies of the 1970s and 1980s. Concentrations of metals, lead in particular, were lower for the Part A sampling than for the FHWA studies. This can be attributed to the discontinuation of leaded gasoline and improvements in sampling and analytical techniques over the years. The FHWA database also contains only limited information on the dissolved form of metals, a critical consideration regarding effects of metals on aquatic biota. Organic compounds were, for the most part, not detected in MDOT runoff samples.

Part A results for total metals also indicated that formal in-stream criteria for protection of aquatic life generally are not exceeded in undiluted highway runoff. Only total copper and zinc concentrations occasionally exceeded these criteria. However, when consideration is given to in-stream dilution and the fact that the dissolved form of the metal is the more toxic form, it is probable that discharges of metals would not cause actual in-stream toxicity.

Part B was designed to assess the source, fate, and potential effects of metals in highway runoff. Samples of rainfall, stream sediment, soil, and highway runoff were collected. Of the three sites sampled during Part B, two discharged through a grassed swale and one discharged directly from the roadway to the stream. The results demonstrated the benefits

of the grassed swale in reducing pollutants. The concentrations of pollutants at the site without a grassed swale were substantially higher than at the two sites where runoff passed through a swale before discharge.

The results of soil sampling for metals supported the conclusion that swales effectively remove metals, but also showed that metals concentrations in soils were well below applicable soil cleanup criteria established by DEQ. Metals concentrations in sediments upstream and downstream of the highway sites were lower than recently developed informal sediment quality criteria for protection of aquatic life, and were of the same magnitude as natural background sites sampled recently in Michigan.

Metals concentrations at Part B sites were all lower than in-stream criteria designed to protect aquatic life from acute toxicity, and all but a few of the samples were lower than in-stream criteria designed to protect aquatic life from chronic toxicity. As with the Part A results, when in-stream dilution and other mitigating factors are considered, it is probable that in-stream concentrations will be well below levels of concern at these sites.

Part B sampling also demonstrated that rainfall is a significant source of metals in highway runoff. In several cases, the concentration of metals in the rainfall exceeded the concentration in the runoff. Considering the Part B results together, it can be concluded that metals originating from the road surface alone are not likely to pose a significant threat to water quality in receiving waters.

Phase II of the project consisted of a literature search on measures for controlling metals in highway runoff. A detailed survey of all 50 states' departments of transportation also was performed to evaluate the status of highway stormwater programs in other states. Phase II investigations concluded that vegetative best management practices, such as the grassed swale, are the most practical and effective method of reducing runoff pollutants (i.e., metals) from Michigan highways. Treatment of runoff using physical or chemical treatment methods would not be feasible, except perhaps in unusual site-specific conditions.

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Introduction

Federal regulation (40 CFR 122.26) requires municipalities with separate stormwater sewer systems and a population greater than 100,000 to obtain a National Pollutant Discharge Elimination System (NPDES) permit to regulate discharges from storm sewer systems. Five municipalities in Michigan fit these criteria: Ann Arbor, Flint, Grand Rapids, Sterling Heights, and Warren. According to the U.S. Environmental Protection Agency's (USEPA) final rule, as published in the *Federal Register* of November 16, 1990, highways of the Michigan Department of Transportation (MDOT) located in municipalities fitting the above criteria are subject to the NPDES municipal stormwater permitting and monitoring requirements.

To satisfy those requirements, MDOT undertook a sampling and research project to evaluate the characteristics of stormwater runoff quality from highways in Michigan and to evaluate what, if any, mitigation is feasible to protect Michigan's receiving waters from the effects of metals in highway runoff. The study had three primary goals: (1) to provide monitoring as required by the Michigan Department of Environmental Quality (DEQ) to satisfy requirements of the NPDES stormwater permitting program; (2) to analyze highway runoff for specific toxic metals to determine their source, fate, and potential effects; and (3) to conduct a literature search on mitigation measures for controlling persistent toxic metals.

The study was conducted in two phases. Phase I consisted of wet-weather monitoring for NPDES requirements (Part A) and an evaluation of the source, fate, and potential effects of persistent toxics (Part B). Field sampling activities were conducted by McNamee, Porter, and Seeley (MPS) under subcontract to CH2M HILL. Routine laboratory services were provided by MPS, Trace Analytical Laboratories, Matrix Environmental Group, and the University of Michigan. Battelle Marine Sciences performed all "clean" metals analysis. Phase II consisted of a literature search of mitigation measures.

Phase I: Wet Weather Monitoring and Metals Evaluation

Part A: NPDES Regulations Monitoring

To satisfy USEPA requirements in the NPDES program, MDOT undertook a sampling program for select outfalls in three of the five regulated municipalities. The sites sampled were: (1) Highway 131 (US 131) in Grand Rapids, (2) Interstate 94 (I-94) in Ann Arbor, and (3) Interstate 475 (I-475) in Flint. Outfalls were chosen to characterize runoff that drains directly from highway pavement. Runoff samples for the Part A sites were analyzed for conventional constituents, metals, cyanide, total phenols, volatile organics, acid-extractable organics, base-extractable and neutral organics, pesticides, and polychlorinated biphenyls (PCBs). Conventional sampling and analyses were performed for all parameters. Clean sampling and analysis (where special precautions are taken to prevent incidental metals contamination during sampling and analyses) also were conducted for cadmium, copper, lead, and zinc for some rain events and selected sites. Details on the clean sampling and analysis techniques used in this study are included in Appendix A.

Site Descriptions and Sampling Conditions

Site descriptions and sampling conditions for the three sampling locations are summarized in Tables 1 and 2. Sampling and quality assurance/quality control procedures are described in Appendix A.

TABLE 1
Sampling Site Characteristics at Part A Sites

	Ann Arbor	Grand Rapids	Flint
Highway	I-94	US 131	I-475
Impervious Drainage Area ^a	18,200 ft ²	20,200 ft ²	53,143 ft ²
Highway Length	600 ft	820 ft	622 ft
Average Daily Traffic (vehicles per day, vpd)	41,000	120,000	51,000
Ratio of impervious area to ADT (ft ² to vpd)	0.44	0.17	1.04
Average Annual Precipitation	31 in	36 in	31 in
Receiving Water	grassed ditch leading to a wetland	city storm sewer to the Grand River	city storm sewer to the Flint River

^aAll three Part A sites drain entirely from impervious highway pavement.

TABLE 2
Sampling Conditions at Part A Sites

Location	Event Date	Rainfall Vol. (in.)	Duration (min.)	Avg. Intensity (in./hr)	Dry Days Preceding ^a
Ann Arbor	6/26/95	0.15	90	0.10	1 (28)
Ann Arbor	10/20/95	0.14	210	0.04	13 (14)
Ann Arbor	6/17/96	0.10	80	0.08	3 (7)
Average	—	0.13	130	0.07	6 (16)
Grand Rapids	6/26/95	0.33	60	0.33	11 (11)
Grand Rapids	9/19/95	0.07	170	0.03	1 (3)
Grand Rapids	10/13/97	0.26	230	0.07	4 (4)
Average	—	0.22	150	0.14	5 (6)
Flint	6/28/95	0.10	100	0.06	0 (24)
Flint	9/7/95	0.08	20	0.24	5 (6)
Flint	9/26/96	0.17	120	0.34	1 (3)
Average	—	0.12	80	0.18	2 (11)

^aNumber outside parentheses is the continuous days without rainfall prior to sampling; number inside parentheses is the continuous days with rainfall less than 0.1 inch prior to sampling.

Ann Arbor

The highway runoff outfall selected for sampling in Ann Arbor is on the south side of the eastbound I-94 lanes, east of the Jackson Road interchange and west of mile marker 174. The outfall drains roughly 18,200 square feet (ft²) of impervious roadway surface, including the westbound and eastbound travel lanes and the paved shoulder. Traffic volume averages 41,000 vehicles per day, the lowest traffic volume of the three sites sampled in Part A.

Sampling was conducted at the Ann Arbor site on June 26, 1995; October 20, 1995; and June 17, 1996. In accordance with the MDOT Stormwater Sampling Standard Operating Procedures (MDOT 1995), sampling was performed only if rainfall was less than 0.1 inch for 72 hours before sampling. Total rainfall during the sampling events was 0.15 inch for the June 1995 event, 0.14 inch for the October 1995 event, and 0.10 inch for the June 1996 event. Average annual precipitation for the Ann Arbor area is about 31 inches.

Grand Rapids

The Grand Rapids site is at the Wealthy Street and US 131 interchange at MDOT Station 787. The outfall is roughly 200 feet south of Wealthy Street in the west right-of-way. It drains the impervious roadway area for the southbound lanes of US 131 and a small part of the Wealthy Street entrance ramp. The total drainage area of the catchment is 20,200 ft². This site is the most urban of the three Part A sites and, accordingly, has the highest average traffic volume (120,000 vehicles per day).

Samples were collected on June 26, 1995; September 19, 1995; and October 13, 1997. Antecedent rainfall requirements were met for all sampling events. Total rainfall was 0.33 inch during the June 1995 event, 0.07 inch during the September 1995 event, and 0.26 inch during the October 1997 event. Average annual precipitation for the Grand Rapids area is about 36 inches.

Flint

The outfall at the Flint site is located off northbound I-475, 400 feet south of Massachusetts Avenue and 1,000 feet north of Leith Street (MDOT Station 496+00). The catchment is impervious roadway that includes both the northbound and southbound travel lanes as well as the paved shoulders. The total drainage area of the catchment is 53,143 ft². Traffic volume averages 51,000 vehicles per day.

Samples were collected on June 28, 1995; September 7, 1995; and September 26, 1996. As required, rainfall did not exceed 0.1 inch for the 72 hours before sampling. Total rainfall during the sampling events was 0.10 inch for the June 1995 event, 0.08 inch for the September 1995 event, and 0.17 inch for the September 1996 event. Average annual precipitation for the Flint area is about 31 inches.

Sampling Results

Runoff Monitoring

Conventional Parameters. Wet weather monitoring results for conventional parameters at the three sites are summarized in Table 3. The concentrations for the three events were averaged for presentation in the table. If a sample concentration was reported as below detection, a value equal to one-half the detection limit was used to calculate the average. This method is consistent with Michigan DEQ's method for averaging NPDES monitoring results and provides a reasonably moderate estimate of the average chemical concentration at a site (i.e., use of zero for the result may under estimate the true value, while use of the detection limit for the result may over estimate the true value). Individual monitoring results from each storm, showing which samples were actually below the detection limit, are presented in Appendix B.

Concentrations of conventional constituents generally were higher at the Grand Rapids site than at the Ann Arbor and Flint sites. This may be attributable to higher traffic volume at Grand Rapids. There appeared to be no positive correlation in the MDOT data between stormwater runoff concentrations and size of the drainage area. The Flint site has a drainage area twice as large as the Grand Rapids and Ann Arbor sites, yet the Grand Rapids site had the highest runoff concentrations. The Ann Arbor and Flint sites had fairly similar concentrations to each other at a level often substantially lower than the concentrations at the Grand Rapids site. Although a larger drainage area would be expected to contribute to higher loadings of constituents (i.e., mass per unit time), it does not appear to cause higher concentrations.

TABLE 3
Average Concentration of Conventional Constituents at Part A Sites

Constituent	Grand Rapids	Ann Arbor	Flint	FHWA ^a	FHWA ^b
BOD ₅ (mg/L)	18	13.4	13.3	—	21
Chemical Oxygen Demand (COD) (mg/L)	132	47.7	55.1	92 ^c	105
Ammonia-nitrogen (mg/L)	2.1	1.2	0.55	—	—
Nitrate/Nitrite-nitrogen (mg/L)	1.5	1.3	0.84	0.66 ^d	1.57
TKN (mg/L)	2.7	3.1	2.8	2.88 ^d	2.04
Total Phosphorus (mg/L)	0.32	0.20	0.17	0.33 ^c	0.31
Dissolved Phosphorus (mg/L)	0.10	0.09	0.09	—	—
TSS (mg/L)	125	57.8	33.8	157 ^c	138
Total Dissolved Solids (TDS) (mg/L)	183	148	143	—	—
Oil and Grease (mg/L)	9	7.9	55.8	5 ^c	8
Total Chlorine (mg/L)	Not Measurable	0.09	Not Measurable	—	—
Fecal Coliform (#/100 mL)	>5,000	66,380	4,807	—	10->100,000
Fecal Streptococcus (#/100 mL)	>100,000	30,536	9,143	—	40-4,300

^aKobriger and Geinopolos 1984. Highway runoff concentration at I-94 in Milwaukee, nonwinter period. Average daily traffic = 115,000. Comparable to the Grand Rapids site.

^bGupta, et al. 1981. Average Highway runoff concentration at highway I-794 in Milwaukee, nonwinter period. Average daily traffic = 53,000. Comparable to the Flint and Ann Arbor sites.

^cMean concentration.

^dMedian concentration.

The Grand Rapids site had a much smaller drainage area per unit traffic volume (Table 1) than the other sites. Several highway runoff studies in other states have shown that the concentration of constituents is positively correlated with the number of vehicles traveling the highway during the storm (Racin et al. 1982; Kerri et al. 1985; Mar et al. 1982). It is hypothesized that splashing and washing of pollutants from vehicles is more important than washoff of pollutants from the highway surface that accumulated during the antecedent dry period. Thus, a greater number of vehicles during the storm per unit area of highway could lead to relatively higher constituent concentrations as long as rainfall/runoff volumes are comparable. This MDOT study did not quantify vehicles during storms, but it would be expected that this would be positively correlated with ADT assuming a relatively comparable mix of storms during on-peak and off-peak travel times.

Other factors that could influence differences between average concentrations at each site include average rainfall volume, average rainfall intensity, and average antecedent dry period (Table 2). Rainfall volume was highest at Grand Rapids and comparable at Ann Arbor and Flint. Intensity was lowest at Ann Arbor and comparable at Grand Rapids and Flint. Duration was lowest at Flint and comparable at Ann Arbor and Grand Rapids. The antecedent dry period with rainfall less than 0.01 inches was longest at Ann Arbor and

shortest at Grand Rapids. Thus, there is no consistent factor among these that explain the higher concentrations at Grand Rapids.

Atmospheric contributions can also be a significant determinant to highway runoff concentrations (Driscoll et al. 1990). The relative contribution of atmospheric sources (precipitation and dry deposition) was not evaluated in Part A. Concentrations of metals in rainfall as measured in Part B indicate that metals in rainfall in the Grand Rapids area generally are higher than in Ann Arbor.

The overall conclusion is that data collected in Part A do not allow definitive conclusions regarding mechanisms or sources that might explain higher concentrations at Grand Rapids. Given that there are only three data points per constituent at each site, it would be inappropriate to arrive at conclusions regarding mechanisms or sources.

Table 3 also includes results from relevant Federal Highway Administration (FHWA) highway runoff monitoring studies performed in the late 1970s and early 1980s. One FHWA site, I-94 in Milwaukee, is presented for comparison to the Grand Rapids site because of its similar high traffic volume and 100 percent impervious drainage area. The other FHWA site, I-794 in Milwaukee, has an intermediate average daily traffic volume and is 100 percent impervious. Therefore, it is comparable to the Ann Arbor and Flint sites. Concentrations of conventional constituents for Grand Rapids, Ann Arbor, and Flint were comparable to the concentrations reported for respective FHWA sites, indicating that highway runoff quality at MDOT sites is about what would be expected for these constituents.

