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SOURCES OF POLLUTANTS IN WISCONSIN STORMWATER

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ABSTRACT

Rainfall runoff samples were collected from streets, parking lots, roofs, driveways, and lawns. These five source areas are located in residential, commercial, and industrial land uses in Madison, Wisconsin. Solids, phosphorus, and heavy metals loads were determined for all the source areas using measured concentrations and runoff volumes estimated by the Source Load and Management Model. Source areas with relatively large contaminant loads were identified as critical source areas for each land use.

Streets are critical source areas for most contaminants in all the land uses. Parking lots are critical in the commercial and industrial land uses. Lawns and driveways contribute large phosphorus loads in the residential land use. Roofs produce significant zinc loads in the commercial and industrial land uses.

Identification of critical source areas could reduce the amount of area needing best-management practices in two areas of Madison, Wisconsin. Targeting best-management practices to 14% of the residential area and 40% of the industrial area could significantly reduce contaminant loads by up to 75%.

KEYWORDS

Urban runoff; stormwater contaminants; street runoff; parking-lot runoff; lawn runoff; urban storm-water modeling; urban contaminant loads; best-management practices.

INTRODUCTION

Many Wisconsin urban lakes and streams are degraded by contaminants from urban stormwater runoff. Quantities of heavy metals, polycyclic aromatic hydrocarbons (PAHs), bacteria, pesticides, and suspended solids in urban runoff often exceed Federal water-quality regulations (U.S. Environmental Protection Agency, 1983; Bannerman *et al.*, 1983; Bannerman, 1990).

Efforts to restore the quality of urban water resources have begun. Cost-share dollars for best-management practices are being made available through Wisconsin's voluntary Nonpoint Source Program. Also, new U.S. Environmental Protection Agency (EPA) stormwater regulations are being implemented in some of Wisconsin's largest cities and certain industries. Water-quality data are needed for effective implementation of these two water-pollution control programs.

Identification of sources which produce large contaminant loads, critical sources, are important to any water-pollution control program. A program can be made more cost effective by implementing the best-management practices as close to the critical contaminant sources as possible. The purpose of the study described in these proceedings was to identify the critical source areas for contaminants washed off residential, commercial, and industrial land uses. A source area is an urban surface generating contaminants during runoff. Source areas investigated by the study were streets, roofs, parking lots, driveways, and lawns in two distinct areas, 46 and 94 hectares (ha), within the city of Madison, Wisconsin.

Few data are available on concentrations of contaminants in source-area runoff (Bannerman *et al.*, 1983; Pitt and Barron, 1989) although some results describe large concentrations from certain source areas, such as large zinc concentrations detected in Milwaukee roof runoff. However, previous studies do not provide the contaminant-load data needed to identify critical contaminant source areas.

A source area, such as a street, is considered critical if it produces large contaminant loads. The source area needs to produce a large amount to be considered critical because stormwater management programs need to target a large percentage of the contaminant load to help compensate for possible ineffective best-management practices. The critical source areas for this study were determined by adding the largest contaminant load to the next largest load until 75% or more of the total contaminant load from the land use was obtained. Each land use may have more than one critical source area.

Wisconsin expects to make the determination of the critical source areas an important part of its stormwater management program. If each contaminant has one or two critical source areas, significant contaminant reduction could be achieved by targeting best-management practices in those critical areas. Three types of best-management practices usually are recommended for source areas; these are pollution-prevention, on-site and housecleaning practices. Education and infiltration devices are examples of the two types of management practices. At times these practices may be implemented without knowing the relative importance of the contaminant source area.

Comparing the benefits of source-area practices to storm-sewer outfall management also would be easier if critical source areas were identified. Because there is more information about the benefits of storm-sewer outfall practices, such as wet-detention basins, most management recommendations rely extensively on these practices. Although one wet-detention basin can reduce the contaminant loads from an entire land use, some contaminants could be controlled more effectively in the critical source area. High costs, space requirements, and their inability to control all contaminants can decrease the desirability of depending entirely on storm-sewer outfall management.

METHODS

The approach of the study described herein and conducted by Wisconsin Department of Natural