Metals, Phenols, and Cyanide Analyses. Concentrations of metals in stormwater runoff at the three sites were determined using both conventional and clean sampling and analysis techniques to determine if contamination was a significant component of conventional analysis results. Table 4 illustrates the results of both the clean and conventional sampling and analysis performed for four metals at each site. Overall, differences between the clean and conventional sampling for total recoverable analysis results were minor, with no consistent trends between the two (see Appendix A for further discussion).

TABLE 4
Average Concentration of Metals in Stormwater Using Conventional and Clean Sampling Techniques at Part A Sites

Constituent (µg/l)	Grand Rapids ^a		Ann Arbor ^b		Flint ^c	
	Clean	Conventional	Clean	Conventional	Clean	Conventional
Cadmium	2.7	2.9	0.83	1.1	0.62	0.67
Copper	88	86	45	30	43	43
Lead	59	65	26	10	23	11
Zinc	413	460	205	218	133	122

^aAverage for samples taken on 6/26/95 and 9/19/95.

^bAverage for samples taken on 6/26/95 and 10/20/95.

^cAverage for samples taken on 6/28/95 and 9/7/95.

Table 5 summarizes the sampling results for metals, phenols, and cyanides at the three sites. The values presented represent mean concentrations averaged over the three events at each site. Because there was no significant difference between total recoverable clean and conventional analyses for cadmium, copper, lead, and zinc, both sets of results were averaged to develop the overall mean concentrations that are presented in Table 5.

TABLE 5
Average Concentrations of Metals, Phenols, and Cyanide in Stormwater Using Conventional Sampling Techniques at Part A Sites

Constituent ^a (µg/L)	Grand Rapids	Ann Arbor	Flint	FHWA ^b	FHWA ^c
Antimony	2.2	1.7	0.8	—	—
Arsenic	1.5	1.5	1.6	—	—
Beryllium	ND	ND	0.15	—	—
Cadmium	2.4	0.86	0.59	ND	40
Chromium	49	7.5	6.0	ND	50
Copper	81	35	39	140 ^d	100
Cyanide	6.7	9.3	5.8	—	—
Lead	55	17	17	600 ^d	1500
Mercury	ND	0.19	0.13	ND	3.85
Nickel	34	5.3	3.9	ND	—
Total Phenols	51	53	54	—	—
Selenium	ND	0.87	1.0	—	—
Silver	ND	0.38	0.23	—	—
Thallium	ND	ND	ND	—	—
Zinc	413	193	130	355 ^e	350

^aMetals concentrations for MDOT samples are total recoverable, metals for FHWA are total.

^bKobriger and Geinopolos 1984. Stormwater concentration at I-94 in Milwaukee, nonwinter period. Average daily traffic = 115,00. Comparable to the Grand Rapids site.

^cGupta, et al. 1981. Average stormwater concentration at I-794 in Milwaukee, nonwinter period. Average daily traffic = 53,000. Comparable to the Ann Arbor and Flint sites.

^dMean concentration.

^eMedian concentration.

ND = Not detected.

Of the thirteen metals monitored, eight were present at concentrations that were consistently low or below detection (antimony, arsenic, beryllium, mercury, nickel, selenium, silver, and thallium). In Table 5, if all samples at a site were below detection, the average concentration is reported as not detected (ND). However, if at least one sample had a concentration above detection, the average concentration for the site was calculated using both the detected values and one-half the detection limit for the samples below detection.

Concentrations of copper, lead, zinc, cadmium, and chromium; which were consistently above detection; were highest at Grand Rapids and lowest at Flint. The potential reasons for higher pollutant concentrations at Grand Rapids were previously discussed for conventional parameters. This same discussion is pertinent for metals.

Concentrations of metals, lead in particular, were greater for the FHWA sites than the MDOT sites. The low lead levels reflect discontinued use of leaded gasoline in the mid-1980s. Also, the FHWA studies were performed before the widespread application of clean sampling and laboratory techniques and thus may have experienced some metals contamination. Thus, the current results of this monitoring program accurately reflect the metals concentrations currently found in Michigan's highway runoff.

Organics. With the exception of bis(2-ethylhexyl)phthalate and di-n-octylphthalate, the concentration of organics was below detection for all highway runoff samples. The compounds bis(2-ethylhexyl)phthalate and di-n-octylphthalate belong to a class of compounds called phthalate esters. They are known laboratory contaminants that originate from plastic equipment commonly used in laboratory procedures (USEPA 1988). Monitoring results for organics are presented in Tables B-4 through B-8 in Appendix B.

Comparison to Water Quality Criteria. Although none of the three sites discharges directly to a receiving water body, water quality criteria for surface waters is one way to conservatively judge the quality of highway runoff from Michigan's high volume highways. Tables 6 and 7 list Michigan's relevant final chronic values (FCV) and final acute values (FAV) along with maximum and average concentrations from monitoring at each site. Acute criteria protect aquatic organisms from the short-term, lethal effects of exposure to a pollutant whereas chronic criteria protect aquatic life from long-term, continuous exposure to a pollutant. It is important to recognize that comparing the final acute and chronic values to runoff concentrations is conservative because it does not account for in-stream dilution. Further, these outfalls do not discharge directly to waters of the state, where the criteria would be applicable. The outfalls at the three sites discharge to storm sewers and a grassed ditch. The final acute and chronic values used are the end-of-pipe values that the DEQ could use to evaluate direct discharges to a receiving water in the unlikely case where no dilution exists. In this context, maximum runoff values are most relevant to final acute values while average runoff values are most relevant to final chronic values. Although Michigan also has water quality criteria for protection of terrestrial wildlife and human health, these criteria are less relevant to direct comparison with runoff concentrations. This is because wildlife and human health effects are manifested over even longer periods of exposure than assumed for acute and chronic aquatic life criteria.

Because several metals criteria are hardness-dependent, the criteria are different for the Grand Rapids site (hardness of about 140 mg/L) and the Ann Arbor and Flint sites (hardness of about 200 mg/L). These hardness values are based on published maps of regional surface water hardness (U.S. EPA 1983). This is a conservative approach because current DEQ policy is to use a hardness of 250 mg/L in the absence of site-specific data (i.e., hardness-related metals criteria are less stringent at higher hardness values).

TABLE 6
Michigan Water Quality Criteria and Monitoring Results at Grand Rapids site

Metal (µg/L)	Final Water Quality Value (µg/L) ^a		Grand Rapids Runoff Concentration (µg/L)	
	Acute	Chronic	Maximum	Average
Arsenic	680	150	2.0	1.5
Beryllium	101	5.6	ND	ND
Cadmium	26	6	4.4	2.4
Total Chromium	2,252	146	86 ^b	49 ^b
Copper	55	18	115	81
Lead	1,188	67	100	55
Mercury	2.8 ^c	0.8 ^c	ND	ND
Nickel	2,460	137	64	34
Selenium	NC	5	ND	ND
Silver	22 ^d	1.2 ^d	ND	ND
Thallium	160	10	ND	ND
Zinc	655	330	590	413

^aCriteria calculated based on hardness of 140 mg/L, which is representative of the surface waters at the Grand Rapids site. Criteria listed in R 323.1057 of Michigan Administrative Code, July 1997. All criteria expressed as total recoverable, using translators provided in R323.1057, where available. The translator for nickel is based on stream suspended solids. A value of 5 mg/L was assumed for the purpose of this comparison.

^bHighway runoff samples analyzed for total chromium only. Actual levels of trivalent and hexavalent chromium, which are the forms of the water quality criteria, are unknown.

^cCriteria shown are for aquatic life toxicity

^dMichigan DEQ's standard approach of applying an approximate uncertainty factor of 20 was used to develop these silver values.

ND = Not detected

NC = No criterion established

Table 7 shows that no maximum concentration reported from Ann Arbor or Flint was above the acute criterion, and only copper showed averages above chronic values (i.e., this is only relevant if it is assumed that the most conservative assumption of no dilution in the receiving water would be applicable). At Grand Rapids (Table 6), the maximum copper concentration in runoff exceeded the acute criterion, and average concentrations of copper and zinc in highway runoff at this site exceeded chronic criteria (again, not accounting for in-stream dilution that would be available). A more appropriate method of evaluating the concentrations in highway runoff, however, is to calculate relative contribution to overall water quality and loadings in the watershed and to account for dilution that ultimately occurs in the receiving water. The metals loading rates calculated in the following section could be used to compare the contribution of highway runoff to the metals loading rates of urban stormwater and other sources.

As discussed previously for conventional parameters, it can be hypothesized that the Grand Rapids site had the only copper concentration that exceeded the end-of-pipe acute criterion because of its smaller ratio of drainage area to traffic volume. However, given the

relatively small number of data points, and the variety of other factors that could have influenced these results, it is not possible to definitively conclude that this ratio is the controlling or dominant factor.

TABLE 7
Michigan Water Quality Criteria and Monitoring Results at Ann Arbor and Flint Sites

Metal (µg/L)	Final Water Quality Value (µg/L) ^a		Ann Arbor Runoff Concentration (µg/L)		Flint Runoff Concentration (µg/L)	
	Acute	Chronic	Maximum	Average	Maximum	Average
Arsenic	680	150	2.6	1.5	2.8	1.6
Beryllium	248	13.8	ND	ND	ND	ND
Cadmium	38	7.8	1.7	0.86	0.75	0.59
Total Chromium	3,016	196	14.6 ^b	7.5 ^b	7.2 ^b	6.0 ^b
Copper	77	24	64	35	57	39
Lead	1,739	98	39	17	26	17
Mercury	2.8 ^c	0.8 ^c	0.36	0.19	0.2	0.13
Nickel	3,326	185	11	5.3	6.1	3.9
Selenium	NC	5	1.1	0.87	1.4	1.0
Silver	22 ^d	1.2 ^d	0.5	0.38	0.5	0.23
Thallium	160	10	ND	ND	ND	ND
Zinc	885	446	314	193	153	130

^aCriteria calculated based on hardness of 200 mg/L, which is representative of the Flint and Ann Arbor sites. Criteria listed in R 323.1057 of Michigan Administrative Code, July 1997. All criteria expressed as total recoverable, using translators provided in R323.1057, where available. The translator for nickel is based on stream suspended solids. A value of 5 mg/L was assumed for the purpose of this comparison.

^bHighway runoff samples analyzed for total chromium only. Actual levels of trivalent and hexavalent chromium, which are the forms of the water quality criteria, are unknown.

^cCriteria shown are for aquatic life toxicity

^dMichigan DEQ's standard approach of applying an approximate uncertainty factor of 20 was used to develop these silver values.

ND = Not detected.

NC = No criterion established.

Loading Rates

Average annual loading rates (pounds/acre/year) were calculated for each site and event for conventional parameters and metals using the Simple Method (Schueler 1987). This method is applicable to watersheds less than 640 acres. The Simple Method formula is:

$$L=(P \times P_j \times R_v/12) \times C \times 2.72$$

where:

- L = loading rate (lb/acre/year)
- P = rainfall depth over one year time period (inches)
- P_j = fraction of rainfall events that produce runoff (0.9)

- Rv = runoff coefficient (0.05 + 0.009 × I)
- I = percent of site imperviousness (100%)
- C = event mean concentration of pollutant (ppm)
- 2.72 = conversion factor (pounds/acre-foot-ppm)

Tables 8 and 9 summarize the annual loading rates for each site and wet weather monitoring event. Higher annual precipitation (i.e., higher runoff flow per unit area) and higher pollutant concentrations contributed to the higher loading rate for Grand Rapids. In all calculations, the average concentration of all sampling events was used. If a sample concentration was reported as below detection, a value equal to one-half the detection limit was used in the average. If all samples at a site were below detection, the loading was not calculated. A notation of not detected (ND) is indicated for these parameters.

TABLE 8
Annual Loading Rates (lb/acre/year) for Conventional Constituents at Part A Sites

Constituent	Grand Rapids	Ann Arbor	Flint
BOD ₅	120	80	80
COD	920	290	330
Ammonia-nitrogen	14.6	7.2	3.3
Nitrate/Nitrite nitrogen	10.3	7.9	5.1
TKN	18.6	18.8	16.6
Total Phosphorus	2.2	1.2	1.0
Dissolved Phosphorus	0.7	0.5	0.5
TSS	870	350	200
TDS	1,280	890	860
Oil and Grease	63	47	335

TABLE 9
Annual Loading Rates (lb/acre/year) for Metals at Part A Sites

Constituent ^a	Grand Rapids	Ann Arbor	Flint
Antimony	0.016	0.010	0.005
Arsenic	0.010	0.009	0.010
Beryllium	ND	ND	0.001
Cadmium	0.017	0.005	0.004
Chromium	0.340	0.045	0.036
Copper	0.56	0.21	0.24
Lead	0.38	0.10	0.10
Mercury	ND	0.001	0.001
Nickel	0.24	0.032	0.023
Selenium	ND	0.005	0.006
Silver	ND	0.002	0.001
Thallium	ND	ND	ND

TABLE 9
Annual Loading Rates (lb/acre/year) for Metals at Part A Sites

Constituent ^a	Grand Rapids	Ann Arbor	Flint
Zinc	2.88	1.16	0.78

^aAll metals concentrations as total recoverable. ND = metal not detected in sampling.

Overall Water Quality Conclusions from Part A Analyses

Several general conclusions can be made as a result of the Part A analyses:

- For all 3 MDOT sites, highway runoff concentrations for conventional parameters such as BOD, COD, nutrients, TSS, oil and grease, and bacteria were comparable to those measured for similar highways in earlier FHWA nation-wide studies. Consequently, it can be concluded that MDOT highways do not produce unusually high loadings for these constituents compared to highways in other states and urban stormwater quality in general.
- Organic compounds were generally below analytical detection limits. The only exception was 2 phthalate esters which commonly are found in samples due to laboratory contamination.
- Concentrations of total recoverable metals in undiluted runoff generally were below in-stream water quality criteria designed to protect aquatic life from acute and chronic toxicity. Copper and zinc concentrations occasionally exceeded these criteria. However, when consideration is given to in-stream dilution and the fact that the dissolved form of the metal is the more toxic form, it is probable that discharges of metals from these sites would not cause actual in-stream toxicity (see Part B discussions also).
- The loading rates calculated for these sites can be used to compare loadings from impervious highway areas to loadings from other sources in a watershed analysis. Note that many highways in Michigan drain to receiving waters after passing through grassed swales or ditches, which substantially reduce metals and other pollutant concentrations and loadings (again see discussion under Part B).

Part B: Source, Fate, and Potential Effects of Metals

In contrast to the Part A sites, which were chosen to characterize runoff from completely impervious highway surfaces in highly urbanized locations, the Part B sites were designed to examine the sources and fate of metals in the highway right-of-way and the potential effects of metals on adjacent aquatic systems. The three sites monitored were (1) I-96 and the West Branch of Sand Creek near Marne (Grand Rapids area), (2) M-37 and Mill Creek (southwest Grand Rapids), and (3) M-14 and Fleming Creek near Dixboro (Ann Arbor area). These sites were chosen to represent a range of medium volume highways in Michigan that discharge to a receiving stream either directly or after passing through a grassed swale.

Highway runoff samples were analyzed for total recoverable and dissolved lead, zinc, copper, and cadmium to quantify the dissolved-to-total recoverable relationship for each metal. Clean sampling and analysis were performed for each event. Methods used in clean

sampling and analysis are discussed Appendix A. Conventional sampling techniques were also performed for the June 17, 1995, event at Marne. Rainfall samples were collected during the sampling events (using clean techniques described below) to establish the relative contribution of rainfall to the metals concentrations observed in the runoff.

Soil samples were collected along the runoff path in the right-of-way to establish a better understanding of the metals loading and removal pathways for each highway system. Soil samples were also taken outside the highway’s region of influence to establish levels of background metals. Sediment samples were taken from each receiving stream upstream and downstream of the outfall to determine whether metals from runoff are depositing in the stream sediment. Soil and sediment samples were analyzed for cadmium, chromium, lead, zinc, and copper.

Site Description and Sampling Conditions

Site descriptions and sampling conditions for the three sampling locations are summarized in Tables 10 and 11. Maps in Appendix C show the locations of the outfalls and the soil and sediment sampling points.

TABLE 10
Sampling Site Characteristics at Part B Sites

	Marne	Grand Rapids	Ann Arbor
Highway	I-96	M-37	M-14
Impervious Drainage Area	27,360 ft ²	14,400 ft ²	18,000 ft ²
Pervious Drainage Area	0 ft ²	16,000 ft ²	14,400 ft ²
Highway Length	1,140 ft	600 ft	600 ft
Average Daily Traffic (vehicles per day, vpd)	25,000	18,000	56,000
Ratio of impervious area to ADT	1.09 (ft ² to vpd)	0.80 (ft ² to vpd)	0.32 (ft ² to vpd)
Average Annual Precipitation	36 in.	36 in.	31 in.
Receiving Water	W. Br. Sand Cr.	Mill Creek	Fleming Creek

TABLE 11
Sampling Conditions at Part B Sites

Location	Event Date	Rainfall Volume (in.)	Duration (min.)	Avg. Intensity (in./hr)	Dry Days Preceding ¹
Marne	10/3/95	0.11	120	0.06	11 (11)
Marne	6/17/96	0.56	140	0.24	3 (3)
Marne	9/26/96	0.06	100	0.04	1 (1)
Average	—	0.24	120	0.11	5 (5)
Grand Rapids	9/26/96	0.37	170	0.13	1 (1)
Grand Rapids	11/7/96	0.05	110	0.03	3 (3)
Grand Rapids	8/12/97	0.05	200	0.02	0 (0)

TABLE 11
Sampling Conditions at Part B Sites

Location	Event Date	Rainfall Volume (in.)	Duration (min.)	Avg. Intensity (in./hr)	Dry Days Preceding ¹
Average	—	0.16	160	0.06	1(1)
Ann Arbor	10/5/95	0.24	260	0.06	1 (1)
Ann Arbor	6/18/96	0.36	100	0.22	0 (0)
Ann Arbor	9/20/96	0.09	240	0.03	5 (5)
Average	—	0.23	200	0.10	2 (2)

¹Number outside parentheses is the continuous days without rainfall prior to sampling; number inside parentheses is the continuous days with rainfall less than 0.1 inch prior to sampling. Note that the Part B sampling was not subject to the antecedent dry day constraints required in Part A sampling.

I-96 and West Branch Sand Creek (Marne)

The highway runoff outfall at I-96 and West Branch Sand Creek in Marne consists of an asphalt channel north of the westbound lanes of I-96 and west of 16th Street. The outfall drains 27,360 ft² of impervious roadway surface that includes the westbound lanes only. The outfall discharges directly to West Branch Sand Creek. Average daily traffic volume at the site is 25,000 vehicles per day. Samples were collected during rain events on October 3, 1995; June 17, 1996; and September 26, 1996. Total rainfall for the sampling events were 0.11 inch for the October 1995 event, 0.56 inch for the June 1996 event, and 0.18 inch for the September 1996 event.

M-37 and Mill Creek (Grand Rapids)

The catchment at M-37 and Mill Creek in Grand Rapids directs runoff from the eastbound and westbound lanes of M-37 to an inlet located in the median strip. The inlet passes highway runoff under the eastbound lanes to a grassed swale that follows alongside M-37 and empties into Mill Creek. Highway runoff was sampled where the swale empties into Mill Creek. A total impervious area of 14,400 ft² and a pervious area of 16,000 ft² contribute to the discharge at Mill Creek. Average daily traffic volume for the Marne site is 18,000 vehicles per day, the lowest of the three sites. Three events were sampled: September 26, 1996; November 7, 1996; and August 12, 1997. The cumulative rainfall of 0.37 inch for the September sampling event was substantially greater than the 0.05 inch events in both the November 1996 and August 1997 events.

M-14 and Fleming Creek (Ann Arbor)

The catchment at M-14 and Fleming Creek in Ann Arbor collects highway runoff from 18,000 ft² of impervious surface (eastbound and westbound lanes of M-14), and 14,400 ft² of associated grassy areas. Runoff from the impervious and pervious areas is directed to an inlet in the median strip that discharges indirectly to Fleming Creek through an outlet and a grassed swale. Highway runoff was sampled at the juncture of the outlet and the swale. The average daily traffic for the Ann Arbor site is 56,000 vehicles per day, which is the highest of the three sites. Three events were sampled: October 5, 1995; June 18, 1995; and September 20, 1996. Total rainfall for the sampling events was 0.40 inch for October 1995; 0.16 inch for June 1995; and 0.11 inch for September 1996.

Sampling Results

Highway Runoff Monitoring

Highway runoff and rainfall samples were collected for three events at each of three sites. Samples were analyzed for total recoverable and dissolved lead, zinc, and copper. Highway runoff samples from the October 1995 events at Marne and Ann Arbor were also analyzed for cadmium. Table 12 summarizes the highway runoff sampling results for all sites. Graphs of the results are provided in Appendix D.

Concentrations for a low volume highway (Todd Drive) in a Midwestern city of similar size to Grand Rapids and Ann Arbor (Madison, Wisconsin) are also presented in Table 12 for comparison. Metals concentrations in MDOT runoff were comparable to, but generally lower than, stormwater runoff sampled at Todd Drive.

TABLE 12
Event Mean Metals Concentrations in Highway Runoff at Part B Sites

Metal (µg/L)	Marne				Grand Rapids			Ann Arbor			Todd Drive ^c
	10/3/95	6/17/96 ^a	6/17/96 ^b	9/26/96	9/26/96	11/7/96	8/12/97	10/5/95	6/18/96	9/20/96	
Total Recoverable Lead	9.0	35.6	40.0	30.5	4.9	1.0	0.08	14.2	14.8	0.54	6–54
Dissolved Lead	2.3	3.1	7.6	3.0	1.0	0.39	U ^d	2.8	1.6	0.15	—
Total Recoverable Zinc	182	177	140	170	69.7	15.3	10.4	13.1	15.5	2.9	149–243
Dissolved Zinc	78.5	43.9	110	63.9	11.5	11.6	6.4	10.9	U ^d	U ^d	—
Total Recoverable Copper	16.3	30.6	38.0	23	10.2	3.1	2.0	11.4	9.8	5.8	22–55
Dissolved Copper	13.9	4.8	U ^d	8.9	8.6	U ^d	1.96	9.0	5.5	5.3	—
Total Recoverable Cadmium	0.32	NA	NA	NA	NA	NA	NA	0.10	NA	NA	0.4–1.0
Dissolved Cadmium	0.14	NA	NA	NA	NA	NA	NA	<0.6	NA	NA	—

^aClean metals data

^bConventional metals data

^cLow volume highway in Madison, Wisconsin. 1994. Unpublished data.

^dU—Data determined unreliable due to probable contamination in the filtering process.

NA—Analysis not performed

Dissolved metals concentrations in highway runoff sampled using clean techniques exhibited generally lower concentrations when compared to highway runoff sampled using conventional techniques (with the exception of total recoverable zinc at Marne).

The dissolved-to-total recoverable ratios averaged 20 percent for lead, 53 percent for zinc, and 63 percent for copper. As indicated in the table, concentrations of dissolved metals were deemed unreliable for five samples. Dissolved metal concentrations for these five data sets were greater than total recoverable concentrations. After reviewing sampling methods and QA/QC laboratory results, it appears that the most probable reason for the high dissolved concentrations is due to incidental contamination occurring in the filtering process. Although every precaution was taken to reduce the risk of contamination, contamination is still possible, especially at the low concentrations that are present in these samples. This apparent contamination appeared in samples collected both by conventional

and by clean techniques. These data were deemed unreliable and were not used in averaging dissolved-to-total recoverable ratios.

Overall, concentrations of total recoverable and dissolved lead, copper, and zinc in runoff at the Marne site were substantially higher than concentrations of total recoverable metals at the Grand Rapids and Ann Arbor sites. A comparison of rainfall volume, dry days, and traffic volume does not adequately explain the higher concentration of metals found at the Marne site. The likely explanation is that highway runoff at Marne was sampled as direct pavement runoff, whereas highway runoff from the Grand Rapids and Ann Arbor sites passed through a grassed swale before being sampled. Phase II of this report documents the potential metals removal capability of up to 80 percent after passing over grassed swales.

Rainfall Monitoring

Concentrations of metals in rainfall were also analyzed to assess the contribution that rainfall has on metals concentrations in highway runoff (Table 13). Metals concentrations in the rainfall samples in this MDOT study are comparable to the range of median concentrations reported in a FHWA study conducted in the late 1970s to early 1980s, in which median concentrations were less than 20 µg/L for lead, between 30 and 170 µg/L for zinc, and 30 to 40 µg/L for copper, as shown in Table 13 (Kobriger and Geinopolos 1984).

TABLE 13
Metals Concentrations in Rainfall

Metal (µg/L)	Marne			Grand Rapids			Ann Arbor			FHWA ^a
	10/3/95	6/17/96	9/26/96	9/26/96	11/7/96	8/12/97	10/5/95	6/18/96	9/20/96	
Total Recoverable Lead	2.2	2.8	2.2	0.74	2.9	1.7	0.37	0.68	1.1	<20
Dissolved Lead	1.5	2.0	NA	0.54	NA	1.0	0.35	0.31	0.88	—
Total Recoverable Zinc	160	33.6	278	37.5	503 ^c	163	9.8	13.2	23.5	30–170
Dissolved Zinc	38.2	^b	NA	27.1	NA	152	^b	^b	^b	—
Total Recoverable Copper	30.5	13.6	16.2	44.1	3.1	5.65	22.3	1.8	1.1	30–40
Dissolved Copper	11.7	10.0	NA	32.6	NA	2.23	19.6	1.7	^b	—

^aKobriger and Geinopolos 1984. Range of median values for four sites.

^bData determined to be unreliable due to probable contamination in the filtering process.

^cData determined to be unreliable—more than two standard deviations above the mean.

NA—Insufficient volume captured for both dissolved and total recoverable analysis. Total recoverable analysis only was performed.

As occurred with the runoff samples, some datasets (5 out of 21) exhibited higher dissolved concentrations than total recoverable concentrations. These data are, therefore, unreliable. The majority of unreliable datasets (4 of 5) were associated with dissolved zinc analytical data. Zinc analyses at these very low-level trace concentrations are often subject to contamination problems due to the numerous sources of zinc in the environment and in laboratory equipment. In addition, the total recoverable zinc sample for the Grand Rapids site on November 7, 1996 was more than two standard deviations above the mean and, therefore, was judged unreliable.

Overall, the dissolved-to-total recoverable ratios were higher in the rainfall samples than in the highway runoff samples. The dissolved fraction in rainfall was about 70 percent of total

lead and total copper and 63 percent of total zinc. This indicates that a majority of the metal is in the dissolved state in rainfall. The ratios of dissolved to total metal in highway runoff indicated most metals were recorded as total metal (i.e., associated with particulates).

Relationship Between Highway Runoff and Rainfall Concentrations

Concentrations of total recoverable and dissolved metals in both highway runoff and rainfall for the three sites were compared to identify any relationships between rainfall and runoff concentrations. Figures 1 through 3 present the mean concentrations of the metals in runoff and the mean concentrations in rainfall for each site, using metals data presented in Tables 12 and 13. The high total recoverable zinc value reported for the November 7, 1996 rainfall event at Grand Rapids was not used to develop the figure because it was deemed unreliable (see Table 13).

Concentrations of lead, copper, and zinc in rainfall were lower than concentrations in runoff for all three total recoverable metals (lead, copper, and zinc) and two of three dissolved metals (lead and zinc) at the Marne site. However, at the Grand Rapids and Ann Arbor sites (where highway runoff is filtered through a grassed swale before being collected), rainfall concentrations exceeded highway runoff concentrations more often. This is presumably because the swales remove metals (see Phase II discussions later in this report).

At the Grand Rapids site, rainfall concentrations (both total recoverable and dissolved) exceeded highway runoff concentrations for copper and zinc. However, lead concentrations (both total recoverable and dissolved) in rainfall were not significantly different than highway runoff concentrations at this site. The average total lead concentration in runoff also was much lower at Grand Rapids than the other two sites, including the Ann Arbor site at which runoff also passed through a swale before sampling. One possible explanation is more effective particulate lead removal in the grassy drainage system at Grand Rapids prior to sampling and discharge to Mill Creek.

At the Ann Arbor site, concentrations of lead in rainfall were substantially less than concentrations in runoff. Total recoverable lead was over 10 times greater in highway runoff than rainfall; dissolved lead concentrations in runoff were about 2 times greater than in rainfall at the Ann Arbor site. Concentrations of copper and zinc (total recoverable and dissolved) concentrations in runoff were similar to concentrations in rainfall.

For direct pavement runoff at the Marne site, where runoff does not pass through a grassed swale, mean rainfall concentrations for total recoverable metals were 41 percent of mean highway runoff concentrations and 83 percent for dissolved metals. This is strong evidence that a substantial amount of metals originate in rainfall rather than being mobilized from highway surfaces. The calculations for these fractions for the Marne site are shown below:

- Total recoverable metals (mean rainfall/mean runoff ratios):

Lead:	2.4/25	=	0.10
Zinc:	68/176	=	0.39
Copper:	17.6/23	=	0.76
Mean of ratios		=	0.41
- Dissolved metals (mean rainfall/mean runoff ratios):

Lead:	1.75/3.0	=	0.58
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Zinc:	44/62	=	0.71
Copper:	10.9/9	=	1.20
Mean of ratios		=	0.83

There are two conclusions that can be drawn from the rainfall-to-runoff concentration comparisons: (1) rainfall provided a substantial source of dissolved and total metals concentrations in runoff during this study period, and (2) the grassed swales at the Grand Rapids and Ann Arbor sites appeared to effectively reduce dissolved and total metals concentrations in runoff, often to concentrations below or at those found in rainfall.

Comparison to Water Quality Criteria

The effect that highway runoff has on the water quality and ecological health of the receiving streams for the Marne, Grand Rapids, and Ann Arbor sites (West Branch Sand, Mill, and Fleming creeks, respectively) can be partially assessed by comparing the concentrations of metals in the highway runoff with Michigan water quality criteria. The maximum dissolved and total recoverable metals concentrations in runoff from the three sites were all less than the appropriate final acute water quality values (Tables 14 and 15).

TABLE 14
Michigan Acute Water Quality Criteria and Part B Highway runoff Monitoring Results at Marne and Grand Rapids

Metal (µg/L)	Final Acute Water Quality Value (µg/L) ^a		Marne Maximum Runoff Concentration (µg/L)		Grand Rapids Maximum Runoff Concentration (µg/L)	
	Total Recoverable	Dissolved	Total Recoverable	Dissolved	Total Recoverable	Dissolved
Copper	55	37	38	14	10	8.6
Lead	1,188	264	40	7.6	4.9	1.0
Zinc	655	312	182	110	70	12

^aCriteria calculated based on hardness of 140 mg/L, which is representative of the Marne and Grand Rapids sites. Criteria listed in R 323.1057 of Michigan Administrative Code, July 1997. Total recoverable criteria developed using translators provided in R323.1057, where available.

TABLE 15
Michigan Acute Water Quality Criteria and Part B Highway runoff Monitoring Results at Ann Arbor

Metal (µg/L)	Final Acute Water Quality Value (µg/L) ^a		Ann Arbor Maximum Runoff Concentration (µg/L)	
	Total Recoverable	Dissolved	Total Recoverable	Dissolved
Copper	77	52	11	9
Lead	1,739	387	15	2.8
Zinc	885	422	16	11

^aCriteria calculated based on hardness of 200 mg/L, which is representative of the surface waters at the Ann Arbor site. Criteria listed in R 323.1057 of Michigan Administrative Code, July 1997. All criteria expressed as total recoverable, using translators provided in R323.1057, where available.

Likewise, the mean dissolved and total recoverable metals concentrations in runoff from the Ann Arbor and Grand Rapids sites were less than the final chronic water quality values. At the Marne site, only 2 of 18 samples exceeded the instream final chronic values (Tables 16

and 17). As noted previously, highway runoff from the Marne site was sampled as direct pavement runoff whereas highway runoff from the Ann Arbor and Grand Rapids sites was sampled after the pavement runoff passed through a grassed swale.

TABLE 16
Michigan Chronic Water Quality Criteria and Part B Highway runoff Monitoring Results at Marne and Grand Rapids

Metal (µg/L)	Final Chronic Water Quality Value (µg/L) ^a		Marne Mean Runoff Concentration (µg/L)		Grand Rapids Mean Runoff Concentration (µg/L)	
	Total Recoverable	Dissolved	Total Recoverable	Dissolved	Total Recoverable	Dissolved
Copper	18	12	23	9	5.1	5.3
Lead	67	15	25	3	2.0	0.7
Zinc	330	157	176	62	32	10

^aCriteria calculated based on hardness of 140 mg/L, which is representative of the Marne and Grand Rapids sites. Criteria listed in R 323.1057 of Michigan Administrative Code, July 1997. Total recoverable criteria developed using translators provided in R323.1057, where available.

TABLE 17
Michigan Chronic Water Quality Criteria and Part B Highway runoff Monitoring Results at Ann Arbor

Metal (µg/L)	Final Chronic Water Quality Value (µg/L) ^a		Ann Arbor Mean Runoff Concentration (µg/L)	
	Total Recoverable	Dissolved	Total Recoverable	Dissolved
Copper	24	16	9	6.6
Lead	98	22	9.8	1.5
Zinc	446	213	11	11

^aCriteria calculated based on hardness of 200 mg/L, which is representative of the surface waters at the Ann Arbor site. Criteria listed in R 323.1057 of Michigan Administrative Code, July 1997. All criteria expressed as total recoverable, using translators provided in R323.1057, where available.

Overall Water Quality Conclusions from Part B Analyses

Despite the very favorable results of comparing the runoff with in-stream chronic criteria, it should be noted that actual results would be even more favorable because dilution in the receiving stream and other mitigating factors have not been considered in the analysis. Overall, this comparison demonstrates that:

- Metals concentrations were all lower than in-stream criteria designed to protect aquatic life from acute toxicity, and all but a few of the samples (i.e., several at the Marne site) were lower than in-stream criteria designed to protect aquatic life from chronic toxicity. When dilution and other mitigating factors are considered, it is probable that in-stream concentrations will be well below levels of concern at these sites.
- A substantial fraction of metals concentrations found in runoff originate in rainfall; specifically, on average, 41 percent of total recoverable metals in runoff originate in rainfall while 83 percent of the dissolved metals in runoff originate in rainfall (based on data from the Marne site where runoff concentrations were measured as pavement runoff, without being biased by passing through grassed swales before sampling).

- These results demonstrate that metals originating from the road surface alone are not likely to pose a major threat to water quality in receiving waters.

Evaluation of Fate and Effects of Metals via Soil and Sediment Sampling

Right-of-way soil and receiving water sediment samples were taken at each Part B site to characterize the spatial distribution and the sinks of metals. Soil samples were taken 90 to 150 feet from the highway. Sediment samples were taken upstream of the highway at each site to define background conditions, and at 2 locations downstream to evaluate potential metals accumulations. Table 18 summarizes the range of concentrations in soil and sediment at the three MDOT sites along with appropriate criteria and background data for sediment and soil. Both the commercial and residential Michigan DEQ soil cleanup criteria are listed in Table 18. However, the commercial criteria are more applicable to a highway right-of-way than the residential criteria because of the much different exposure patterns in a right-of-way compared to a residential neighborhood.

Tables and graphs of the sampling results are presented in Appendix E. Maps of the sampling locations are provided in Appendix C.

TABLE 18
Soil and Sediment Sampling Results (mg/kg dry weight)

Metal	Concentration range in soil at MDOT sites	Concentration range in sediment at MDOT sites	Michigan DEQ Soil Cleanup Criteria ^a		Sediment Effects Concentration ^b		Sediment Background Concentration ^e
			Commercial	Residential	ER-L ^c	ER-M ^d	
Cadmium	ND	ND	7,400	210	1.2	9.6	NA
Chromium	3.2–73	1.3–13	71,000	2,000	81	370	2.9
Copper	2.6–23	1.2–16	560,000	16,000	34	270	3.0
Zinc	13–480	5.9–41	1,000,000	140,000	150	410	16
Lead	6.1–220 ^f	7.0–9.4	400 ^g	400 ^g	46.7	218	4.2

ND=not detected

NA=not available

^aMichigan DEQ soil criteria (Natural Resources and Environmental Protection Act, 1994 PA 451, as amended)

^bIncidence of adverse biological effects guidelines, Long, et al, 1995.

^cER-L represents a minimum effects range; for sediment concentrations below this level, adverse effects would be rarely observed.

^dER-M represents a probable effects range; effects would frequently occur for concentrations above this level.

^eMichigan DEQ Report No. MI/DNR/SWQ-94/055 by Roger Jones, documenting background sediment concentrations in minimally impacted streams and rivers; values listed are for the Southern Michigan Northern Indiana Till Plains ecoregion.

^fA value of 610 µg/L that was observed at Station S07 at the Marne site was considered unreliable because it was more than two standard deviations above the mean.

^gThe Michigan DEQ cleanup criterion of 400 µg/L for commercial and residential land uses is considered a conservative number. It is based on biokinetic uptake for children. Higher site-specific criteria can be used if the land use does not reflect the assumptions used in developing this value. A higher lead criterion would be appropriate for land uses that have no or very low probability of exposure to children, such as a highway right-of-way.

I-96 and West Branch Sand Creek (Marne). Metals concentrations in soils near I-96 were well below, and in many cases an order-of-magnitude less than, the Michigan DEQ soil cleanup criteria for both commercial and the more conservative residential land uses. Metals concentrations in right-of-way surface soils (0–4”) alongside I-96 and in the median were consistently greater than background (soils 90 feet or greater from I-96) and subsurface soils (0–12”). In general, metals concentrations in right-of-way soil were comparable for the median strip and alongside I-96.

The site map in Appendix C demonstrates that, although highway runoff from the westbound lanes of I-96 discharges directly to West Branch Sand Creek (where the runoff sampling was conducted), highway runoff generated from the onramp at 16th Street travels down a grassed swale until it discharges to West Branch Sand Creek. Soil samples taken along the drainage pathway from the onramp to the creek indicate a pattern of increasing and then decreasing metals concentrations to near background levels. This confirms what was found in the runoff sampling—that grassed swales effectively remove metals from runoff. This metals removal pattern is corroborated by other studies (Newbry and Younge 1996; Dorman, et al. 1996) and indicates that the swale is effectively removing metals from highway runoff.

Stream sediment downstream of the highway runoff outfall had greater metals concentrations than sediment upstream of the outfall. This pattern has been well documented. Downstream metals concentrations were similar to the low levels observed by on a low-volume highway (Van Hassel 1980) and were below the concentrations observed on a medium-volume highway (Mudre 1985). Regardless, sediment concentrations above and below the highway runoff outfall contained levels of metals that were less than the “minimum effects range” documented in literature (Long, et al. 1995) and were on the same order of magnitude as the un-impacted background concentrations in a recent Michigan study (Jones 1994).

M-37 and Mill Creek (Grand Rapids). Soils at M-37 were sampled at three locations: in the median strip, along the path of highway runoff flow in an adjacent swale, and roughly 150 feet from the highway. All soil samples contained metals concentrations below the Michigan DEQ cleanup criteria listed in Table 18. All subsurface and median strip samples were below or at background with the exception of sample S02 0–4”. Swale concentrations showed a similar pattern to the West Branch Sand Creek site, with metals levels decreasing from the highway runoff outlet to the discharge point at Mill Creek. Also, similar to the West Branch Sand Creek site, sediment samples below the highway runoff outfall were greater than above the outfall. Sediment concentrations were also below the “minimal effects range” defined in literature (Long et al. 1995) and were on the same order of magnitude as unimpacted background concentrations in a recent Michigan study (Jones 1994).

M-14 and Fleming Creek (Ann Arbor). Metals concentrations in soils at all locations were below the Michigan DEQ cleanup criteria listed in Table 18. Soils in the median strip, except for location S01 0–4”, did not contain metals levels significantly higher than background. Chromium in the swale soil sample was above background. In contrast to the Mill Creek and West Branch Sand Creek sites, sediment below the highway runoff outfall did not exhibit higher metals levels. Upstream and downstream metals concentrations were well below “minimal effects range” (Long et al. 1995) and were of the same order of magnitude

as the unimpacted background concentrations documented in a recent Michigan study (Jones 1994).

Overall Conclusions from Sediment and Soil Analyses

Several specific conclusions from sediment and soils analyses are:

- Right-of-way soils and in-stream sediments are not major ongoing contributing sources of metals, but are likely to represent a sink for these and other particulate pollutants.
- Metals concentrations in soils were below applicable State clean-up criteria.
- Metals concentrations in stream bottom sediments upstream and downstream of the highways were below minimum sediment effect ranges and comparable to unaffected background concentrations in Michigan.
- Soils data collected in this study are consistent with the findings of previous studies. An FHWA study found that metals concentrations were highest in topsoil layers compared to subsurface layers (Kobriger and Geinopolos 1984). Concentrations of copper, zinc, and chromium in soils in the FHWA report were comparable to concentrations in soils found in this study. Lead concentrations in soils, however, were much lower in this MDOT study compared to the FHWA study. This is likely due to the discontinuation of leaded gasoline in automobiles since the FHWA study in the early 1980s.

Phase II: Literature Search for Mitigation Measures to Control Metals in Highway Runoff

Phase II of the study provided a three-part review of highway runoff treatment technologies. The first part of this section contains a summary of a survey that solicited information on the highway runoff mitigation practices carried out by other state transportation agencies, the second contains a review of highway runoff best management practices (BMPs) for the treatment of heavy metals, and the third contains a discussion of the applicability of industrial treatment technologies for the removal of metals in highway runoff.

State Department of Transportation Survey

A questionnaire was sent to all departments of transportation (DOTs) to gather data on BMP usage, field tested BMP performance, BMP construction costs, and state permitting requirements. Survey responses revealed a wide breadth of BMP usage and a highly variable regulatory environment. Texas was the only state that provided field performance data; these data are reviewed below in the section entitled “Best Management Practices for Highway Stormwater Control.” Phone calls to state DOTs were made to clear up inconsistencies in the responses and to gain a better understanding of their permitting and control requirements for highway runoff.

BMPs and Metals Removal

Only four state transportation agencies (Colorado, Oregon, Washington, Texas) have used or would consider the use of a BMP specifically to treat metals in highway runoff. In general, stormwater BMPs have been used to control sediment at highway construction sites; only under special site-specific conditions have BMPs been used to treat metals. For example, Colorado DOT used detention ponds and pH adjustment to remove metals at a construction site near an old mining town. Multiple sand filters have been installed in Austin, Texas, to protect the Edwards aquifer recharge zone. Oregon and Washington are committed to the implementation of BMPs if the water quality of the receiving water would be impaired by the uncontrolled discharge of highway runoff. It is unknown, however, if Oregon or Washington have used water quality BMPs specifically to treat metals, or if BMPs have been retrofitted to existing outfalls. Based upon the results of this survey, it appears likely that very few, if any, state transportation agencies have retrofitted outfalls with BMPs for the exclusive treatment of metals. A summary of the survey responses is provided in Appendix F.

BMP Cost and Use Ranking

State transportation agencies were also asked to provide a list, a ranking, and the construction costs of BMPs used in their state. Most state DOTs were unable to provide

much information on BMP construction costs because of variable site conditions. However, BMP building costs provided by three states are as follows:

Delaware	Delaware Sand Filter	\$400 per linear foot
	Grass Swale	\$12 per linear foot
	Pond Excavation	\$10 per cubic yard \$6,000 per outlet structure
Nevada	Water Quality Vault	\$50,000 per vault
South Carolina	Enclosed Bridge Scupper Storage/ Pump out System	\$1.5 million

State DOTs have made use of the entire range of available stormwater BMPs. For some states, such as Massachusetts and New York, stormwater BMPs that provide infiltration are preferred. Delaware prefers to use BMPs in the following order: wet detention ponds, dry detention ponds, infiltration, sand filters, grass swales, and bioretention (modified vegetative filtration and infiltration system). State transportation agencies also noted that their choice of BMP was influenced by such site-specific factors as height of the water table, right-of-way space, land costs, level of required treatment, and sensitivity of the receiving water body.

Regulatory Climate

Many state highway agencies have not been required to complete a municipal stormwater NPDES permit application, nor have they been required to monitor highway runoff in cities with a population over 100,000. State highways within cities with combined sewer systems are exempt from the municipal stormwater permitting requirement. This is the case in many Eastern states such as Connecticut. Other state environmental agencies are underfunded and do not have the resources to devote to stormwater permitting (Kansas) or have simply decided that state DOTs do not need to apply for municipal stormwater NPDES permits (e.g., Missouri, Iowa, Indiana, North Carolina).

In only select cases, BMPs have been required or needed for purposes other than construction. For example, an enclosed scupper system was installed on a bridge from Charleston, South Carolina, to the Isle of Palms to control and treat runoff from the bridge deck surface because of potential environmental impacts of the runoff. Sand filters in Austin, Texas, and a wet pond in Louisiana were used to protect groundwater and a drinking water reservoir.

State environmental agencies have also established memorandums of understanding or stormwater management guidelines to clarify the required level of treatment for stormwater discharges. According to those documents, states such as New York, Wisconsin, and Maryland are primarily concerned with controlling peak discharges, sediment, erosion, and, occasionally, thermal discharges from highway construction sites. Draft performance standards for new stormwater discharges in Massachusetts require water quantity or additional water quality controls if discharging to an environmentally sensitive area. For example, the draft memorandum of understanding for construction sites in Maine addresses stormwater quality control issues for discharges to sensitive or impaired waters, and has defined the required level of suspended sediment control according to sensitivity of the receiving water. In general, states regulate highway runoff

from construction sites or for newly constructed stormwater outfalls and, in most cases, treatment is required only for sediment and erosion control.

Best Management Practices for Highway Runoff Control

BMPs have come into common use as an effective measure to improve the quality of urban stormwater discharges. One of the most well known and widely used BMP design and planning guidance was developed by Thomas Schueler (Schueler 1987). This, and subsequent guidance by Schueler (Schueler 1992), provide extensive data on design, maintenance, cost, and pollutant removal efficiency of available BMPs.

Much of Schueler's data are timely and relevant to highway runoff quality control in Michigan. Recent research by research institutes and highway agencies in Europe and the United States have added to the body of BMP design knowledge, with much of it specifically addressing highway runoff. This research has offered a better understanding of BMP design, secondary environmental impacts of stormwater BMPs, and the chemistry of metals mitigation with emphasis on dissolved metals. This subsection provides an overview of stormwater BMPs that may be used to treat highway runoff, and a brief review of state-of-the-art BMP design parameters for optimal water quality improvement.

Treatment Requirements

Given metals concentrations in the runoff and the water quality criteria, one can determine which metals require treatment, and which technologies that might be applicable. Assuming, conservatively, that the effluent must meet Michigan water quality criteria final acute values without benefit of dilution (as listed in Tables 6 and 7) treatment could be required only for copper.

Grassed Swales

Grassed swales are grass-lined channels, ditches, or median strips designed to convey and treat stormwater. Swales remove metals by filtering sediment, infiltrating stormwater, and by slowing down stormwater to allow partitioning of metals onto grasses and sediment. Grassed swales are a logical choice for the treatment of highway runoff in Michigan given the availability of grassy areas along highways, and the secondary benefits of swales such as the provision of wildlife habitat.

BMP Feasibility and Applicability for Highway Runoff

Grassed swales are an appropriate water quality BMP for the Michigan DOT. Experimental research indicates that low slopes, permeable (non-clay) soils, and dense grass cover enhance metals removal by swales. In general, the climate, soils, and topography of Michigan are conducive to high metals removal. Grassed swales are ideally suited for the treatment of runoff for Michigan's suburban or rural highways but may be too land-intensive for highly urbanized areas. Nevertheless, grassed swales are an appropriate BMP given that Michigan's highways predominantly reside in rural or suburban areas. Use of grassed swales as a water quality BMP has the following benefits:

- **Costs:** Swales are the least costly water quality BMP, construction costs range from \$5 to \$15 per linear foot.
- **Maintenance:** Swales require little maintenance—only mowing and occasional sediment removal.
- **Longevity:** In contrast to other BMPs, swales can provide long-term highway runoff treatment.
- **Secondary Environmental Benefits:** Swales can provide recharge to groundwater by infiltrating highway runoff; wildlife habitat can be created or preserved.
- **Retrofit Capacity:** Existing median strips and highway ditches can be adapted for use as grassed swales.

Metals Removal

Grassed swales have been shown effectively to remove metals from highway runoff in climates similar to Michigan. Highway runoff and soils monitoring data obtained in Phase I, Part B support the conclusion that grassed median strips and channels that convey runoff from Michigan's highways are effectively removing metals. Although the longevity of metals removal by grassed swales is not well documented, a recent study found lower metals concentrations in grassed swale soil than would be expected for the swale's age of service, leading the investigators to speculate that metals removed during a storm event are eventually flushed downstream rather than accumulating in the swale (Dorman et al. 1996). This phenomenon was not observed in the Phase I, Part B sampling of this study. Metals concentrations in right-of-way soils at the three Part B sites were not substantially different from each other.

The amount of metals removal by grassed swales varies (Table 19), but the variability can be attributed to such factors as climate, contributing watershed area, swale slope and width, maintenance, soil permeability, and highway runoff chemistry. Only the metals copper, zinc, and lead, which are the metals sampled in Phase I of this study, are summarized in Table 19. A few general conclusions can be made concerning the experimental results presented in Table 19:

- Low slope, dense vegetative cover, and check dams enhance metals removal by increasing the residence time of highway runoff in the swale.
- Total and dissolved metals removal is assisted by high rates of infiltration and greater swale length.
- Check dams and enhanced infiltration can be used to overcome the design disadvantage of a high sloped swale.

BMP Design

General Design Considerations.

1. Establish swale vegetation on soil with an adequate infiltration capacity, replace impermeable (clay) soils if needed with a soil mixture consisting of sandy loam, clay, and organic matter. Avoid soil compaction during construction.

TABLE 19
Metals Removal Efficiency of Grassed Swales

Location	Percent Removal			Reference	Comments	Swale Characteristics
	Lead	Zinc	Copper			
Seattle	80	70	60	Wang et al. 1981	Metals removed in particulate form	---
New Hampshire	65	51	48	Oakland 1983	Metals removed in dissolved form (pH = 4)	---
Florida	99	—	—	Kercher 1983	—	—
Florida	91/50	90/82	41/19	Yousef et al. 1985	First number: total metals; second number: dissolved metals	Slope <1%, Residence time: 30-60 minutes, Infiltration rate: 0.6-1.4 in/hr
Virginia	41-55	49	28	Dorman et al. 1989, 1996	Good vegetative cover enhanced metals removal	High slope 4.7%, Length 185 ft
Maryland	18-92	47	14	Dorman et al. 1989, 1996	Poor vegetation affected removal rates	Moderate slope 3.2%, Length 193 ft, Severe erosion
Florida	67-94	81	62-67	Dorman et al. 1989, 1996	Low slope, sandy soils, and dense cover enhanced metals removal	Low slope 1%, Length 185 ft
Washington	>67/—	63/30	46/-7	Municipality of Metropolitan Seattle Publication 657	First number: total metals; second number: dissolved metals	Length 187 ft
Washington	15/0	16/4	2/1	Municipality of Metropolitan Seattle Publication 657	First number: total metals; second number: dissolved metals	Length 90 ft
Enclosed Laboratory	93	84	>99	Newbry and Younge 1996	Grassed swale model, swale characteristics optimized	Swale width 1.2 m, Swale length 3 m, Artificially low flow rate used in experiment
Virginia	—	83.8	—	Kaighn 1996	—	Slope 5%, Check dam used in swale
Virginia	—	17.8	—	Kaighn 1996	—	Slope 2%, No check dam in swale

2. To avoid siltation and impeded vegetation growth, do not discharge construction site runoff through the newly constructed swale (Schueler 1987).
3. To reduce the possibility of channel erosion, swales should be designed with peak flows that do not exceed 5 cfs and velocities no greater than 5 feet per second (fps) (Schueler

1992). A study by the Washington Department of Ecology (1992) suggests that the water quality function of a swale will be maintained if the maximum velocity does not exceed 0.9 fps.

4. Periodic mowing should be performed to promote the growth of dense grass.
5. Design guidance suggests that swale lengths should be 200 feet but no shorter than 100 feet. Shorter lengths should be compensated by greater width, but the width should not exceed 10 feet.
6. Swales are typically designed as trapezoids with side slopes of 3:1 or less. Longitudinal slopes should range from 1 to 5 percent.
7. Use rip-rap for energy dissipation at the swale inlet.

Design Recommendations. Volume 3, Chapter 4 of the *Michigan Design Manual for Road Design* outlines the incorporation of vegetative controls “wherever practicable” for drainage purposes regardless of the need to mitigate a specific highway runoff contaminant problem. The following recommendations derived from a study entitled “Biofiltration Swale Performance, Recommendations, and Design Considerations” (Municipality of Metropolitan Seattle 1992) can be used to augment the design parameters provided by the *Michigan Design Manual*:

1. Determine anticipated swale peak flow rate for a 6-month, 24-hour storm event. If the flow is greater than 5 cfs, consider splitting it between two swales.
2. Use Manning’s equation (as modified below) to calculate the approximate width of the swale channel:

$$\begin{aligned} \text{Trapezoidal Swale: Bottom Width} &= ([Qn] / [1.49y^{1.67} s^{0.5}]) - zy \\ \text{Top Width} &= b + 2yz \end{aligned}$$

$$\text{Parabolic Swale: Top Width} = (Qn) / (0.76y^{1.67} S^{0.5})$$

Where:

- Q = swale peak flow rate (cfs)
- n = Manning’s n (n=0.20 if swale mowed regularly, 0.24 if mowed on occasion)
- y = depth of flow (typically set at 0.33 ft)
- s = longitudinal slope of channel (ft/ft, should be between 0.01 to 0.05)
- z = channel side slope (typically 3:1)

3. Calculate swale flow velocity (fps) from channel dimensions:

$$\text{Velocity} = \text{Flow} / \text{Area}$$

If the velocity exceeds 0.9 fps, either investigate ways to reduce flow, or widen or deepen the channel until the velocity is below 0.9 fps.

4. Calculate swale length (ft):

$$\text{Length} = Vt$$

Where:

- V = swale flow velocity (fps)
t = hydraulic residence time (seconds)

To promote pollutant removal by the swale, the hydraulic residence time should be set at 9 minutes. Greater metals removal is generally achieved with longer swales. If the computed swale length is less than 100 feet, increase it to the minimum length of 100 feet.

The suggested design parameters for flow depth, swale length, and residence time are based upon empirical studies. They can be changed with the understanding that maximum pollutant removal is achieved if residence time and swale length are maximized and flow depth is minimized.

Infiltration and Filtration Devices

Infiltration Trenches

Infiltration trenches are excavated stone-filled trenches that collect and infiltrate runoff from impervious surfaces such as parking lots and roads. The environmental benefits of infiltration trenches include groundwater recharge and attenuation of impervious surface discharges to receiving waters. Infiltration trenches are best suited for small contributing areas (<5 acres). Use of multiple trenches to capture larger areas may not be cost-effective.

BMP Feasibility and Applicability for Highway Runoff. Because of their ability to infiltrate or attenuate runoff, infiltration trenches may be most useful where highways cross receiving waters and where space is limited. However, siting a trench is often difficult. The subsurface soils must be relatively permeable, and the water table must be at least 4 feet below the bottom of the trench. The tendency of trenches to clog with sediment and oil requires that a water quality inlet or grassed buffer strip be placed at the trench inlet. Maintenance requirements are low, but trenches have a tendency to clog and may need to be excavated or replaced to restore function. The functional lifespan of a infiltration trench is usually less than 5 years.

Metals Removal. Metals removal data for infiltration trenches is limited but estimates range from 75 to 90 percent. These removal rates are based upon studies performed in northern Virginia and may prove far lower in Michigan's colder climate.

BMP Design Considerations. There are three types of infiltration trenches: complete exfiltration, partial exfiltration, and water quality exfiltration. The complete exfiltration system relies on the complete infiltration of stormwater to the underlying soils and eventually to groundwater. The partial exfiltration system contains a perforated underdrain to collect and discharge stormwater after it has filtered through the trench. Finally, the water quality exfiltration system is designed to capture only the first flush of stormwater. The following general trench design guidelines are adapted from Schueler 1987, Younge et al. 1996, and the Maryland Department of Natural Resources, 1994.

1. **Drainage:** Soils at the proposed installation site should have a minimum infiltration rate of 0.27 inch/hour. The water table should be 4 feet below the bottom of the trench. The trench should drain completely in 2 to 3 days.
2. **Inlet:** The trench should be protected from sediment accumulation with a grassed buffer or water quality inlet.

3. **Overflow Berm:** A 2- to 3-inch overflow berm should be installed on the downstream side of the trench to detain surface water and allow infiltration.
4. **Trench Dimensions:** Trench volume should be great enough to capture the first flush volume of runoff (0.5 inch) over an impervious watershed area of no greater than 5 acres. Trench dimensions can be calculated using the formula:

$$H_{t_{max}} = Et_{max} / (1,000P)$$

$$H_{t_{min}} = Et_{min} / (1,000P)$$

Where:

$H_{t_{max}}, H_{t_{min}}$	=	Maximum and minimum trench depths (m)
E	=	Exfiltration rate in length per unit time (mm/h)
t_{max}, t_{min}	=	Maximum and minimum target drain-time (h)
P	=	Pore volume ratio of stone aggregate (percent porosity/100)
V	=	Fluid storage volume requirement (m ³)
A	=	Trench bottom surface area (m ²)

Infiltration Basins

Infiltration basins are similar to infiltration trenches in that they are designed to infiltrate stormwater to the subsurface soil or to a perforated underdrain, but basins are larger and can treat a larger drainage area (5 to 50 acres). Infiltration basins consist of a contained flat area with a surface layer of sand covering the existing subsurface soil.

The major benefits of infiltration basins are groundwater recharge and high metals removal (65 to 99 percent). However, they are prone to clogging, and their functional lifespan is short (Schueler 1987; Washington Department of Ecology 1993; Younge et al. 1996). To prevent clogging, design guidance often recommends some sort of pretreatment at the inlet such as a grass buffer strip. This conflicts with a review of basin performance by the Washington Department of Ecology, which concluded that soil permeability rather than pretreatment was responsible for the proper functioning of infiltration basins in the Puget Sound region. Because of the low success rate and potentially high cost, infiltration basins are not a feasible BMP for the Michigan DOT.

Porous Pavement

Porous pavement is a specialized asphalt designed to allow infiltration. It is typically applied over an excavated trench filled with gravel, much like a partial infiltration trench. Cahill Associates have successfully installed porous pavement in parking lots but cautions that porous pavement may not be appropriate for intensively traveled areas (Cahill 1994). In contrast, John Sansalone of the University of Cincinnati (1995) cites European research that shows porous pavement could be located along highway shoulders to treat runoff.

High metals removal rates (98 to 99 percent) and groundwater recharge make porous pavement an attractive stormwater BMP. However, porous pavement may be inappropriate for Michigan highways for the following reasons:

- Extensive planning and site selection work (geotechnical investigations, permitting) is costly.

- There is a lack of construction cost data.
- There is a high risk of clogging due to high traffic volume, sand application, and snow removal.
- Specialized maintenance practices (vacuum cleaning) are required.

Additional research must be conducted before porous pavement can be used on Michigan's highways.

Sand Filters

Unlike the other filtration systems, sand filters are contained systems that do not infiltrate to the underlying subsurface soils but discharge to a receiving water. Most sand filters consist of three units: a sedimentation chamber, a filtration chamber, and a surface discharge pipe. Sand filters have been used mainly because of their ability to function in arid climates and fit in the limited space of the highway right-of-way.

Sand filters have been primarily implemented in warm southern climates such as Delaware, Maryland, and Texas. Hence, it is unknown whether they can function properly in Michigan. However, sand filters tested in warmer climates have shown generally high metals removal, varying by sand filter design. Horizontal sand filters built in Austin, Texas, have demonstrated metals removal of 19 to 86 percent, while vertical sand filters used by the Texas DOT have shown less promising rates with negative to 65 percent removal (Barrett et al. 1995). Sand filters designed for underground installation have demonstrated similar metals removal rates to the horizontal filters but have the added advantage of minimal space requirements. Sand filters are more expensive than other BMPs. Construction costs per impervious hectare range from \$8,400 to \$37,500 for above ground filters and \$25,000 to \$58,000 for underground filters.

Pond Systems

A pond system includes an inlet, water pool, and outlet or multiple configurations of these. One or more inlets enter the pond system and convey the runoff from the pond watershed to the water pool. The water pool, depending upon design and BMP purpose, may be either permanent or empty during dry weather. Outlets are designed to control the retention time and peak flows leaving the pond. Many different pond systems are possible by varying the inlet, water pool, and outlet designs to produce pond configurations for various regulatory and BMP water quality purposes. Pond systems can be combined with other BMP designs such as wetlands, infiltration ponds, and grassed swales.

Pond systems remove metals primarily through sedimentation of particulates. Moderate to high metals removal rates are typical for pond systems. Moderate dissolved metals removal has been achieved in pond systems and is typically attributed to adsorption onto sediment particles or vegetation. Pond systems have very good applicability to metals removal, but designs for highway applications will typically be affected (and often limited) by availability of adjacent land and minimum tributary area requirements.

BMP Feasibility and Applicability for Highway Runoff

The Michigan DOT should consider pond systems on a site-specific basis. The land use requirement, which typically ranges from 0.5 to 3.0 percent of the total tributary area (Younge et al. 1996) limits the feasibility of pond systems. Rural and suburban site locations are more feasible for pond systems than highly urbanized sites because of land availability.

For a pond design normally having a dry water pool, minimum tributary area requirements are more flexible than a pond design normally having a wet water pool. However, as the tributary area to a dry pond decreases below 10 acres, the dry pond requires smaller and smaller outlet openings, which are more prone to clogging. Wet ponds function better with a dependable baseflow available from larger tributary areas. The recommended minimum tributary area for a pond normally having a wet water pool is 10 acres (Younge et al. 1996).

Pond systems require regular maintenance. Areas planted with grass must be mowed to prevent the growth of woody vegetation. Outlet structures must be cleared regularly of obstructions. Regular maintenance should note and correct such observable problems as side-slope erosion or debris accumulation. Sediment removal from the pond system necessarily depends upon sediment accumulation rates. Sediment removal typically is necessary every 5 to 10 years, depending upon design and watershed erosion potential. Pond system inspections every 2 to 5 years provide observations on pond system performance and necessity for sediment removal (Dedering and Potter 1995).

Although pond systems can improve water quality, they can also affect water quality adversely, which may affect the feasibility and design of the pond system. Potentially detrimental effects include thermal warming of the downstream channel from release water and low dissolved oxygen levels in release water (Schueler and Galli 1995).

Metals Removal

Pond systems have been shown effectively to remove metals from urban stormwater runoff. Metals removal rates vary according to average retention time of runoff within the pond system, sediment size distribution, inlet design, outlet design, water depth, and other factors. The removal rates for the investigations listed in Table 20 indicate there is a wide variation in metals removal efficiency in pond systems. The rate of removal depends upon the pond storage volume per acre of tributary area, as well as the detention time within the pond system. Generally, a larger volume of pond storage per tributary acre and a longer detention time will result in greater removal efficiencies. The one negative value for zinc removal indicates that BMPs can, on occasion, be a source of pollutants.

Pond Systems BMP Design

Pond systems design should concentrate on enhancing metals removal while considering secondary design issues and potential environmental impacts. Emphasis should be on promoting sediment particle settling within the pond system. Pond design should result in a detention time between 12 to 24 hours. Pond systems should always be designed to include easy access to inspect hydraulic structures, to remove accumulated sediment, and to perform additional regular maintenance activities.

Embankment side slopes should not be greater than 3:1 horizontal to vertical. The use of milder side slopes promotes lower erosion rates, enhances aquatic vegetation growth, and provides greater safety.

TABLE 20
Metals Removal by Pond Systems

Location	Percent Removal			Reference	Comments	Characteristics
	Lead	Zinc	Copper			
Maryland and Virginia	84	57	na	MWCOG 1987	summary of studies on extended detention dry ponds	6- to 12-hour detention time
London Commons, VA test A ^a	39	24	na	MWCOG 1992	dry pond	holds 0.22 inch per acre; area is 11.4 acres
London Commons, VA test B ^a	25	40	na	MWCOG 1992	dry pond	holds 0.22 inch per acre; area is 11.4 acres
Maple Run III, TX ^a	29	(-38)	31	MWCOG 1992	dry pond	holds 0.50 inch per acre; area is 28.0 acres
Kansas ^a	66	65	na	MWCOG 1992	dry pond	holds 3.42 inch per acre; area is 12.3 acres
Seattle, WA ^a	65	66	67	MWCOG 1992	wet pond	area is 0.75 acre
Grace Street, MI ^a	26	na	na	MWCOG 1992	wet pond	VB/VR equals 0.52
Waverly Hills, MI ^a	95	91	57	MWCOG 1992	wet pond	VB/VR equals 7.57
Buckland, CT ^a	18–59	51	38	MWCOG 1992	wet pond	holds 0.40 inch per acre; area is 20.0 acres
SR 204, WA ^a	88	97	90	MWCOG 1992	wet pond	holds 0.60 inch per acre; area is 1.8 acres
Mercer, WA ^a	23	38	51	MWCOG 1992	wet pond	holds 1.72 inch per acre; area is 7.6 acres

^a Data found in *A Current Assessment of Urban Best Management Practices*, Appendix A, prepared for the Metropolitan Washington Council of Governments (MWCOG), 1992.

na = not sampled in this study

VB/VR = volume of basin divided by the runoff volume for the mean storm

Length-to-width ratios of 4:1 or greater should be used to reduce the possibility of short circuiting across the pond, thereby reducing the detention time.

A vegetated buffer between the edge of the pond and adjacent land uses provides functionality by reducing sediment originating from cultivated fields or barren land. A secondary benefit of vegetated buffers is to provide wildlife habitat. Buffers are typically designed to be 25 feet wide (Schueler 1987).

Inlet. The pond inlet should dissipate energy from any water entering the pond with high velocities, without scouring previously settled sediment. Rip-rap, pond forebay, plunge pool, or stilling basin are all appropriate designs for the pond inlet.

A forebay near the pond inlet will enhance settling of particulates that enter the pond. Designing the forebay to contain the anticipated sediment volume for a 10- to 20-year period will enhance removal efficiencies and reduce future maintenance costs. For areas where high rates of sedimentation are expected, sediment should be removed more often than every 5 to 10 years to maintain sediment removal performance. Nationally, about 1 percent of the storage volume associated with a 2-year design storm is lost annually to sediment accumulation (Younge et al. 1996). It is typically several times cheaper to excavate additional sediment storage when building the pond than to excavate sediment at a later date, especially for ponds with permanent wet pools.

The pipe invert entering the pond should be located no higher than 1 foot above the normal water surface to prevent erosion along the slope to the water pool.

Pool. The pool area stores runoff after a rain event. The volume of the pool should be designed to provide a minimum of 12 to 24 hours detention time for the design storm. Some additional metals removal could be achieved with longer detention times. Coordination between the outlet structure hydraulic design and the pool volume is necessary to provide the 12 to 24 hour detention time for the full range of storms having frequencies less than the BMP design storm. Typical design storms include:

- First flush (the first 0.50 to 1.00 inch of runoff)
- Runoff from the mean storm
- 1 to 2 times the runoff from the mean storm

The volume of the pool should be increased accordingly to meet other design or regulatory considerations. For example, if regulations require flood control and release rate requirements for a 100-year storm, the pool volume should be increased accordingly, and the outlet structure hydraulic design should accommodate the release rate requirements of both the BMP design storm and the release rate required by the flood control regulations.

Side slopes down into the pool area should be a maximum of 4:1 horizontal to vertical. A minimum slope of 2 percent is necessary if the bottom of a dry pond is to drain adequately and not develop marshy, saturated conditions. The minimum slope of 2 percent should be maintained on all areas that will be mowed (Schueler 1987).

The pond shape should gradually expand from the inlet toward the outlet. Adding berms that function as baffles will reduce the chance of short circuiting within the pool.

Pond systems designed as dry ponds should have a low flow channel from the inlet to the outlet. The low flow channel should be protected to prevent erosion.

Pond systems designed as wet ponds with a permanent pool should have a minimum depth of 3 feet. Shallow ponds having permanent pool depths less than 3 feet do not trap sediment efficiently. Permanent pool depths greater than 8 feet should be avoided, except for local fish habitat refuges, because sediment removal is not enhanced at depths greater than 8 feet. Depths greater than 8 feet can lead to water quality issues such as thermal stratification that can develop into significant problems (Schueler 1987).

Pond systems designed as wet ponds with a permanent pool should, as a safety precaution, be ringed by a shallow shelf up to 2 feet deep for a 10-foot width before descending into deeper water. The shallow shelf will also promote vegetation growth which serves to protect the shore from erosion (Schueler 1987).

Ponds having dry pools are typically less effective and reliable than ponds with wet pools (Barrett et al. 1993). Problems associated with dry pools include frequent sediment clogging of the outlet, difficulty maintaining mowing operations, and debris accumulation. It is recommended that proper basin slopes be designed to encourage drainage and allow for convenient mowing operations. Including either a small wet pool or a shallow marshy area near the outlet on dry ponds has been promoted as a means to reduce outlet sediment clogging on dry ponds (Schueler 1992). Within the pool area, the depth of water can be varied to promote sediment removal. The water depth could be varied to add an area that function as a marsh to reduce resuspension of sediment.

Outlet. The pond outlet controls the release of water leaving the pond system. A typical pond would include both an emergency spillway and a hydraulic structure. Including an emergency spillway recognizes that floods will occur greater than the design storm used for the basin design and provides passage of extreme flood events to reduce the chance of catastrophic pond failure. The hydraulic structure is often designed using orifices, weirs, or a combination of both. The hydraulics of the outlet are designed to limit water release to a level that provides the required detention time for significant particle settling. To facilitate maintenance work, the pond outlet should be equipped with a valved pipe to draw down a permanent water pool. Designing an adjustable flow outlet will allow alterations to the detention time if detention times must be increased or decreased to improve pond operation. Adjustable outlets are important for wetland management if a wetland is incorporated into the pond design and active management is a planned maintenance activity.

Since outlet structures can often become clogged with debris, they should be designed to prevent clogging. Orifices can be protected from clogging by encompassing them with a hood that prevents floating materials from clogging the orifice opening. An alternative is to have a pipe negatively sloped so that it draws water from 1 or 2 feet below the normal water surface. Such a configuration draws water at a level below the level of floatables.

The outfall and receiving channel leaving the pond should be protected from erosion with rip-rap.

Additional Considerations. Depending upon the quality of the receiving stream, the outlet design may have to consider the effect of water quality leaving the pond system. As water flows through a pond system, the water temperature can increase more than 10 degrees Fahrenheit in summer (Schueler and Galli 1995). For receiving streams with high water

quality, especially those containing species adversely affected by temperature increases, the outlet design may have to be altered to release deeper, cooler water from the pond.

Dissolved oxygen levels in water leaving the pond can also be a problem if the water is withdrawn from deeper levels of the pond. Where there is concern over dissolved oxygen levels, the hydraulic structure and outfall should be designed to maximize the re-aeration while the water falls through the outlet structure.

Wetland Systems

BMP Feasibility and Applicability for Highway Runoff

Wetland systems are a type of wet pond system having a permanent pool and established wetland vegetation. Wetland systems remove metals in the particulate form primarily through settlement. Plant uptake of soluble metals is also an important removal mechanism along with groundwater infiltration if the pond is in a recharge area (Reinelt and Horner 1993). Wetland systems can be constructed or naturally occurring.

Metals Removal

Wetland systems have been shown effectively to remove metals from highway runoff, but they may not perform acceptably in the winter. Reported removal efficiencies average 80 percent for lead and 53 percent for zinc (Barrett et al. 1993). Lead may accumulate in plant roots and could be passed through the food chain.

Feasibility

Constructed wetland systems are most effective when used with other BMPs such as dry ponds and grassed swales. Land area requirements for wetland systems are generally greater than that required for most other BMPs. The use of constructed wetland systems in Michigan may be limited because the effectiveness of such systems is seasonally dependent. The following points should be considered when evaluating the appropriateness of wetland systems for use as a highway runoff BMP:

- **Costs:** Construction costs associated with wetland systems have been reported to be about \$1.50 per foot. Annual maintenance costs range from 3 to 5 percent of construction costs (Barrett et al. 1993).
- **Maintenance:** Wetland systems require intensive maintenance for the first 3 years to ensure the establishment of vegetation. After that time, maintenance is comparable to wet pond systems.
- **Longevity:** Wetland systems could provide stormwater treatment for an extended period of time.
- **Secondary Environmental Benefits:** Wetland systems can provide enhanced wildlife habitat and visual aesthetic appeal. They can also reduce peak runoff rates and flow stabilization to receiving streams.
- **Retrofit Capacity:** Wetland systems may be created in existing borrow pits adjacent to highways.

- **Potential Drawbacks:** Wetland systems are difficult to establish in sandy or other highly permeable soils, have reduced removal efficiencies in winter, and the seasonal die-off of vegetation may release metals back into the system.

BMP Design Considerations

The following items should be considered when designing a wetland treatment system:

- Constructed wetlands should be located at the lower part of sites.
- To improve wetland systems performance, the raw stormwater runoff should be pretreated in dry ponds before entering the wetland system. Dry ponds provide attenuation and equalization of flows to the wetland system.
- Relatively long retention times of 6 to 14 days (Barrett, et al. 1993) to 14 to 21 days (Dorman, et al. 1996) are recommended when treating for metals.
- Shallow areas allow emergent vegetation to grow; submerged plants require deeper water. As a rule, shallow water should cover at least 80 percent of the wetland area.
- Installation of a clay liner may be necessary to prevent excessive exfiltration.
- Design inflow rate is computed using the water quality design storm.
- Additional designs considerations may be necessary to improve performance during winter conditions (Oberts 1994), such as meltwater treatment facilities (e.g., infiltration trenches) and seasonal drawdown of the water level in the wetland system.
- The design of the outlet works should incorporate a low-level outlet designed to pass the design flow with provisions to adjust the water level manually and a high level outlet capable of passing at least the 100-year, 24-hour storm event.

Underground Treatment Systems

Underground treatment systems have been used in specialized conditions to treat stormwater from small urban catchments such as parking lots and other impervious “hot spots.” These systems can consist of one to three underground concrete chambers designed to retain stormwater and promote sediment and petroleum product removal. Metals attached to the sediment are also removed. Where land costs or space are constraining, underground systems may be practically applied to small catchments.

Underground systems such as water quality inlets/vaults, multichamber treatment trains, and single chamber treatment systems all work by providing a permanent pool for sediment and petroleum removal. Single chamber systems (Stormceptor, Vortechs) function by capturing small to medium sized storms but effectively avoid resuspension of sediments by allowing large storms to bypass the sedimentation chamber. Water quality inlets/vaults contain three chambers: sedimentation, oil separation, and outlet. Average cost to install a water quality inlet is about \$7,000 to \$8,000 (Schueler 1987). Metals removal is about 10 to 25 percent, significantly lower than infiltration trenches and sand filters. Higher metals removal has been achieved by a similar system (multi-chamber treatment train) with some design improvements. This system uses aeration, a specially designed sedimentation chamber that makes use of inclined tubes to increase surface area, and a sand filter/

perforated underdrain outlet chamber to maximize metals removal (43 to 100 percent). Construction costs are estimated at about \$10,000 to \$20,000 (Watershed Protection Techniques 1997).

Non-Structural BMPs

The use of a structural BMP is not necessarily the most cost-effective or efficient means to improve the water quality of highway runoff. Other measures include the development of a stormwater pollution prevention plan, street sweeping, control of litter and debris, public education, and sediment removal from storm drain inlets.

Because storm drain inlets can trap sediment in much the same way as water quality inlets, and because sediment has been found to contain concentrations of metals comparable to stormwater detention ponds (Mineart and Singh 1994), the removal of sediment could be an effective method to reduce metals loading from highways. A study performed in Alameda County, California concluded that monthly cleaning of the inlets would provide the greatest annual sediment removal while annual cleaning was as effective as semiannual or quarterly cleaning (Mineart and Singh 1994).

Industrial Treatment Technologies

This section describes industrial wastewater metals removal technologies and how they could be applied to the treatment of highway runoff. It includes a survey of the available technologies, a brief description of each, and the effectiveness of the technologies to remove the levels of metals found in the sampling study. Feasible technologies are evaluated further for cost and applicability of these technologies to highway runoff from a 1-acre impervious catchment area.

Highway runoff Characteristics

Based on sampling performed during this project, four metals were found in significant concentrations: copper, cadmium, zinc, and lead. The estimated concentrations of soluble and total metals are shown in Table 21. Roughly three-quarters of the lead (and about half of the remaining metals) is present in the particulate form and the remainder is soluble.

TABLE 21
Metals Concentrations in Highway runoff Sampled Directly from Pavement

Metal ^a	Total Metals		Dissolved Metals ^d	
	Worst Case ^b (µg/L)	Best Case ^c (µg/L)	Worst Case ^b (µg/L)	Best Case ^c (µg/L)
Copper	88.1 (61.1–115)	27.0 (16.3–38.0)	48.4 (33.6–63.3)	18.9 (4.8–48.0)
Cadmium	2.7 (1.5–3.8)	0.32	1.4 (0.79–2.0)	0.14
Zinc	413 (313–513)	167 (140–182)	297 (225–369)	74 (43–110)
Lead	58.6 (45.3–71.8)	28.8 (9.0–40.0)	16.4 (12.7–20.1)	4.0 (2.3–7.6)

^aValue outside parentheses = average; values inside parentheses = range.

^bHigh Volume Highway in Grand Rapids Michigan, Wealthy Street, and US 131.

TABLE 21
Metals Concentrations in Highway runoff Sampled Directly from Pavement

Metal ^a	Total Metals		Dissolved Metals ^d	
	Worst Case ^b (µg/L)	Best Case ^c (µg/L)	Worst Case ^b (µg/L)	Best Case ^c (µg/L)

^cLow Volume Highway in Grand Rapids Michigan, I-96, and West Branch Sand Creek.

^dDissolved concentrations for the worst case condition converted from total recoverable metals. Conversion factors derived from Sansalone (1996) are copper 0.55, lead 0.28, zinc 0.72, and cadmium 0.53.

Candidate Treatment Systems

Treatment technologies that have been developed for removal of metals from industrial wastewater include:

- Sedimentation/Filtration
- Ultrafiltration
- Hydroxide Precipitation
- Sulfide Precipitation
- Iron Co-precipitation
- Reverse Osmosis
- Evaporation
- Ion Exchange
- Carbon Absorption
- Peat Absorption

These are generally discussed below, along with an analysis of their applicability to stormwater treatment.

Sedimentation / Filtration

Where metals are present as particles, they can be removed by settling in a sedimentation basin or a tank clarifier. Sedimentation basins are typically cheaper, but require larger land area than tank clarifiers, and require periodic manual cleaning to remove collected solids. Due to the intermittent nature of stormwater runoff, there would be less cleaning than if they were operated continuously.

Typically, filtration is needed to achieve low parts per billion metals limits. Filtration is carried out in either a rapid sand or slow sand filter. For intermittent use, slow sand filters may be preferable. Slow sand filters consist of sand beds, underlain by perforated pipe. Rapid sand filters are smaller, but require backwashing to clean them. This ancillary equipment more than compensates for their size advantage. Slow sand filters are cleaned by periodically shoveling a layer off the surface. For intermittent use, such as the case with highway runoff treatment, this is not expected to be significant.

Because this process only removes metals associated with particulates and concentrations of soluble metals in the highway runoff would not be reduced, sedimentation/filtration is not applicable as the sole treatment process for this application.

Ultrafiltration

Ultrafiltration is another process for removal of particulate metals, substituting a membrane filter for sedimentation/filtration. Its advantage over sedimentation/filtration is that it requires less land area. Typically ultrafiltration is a polishing process, with pretreatment, such as cartridge filtration, required to remove gross particulate concentrations. It is a concentration process, producing a concentrated wastewater that must be further processed. Soluble metals in the highway runoff will not be reduced by ultrafiltration, so it is not applicable as the sole treatment process for this application.

Hydroxide Precipitation

Where metals are present in the dissolved form, they can be precipitated to a particulate form and then removed by processes that remove that form of metals (sedimentation, filtration, or ultrafiltration). The traditional and simplest process of doing this is hydroxide precipitation. In hydroxide precipitation, the pH of the wastewater is raised by addition of a hydroxide salt (such as sodium hydroxide, lime, or magnesium hydroxide). This process is effective at treating relatively high concentrations of cationic (positively charged) metals, such as those present in highway runoff. The process is not effective at reducing concentrations of metals to low parts per billion levels because of the practical solubility limits for a mixture of metals. Therefore, there is the high probability that hydroxide precipitation is not technically feasible for this application.

Sulfide Precipitation

Due to the solubility limits of hydroxide precipitation, and the fact that metal sulfides are much less soluble than metal hydroxides for divalent metals (those with 2^+ charges, such as copper, cadmium, lead and zinc), researchers have attempted to develop a treatment process using sulfide as the precipitating agent. These have had limited success because of problems with hydrogen sulfide toxicity, production of a fine precipitate that is poorly removed by sedimentation and conventional filtration, and process control. Therefore, sulfide precipitation is not feasible for this application.

Iron Co-Precipitation

In iron co-precipitation, an iron salt is added to conventional hydroxide precipitation. By precipitation of a relatively higher concentration of iron hydroxide along with the other metal hydroxides, the process has been found to reduce the solubility of the other metals over that of the metals by themselves. This is most applicable to wastewater with low concentrations of metals, such as is found in highway runoff. The final concentration of each metal can be adjusted by varying the dose of iron added. The process uses conventional wastewater treatment processes of clarification and filtration. Iron co-precipitation only involves adding an iron salt to the basic hydroxide precipitation system, and so it does not add significantly to the cost for a substantial improvement in metals removal performance.

Reverse Osmosis

Reverse osmosis is a membrane process that separates dissolved ions from water, producing two streams: (1) a finished water low in salts, and (2) a concentrated brine containing most of the metals and other salts. This process requires pretreatment to remove

particulates, which would foul the membrane system. It also requires treatment of the resulting brine (which can be 10 to 20 percent of the treated water) for metals removal, typically by metal hydroxide precipitation. As a result, this is not a standalone treatment process. It typically is used when one of the precipitation processes will not achieve the desired discharge criteria. Therefore, this process is much more expensive than precipitation, and is justified only where there is a need for a high quality, low-salt water to pay for the process. This technology is therefore not applicable to highway runoff treatment.

Evaporation

Evaporation is used to separate water from dissolved salts to produce high purity water. The equipment is energy-intensive and expensive to purchase and operate, and it is justified only where there is a need for a high quality, low-salt water to pay for the process. The technology is therefore not applicable to highway runoff treatment.

Ion Exchange

There are selective ion exchange resins for removal of specific metals. After the ion exchange resin no longer has the capacity to remove metals, it is regenerated with acid, producing a metal- and salt-laden brine. The wastewater needs to be pretreated to remove particulates, and the brine must be treated for metals removal. As a result, its cost is similar to reverse osmosis, and therefore it is not applicable to highway runoff treatment.

Carbon Absorption

Activated carbon has been found to remove some metals, particularly hexavalent chromium and mercury and has a limited capacity for removal of other metals. It is primarily used to remove organic materials and does not have significant metals removal capacity. Regeneration of spent carbon removes organic contaminants, and so it is not designed to replenish metals removal capacity. As a result, it is usually used once and disposed of when used for metals removal. Pretreatment is required, usually for particulate removal, which accounts for most of the cost of a metals hydroxide treatment process, and for this reason carbon absorption is not applicable to highway runoff treatment.

Humus Adsorption

Research has shown that humus-containing materials, such as composted leaves or peat, have a high cation exchange capacity, and therefore can remove soluble metals. The capacity and selectivity is not as high as in ion exchange, but the medium is less expensive and so it can be used to capacity and then replaced.

A treatment system has been developed specifically for highway and parking lot runoff, incorporating a pelletized compost material in cartridges that are placed in concrete vaults, which can be placed under pavement or next to the paved area. Besides removing metals, the system also provides some particulate and oil and grease removal. Unlike other treatment technologies, the method does not need an operator, but it must be checked periodically and the media replaced as needed. Since the annual average stormwater flow is relatively low compared to the treatment capacity needed to treat peak storm events, replacement of the medium is considerably lower than in a system used for continuously generated wastewater, where a regenerable medium, such as ion exchange, is justified.

This technology therefore may be applicable to highway runoff. The effects of road salt on exchange capabilities and performance needs further evaluation, as indicated by previous studies in Michigan (Merva, et al., Undated).

Treatment System Evaluation

Based on the above analysis, two technologies are potentially applicable to highway runoff treatment: iron co-precipitation and humus filters. Both are likely to treat the concentrations of metals in runoff and achieve the desired effluent quality, and both are likely to be less expensive than other technologies that can achieve the desired results.

Iron co-precipitation is an active treatment process, requiring operator attention to make it work. The least-cost application of this technology would likely consist of a pH-neutralization/iron-salt-addition tank followed by a sedimentation basin or tank, followed by a slow sand filter. For a 1-acre catchment area, the peak stormwater flow would be about 0.85 cfs (for a 6-month, 1-hour storm). This would entail a mixing tank of about 4,000 gallons and a settling/equalization basin of about 1,000 square feet of surface area able to handle about 6 feet variation of water depth to provide storage (for the 24-hour 6-month storm volume of 5,700 cubic feet, produced in the 6-month, 24-hour storm of 1.58 inches), and a slow sand filter with a surface area of about 500 to 1,000 square feet.

The humus filters have several advantages to the iron co-precipitation system. The filters are located in a concrete vault, with a surface area of about 200 square feet, using about 25 humus cartridges (based on reported capacity of 15 gallons/minute per cartridge, and treating peak flow of 0.85 cfs) (Richman 1997). Treatment is passive. The system operates continuously to handle flow as it comes. Treatment chemicals are not needed. One disadvantage is the need to replace the filter medium on an unknown schedule. On small systems, operator attention is usually the major operating cost, but this system would be less labor intensive than operation of an iron co-precipitation system, even when such a system is based on a sedimentation basin and slow sand filter rather than a clarifier and sand filter requiring backwashing. Again, the effect of road salts on system performance would need further consideration and evaluation before the long-term feasibility would be known.

Costs

The cost of treating highway runoff from a 1-acre catchment area was estimated based on a 6-month, 1-hour storm producing a peak flow of 0.85 cfs and using a 6-month, 24-hour storm of 1.58 inches producing 5,700 cubic feet of water. These order-of-magnitude estimates are based on experience with similar treatment systems and rules of thumb. The estimates are not based on sizing of individual treatment units, quantity takeoffs, or actual design and are meant to be used only for relative comparison of treatment technologies.

A tank-based iron co-precipitation system, with an equalization basin, mixing tank, chemical feed, clarifier, and rapid sand filter would cost from \$500,000 to \$1 million. If this process were based on a sedimentation basin and a slow sand filter, then it would cost \$200,000 to \$400,000. The humus filter system is estimated to cost \$30,000 to \$50,000.

Discussion

Pollutant concentrations in typical highway runoff in Michigan showed substantial variability between events and sites. Concentrations generally were highest at US 131 in Grand Rapids and lowest at sites M-37 in Grand Rapids and M-14 in Ann Arbor. The general ranking of concentrations at the sites was as follows:

1. Wealthy Street and US 131 (Grand Rapids); Part A
2. I-94 (Ann Arbor); Part A
3. I-475 (Flint); Part A
4. I-96 and West Branch Sand Creek (Marne); Part B
5. M-37 and Mill Creek (Grand Rapids) and M-14 and Fleming Creek (Ann Arbor); both Part B.

For the two sites ranked as number 5, the Grand Rapids (M-37) and Ann Arbor (M-14) sites, highway runoff samples were collected after passing through grassed swales. These two sites exhibited much lower total metals concentrations than the three Part A sites and lower total and dissolved metals than the Marne Part B site. The three Part A sites and Marne Part B site quantified direct pavement runoff at the sampling point. These results illustrate the effectiveness of grassed swales at reducing metals concentrations in runoff.

In general, total metals concentrations obtained in this study were comparable to the results of other studies (Driscoll et al. 1990; Maltby et al. 1995; Montgomery Watson 1995). This study also showed that total and dissolved metals concentrations are highly variable by site and storm event. Part A sampling results for conventional constituents (e.g., BOD, TSS, nutrients) were similar to those from the FHWA studies of the late 1970s and 1980s. However, total metals concentrations in Part A and B, particularly lead, were generally lower in this study than those in the FHWA studies, which can be attributed to the discontinuation of the use of leaded gas and to the improvement in sampling and analytical techniques.

The results of side-by-side sampling using clean and conventional techniques at Part A sites showed no significant difference for total recoverable metals. For Part B sites, both clean and conventional techniques were used at Marne for only one event (clean techniques only were used for all other events). There was no substantial difference between clean and conventional results for total recoverable metals, but dissolved metals concentrations for two of the three metals were substantially lower in the clean samples. This finding is important because the dissolved form more accurately represents the bioavailable form, and hence the more toxic form, of the metal.

The results also indicate that the FHWA data for conventional parameters collected 10 to 20 years ago may be comparable to highway runoff outfalls in Michigan, but the older data are not representative of current runoff quality for metals and therefore should not be used. The FHWA data, if used to estimate current loads from Michigan highways, would substantially overestimate the amount of metals entering Michigan receiving waters. In addition, the FHWA metals database does not include an adequate number of dissolved metals concentrations, the most important form from an aquatic life toxicity perspective.

Sampling from direct pavement runoff (Part B—Marne site) in this study demonstrated that rainfall contributes a substantial portion of the total recoverable and dissolved metals concentrations found in runoff. The mean rainfall concentrations for total recoverable metals were 41 percent of mean direct pavement runoff concentrations and 83 percent for dissolved metals at the Marne site. This is strong evidence that a substantial amount of total recoverable metals and a majority of dissolved metals originate in rainfall rather than being mobilized from highway surfaces.

A comparison of runoff quality to stream metals criteria indicates that runoff from MDOT's highways is of the same order of magnitude or less than the water quality final acute and chronic values. In fact, the vast majority of highway runoff samples were lower than the chronic in-stream water quality criterion. Despite the very favorable results of comparing the runoff with in-stream chronic criteria, it should be noted that this analysis is conservative because it does not consider dilution in the receiving stream and other mitigating factors.

Some researchers argue that existing surface water criteria may not even be an appropriate metric to judge the effect of stormwater on receiving water quality (Lee and Lee 1996; Novotny 1996). Surface water criteria are based upon bioassays of the most sensitive species for durations longer than a typical storm event (96 hours for acute tests, 7 days for chronic tests). In addition, bioassays are performed in laboratory water that lacks levels of organic and inorganic substances that are typically found in stormwater. The presence of inorganic and organic substances in stormwater and receiving waters tends to reduce metals toxicity (Stumm and Morgan 1996).

Studies of the effects of highway runoff on receiving waters have been inconclusive or have shown no effect. A study of seven streams that receive drainage from the M1 motorway in England showed that four had reduced macroinvertebrate assemblages and pollutant-sensitive taxa at downstream sites (Maltby 1995). Only one site showed a statistically significant reduction downstream, and three of the sites actually had higher macroinvertebrate assemblages downstream of the highway outfall. Sediment metals levels for zinc (338 $\mu\text{g/g}$), cadmium (2.28 $\mu\text{g/g}$), lead (133 $\mu\text{g/g}$), and chromium (76 $\mu\text{g/g}$) downstream of the M1 motorway were far greater than those found in West Branch Sand, Fleming, and Mill creeks in Michigan. Other studies have found no or inconclusive effects of highway discharges on aquatic biota (Dupuis et al. 1985; Dusart 1984; Mudre 1985). These studies support the conclusion that aquatic effects of highway runoff are difficult to quantify and cannot be determined based solely upon runoff chemical monitoring data.

Grassed swales are effectively removing metals in runoff from Michigan highways. They do not achieve the highest pollutant removal efficiency of the BMPs reviewed above, but their advantages include low cost, infiltration, toxicity reduction/removal (Portele 1982), acceptable aesthetics, and good pollutant removal. In high-density urban areas, where the use of grassed swales is impractical, periodic removal of sediment from storm drain inlets may reduce the loading of metals to urban storm sewer systems.

Metals concentrations in soils in MDOT rights-of-way exhibit concentrations and patterns consistent with other highways in various locations throughout the country. Metals concentrations in surface soils at MDOT Part B sites exceeded subsurface concentrations by an average factor at each site of 1.3 to 2.7. A previous FHWA study (Kobriger and Geinopolos 1984) found a similar pattern in surface soils. Concentrations of metals in soil samples in the FHWA study (with the exception of lead) were also similar to soils metals

concentrations in this study. Lead concentrations in the FHWA study, which was conducted in the late 1970s to early 1980s, exhibited much higher lead concentrations in soils. This suggests that lead concentrations in soils may have decreased substantially since the discontinuation of the use of leaded gasoline in automobiles in the 1980s. This supports the theory presented in another investigation that metals removed during a storm event in grassed channels eventually move downstream rather than accumulating in the swale (Dorman, et al. 1996).

Overall, the quality of the highway runoff sampled during the study demonstrates that there is no compelling need for BMPs at all MDOT outfalls. The quality of runoff is such that it probably would not cause significant adverse effects on receiving water quality, although a limited number of runoff concentrations did exceed in-stream criteria. Considering that a substantial amount of metals found in runoff originates in rainfall, this comparison demonstrates that metals originating from the roadway alone are not likely to pose a significant threat to water quality in receiving waters. The data collected in this study also demonstrate how effective vegetative BMPs can be at removing metals from runoff before it enters the receiving stream. This would be the ideal condition, particularly for new outfalls, where space permits.

Overall Conclusions

Phase I, Parts A and B, and Phase II of this study provided sampling data and other information leading to the following overall conclusions:

- A substantial fraction of the metals concentrations found in runoff originate in rainfall; specifically, on average, 41 percent of total recoverable metals in runoff originate from rainfall while 83 percent of the dissolved metals in runoff originate from rainfall (based on data from the Part B Marne site where runoff concentrations were measured as direct pavement runoff, without being influenced by passing through grassed swales before sampling). The high fraction of dissolved metal originating from rainfall is particularly noteworthy because the dissolved fraction is the more bioavailable form and hence more toxic to aquatic life.
- Total and dissolved metals concentrations at the three Part B sites were all lower than in-stream criteria designed to protect aquatic life from acute toxicity, and all but a few of the samples (i.e., two copper values at the Marne site) were lower than in-stream criteria designed to protect aquatic life from chronic toxicity. When dilution and other mitigating factors are considered, it is clear that in-stream concentrations will be below levels of concern at these sites.
- At the three Part A sites, concentrations of total recoverable metals in undiluted runoff generally also were below in-stream water quality criteria designed to protect aquatic life from acute and chronic toxicity. Copper and zinc concentrations occasionally exceeded these criteria. However, when consideration is given to in-stream dilution and the fact that the dissolved form of the metal is the more toxic form, it is probable that discharges of metals from these sites also would not cause actual in-stream toxicity.
- The above conclusions demonstrate that metals originating from the road surface alone are not likely to pose a significant threat to water quality in Michigan receiving waters.
- For all three MDOT Part A sites, highway runoff concentrations for conventional parameters such as BOD, COD, nutrients, TSS, oil and grease, and bacteria were comparable to those measured for similar highways in earlier FHWA nation-wide studies. Consequently, it can be concluded that MDOT highways do not produce unusually high loadings for these constituents compared to highways in other states and urban stormwater quality in general.
- Metals concentrations in the FHWA database are clearly not representative of current metals concentrations in runoff from Michigan highways, and therefore should not be used for water quality impact or loading assessments.
- Organic compounds were generally below analytical detection limits in Part A samples. The only exception was two phthalate esters which commonly are found in samples due to laboratory contamination.
- The pollutant loading rates calculated from Part A data can be used to compare loadings from impervious highway areas to loadings from other sources in a watershed

analysis. Note that many highways in Michigan drain to storm sewers or receiving waters after passing through grassed swales or ditches, which substantially reduce metals and other pollutant concentrations and loadings.

- Right-of-way soils and in-stream sediments are not major ongoing contributing sources of metals, but are likely to represent a sink for these and other particulate pollutants.
- Metals concentrations in soils were below applicable State clean-up criteria.
- Metals concentrations in stream bottom sediments upstream and downstream of the highways were below minimum sediment effect ranges and comparable to unaffected background concentrations in Michigan.
- Soils data collected in this study are consistent with the findings of previous studies. An FHWA study found that metals concentrations were highest in topsoil layers compared to subsurface layers (Kobriger and Geinopolos 1984). Concentrations of copper, zinc, and chromium in soils in the FHWA report were comparable to concentrations in soils found in this study. Lead concentrations in soils, however, were much lower in this MDOT study compared to the FHWA study. This is likely due to the discontinuation of leaded gasoline in automobiles since the FHWA study in the early 1980s.
- Grassed swales have been shown in this study and others to be effective in removal of pollutants, including metals (up to 80 percent removal).

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Sampling Methods and QA / QC Results

Part A

Wet weather sampling was performed for nine storm events in total. Runoff constituents were measured by taking either flow-weighted composite samples, grab samples, or direct field measurements. Flow-weighted composite samples were taken to represent the event mean concentration (EMC) of a storm. Table A-1 summarizes the constituents monitored and the sampling methods used.

TABLE A-1
Sampling Methodology by Runoff Constituent

Constituent	Sampling Methodology		
	Composite	Grab	Field Measured
Conventional Constituents ^a	X		
Oil and Grease		X	
Fecal Coliform and Fecal Streptococcus		X	
Phenols and Cyanide		X	
Temperature, pH, and Free Chlorine			X
Total Recoverable Metals	X		
Volatile Organics		X	
Acid-Extractable Organics	X		
Base-Extractable and Neutral Organics	X		
Pesticides and PCBs	X		

^aConventional constituents include BOD, TSS, TDS, NH₃, COD, NO₂/NO₃, Total P, and TKN.

Sampling procedures for all constituents were conducted according to MDOT's Stormwater Sampling Standard Operating Procedures (MDOT 1995). Cadmium, copper, lead, and zinc were sampled using both clean and conventional sampling and analysis techniques for two storms at each site. Clean techniques were employed in addition to conventional techniques for the four metals to determine whether incidental contamination significantly affects concentrations of metals in highway runoff. Samples for all other metals were collected using conventional sampling techniques.

A thorough quality assurance/quality control (QA/QC) process was followed to ensure the integrity of the field data. QA/QC procedures included the use of field blanks, field duplicates, and laboratory blanks, and the review of laboratory analytical accuracy using

recovery analysis. Table A-2 lists the QA/QC analysis performed for each sampling event. Complete QA/QC results are presented by site and event later in this appendix.

TABLE A-2
QA/QC Procedures

Location	Event Date	Conventional Parameters	Organics	Metals, Phenols, and Cyanide	Clean Metals
Ann Arbor	6/26/95	1, 2	1, 2	1, 2	1, 2, 3, 4
Ann Arbor	10/20/95	1, 2	1, 2		1, 2
Ann Arbor	6/17/96	1, 2	1, 2	1, 2	NA
Grand Rapids	6/26/95	1	1	1	1, 2
Grand Rapids	9/19/95	1	1	1	1, 2
Grand Rapids	10/13/97	1	1, 2, 5	1, 2, 6	NA
Flint	6/28/95	1, 2	1, 2	1, 2	1, 2
Flint	9/7/95	1, 2	1, 2		1, 2
Flint	9/26/96	1, 2	1, 2	1, 2	NA

1=Lab Blank, 2=Spiked Recovery, 3=Field Blank, 4=Field Duplicate, 5=Trip Blank, 6=Split Sample

Review of laboratory and field QA/QC data revealed no field contamination. Field duplicates taken at Ann Arbor verified that the sampling techniques employed did not promote variability in the sampling results. However, laboratory blanks were reported above established detection limits in several cases. The mercury value reported for Ann Arbor on June 17, 1996, may have been the result of laboratory contamination (laboratory blank reported as 0.29 µg/L). Also, laboratory blanks for total Kjeldahl nitrogen (TKN) had reported concentrations above detection limits for all events at Ann Arbor and Flint. A split sample sent to Trace Analytical Laboratories for the October 13, 1997, sample at Grand Rapids for analysis of four metals showed generally good agreement with the results from the MPS lab. Copper and zinc results from the two labs agreed within 10 percent, whereas cadmium results from the MPS lab were 25 percent and lead results were 47 percent lower than the Trace lab results. These interlaboratory discrepancies are not unusual at low trace metals concentrations.

Clean sampling and analysis procedures used in Part A are the same as those used in Part B with the exception that dissolved analyses were not performed for Part A. Clean techniques are described in the Part B section later in this Appendix.

One possible explanation for the lack of substantial difference between the conventional and clean metals analysis results presented in Table 4 of the main report is that the same field crew was responsible for performing the clean and conventional sampling. The sampling crew's awareness of potential sources of metal contamination may have reduced the probability of field contamination during conventional sampling. Nevertheless, clean analytical techniques are still advisable in studies such as this because the analytical limits

with clean techniques are substantially lower than with conventional techniques. A sample that is reported as below the conventional analytical detection limit may have a quantifiable concentration when analyzed with a lower detection limit using clean analytical techniques. To illustrate, cadmium and lead concentrations were below detection limits at Ann Arbor using the conventional analytical techniques but above detection limits and reported as a specific concentration using the clean analytical techniques. Thus, lower analytical detection limits that are obtained using clean techniques can provide benefits by quantifying the pollutant concentration rather than providing a reported result of below detection limit.

Part B

Incidental contamination from a variety of sources can cause erroneously high sample results unless special precautions are taken in both the sampling and analytical techniques. To minimize the amount of potential contamination in highway runoff and rainfall samples collected in this study, clean sampling and analysis techniques were implemented for highway runoff samples from two storms at each site in Part A and from all storms and sites in Part B. Although USEPA's final clean sampling guidance and method (Method 1669) had not been published at start of the study, clean techniques were available from a variety of relevant sources and were used as appropriate in preparing the sampling protocol for this study (MDOT 1995).

The field sampling team consisted of two people: one sample collector was designated as "dirty hands" and the other as "clean hands." All operations involving contact with the sample bottles, transfer of the sample, sample filtering, and any sample preparation were handled by the individual designated as "clean hands." All operations involving preparing the sample pump, batteries, and opening plastic containers were performed by the individual designated as "dirty hands."

All sample bottles were made of Teflon and were supplied by Battelle Laboratories. The bottles were prepared according to clean analytical procedures at Battelle. The filters for preparing the dissolved metal samples were precleaned 0.45- μm polycarbonate filters, also supplied by Battelle.

Both sample collectors were outfitted in Tyvek coveralls, including hoods and booties. New Tyvek coveralls were used for each sample location. A new pair of nontalc latex sampling gloves was used at each sample location, after filtering, after preservation, and any time the "clean hands" individual touched a potentially dirty surface. All samples were collected using a peristaltic pump fitted with Teflon tubing. A new specially cleaned piece of tubing was used at each sample location. Clean tubing was also provided by Battelle.

All samples were preserved with certified metals-free, double-distilled nitric acid. The acid was premeasured and stored in Teflon ampules. Samples were preserved after filling all sample bottles for that individual location. One sample bottle was filtered at a time, and gloves were changed between each sample bottle. The "clean hands" individual first loosened the cap on the sample bottle but did not remove it. The "clean hands" individual then opened the preservation ampule, removed the cap from the sample bottle, poured the acid into the sample bottle, and replaced the cap on the sample bottle as quickly as possible.

Sample bottles were then individually bagged in plastic and cooled to 4°C. Ice was double bagged to prevent leaking. The samples for metals analysis were sent on ice by overnight courier to Battelle Laboratories in Sequim, Washington (Class 100 clean lab), for analysis of total recoverable and/or dissolved metals by clean analytical methods.

The chemical analyses for total recoverable and dissolved metals were performed by Battelle by inductively coupled plasma, mass spectrometry (ICP/MS), as defined in the sampling protocol for this study (MDOT 1995).

QA/QC procedures for Part B included procedural blanks, analysis of standard reference materials, matrix spikes, and lab replicate analyses. Results are included in Appendix D along with the raw data results as reported by Battelle. The QC results indicate that reasonable QC objectives generally were met and therefore no data were rejected based on data validation considerations.

Appendix A
Sampling Methods and QA / QC Results

Grand Rapids, 6/26/95

Grand Rapids, 9/19/95

Grand Rapids, 10/13/97

Ann Arbor, 6/26/95

Ann Arbor, 10/20/95

Ann Arbor, 6/17/96

Flint, 6/28/95

Flint, 9/7/95

Flint, 9/26/96

Appendix B
Part A Sampling Results

Appendix C
Part B Site Maps

Appendix D
Part B Highway runoff and
Rainfall Sampling Results

Appendix E
Part B Soil Sampling Results

Appendix F
Summary of Survey Responses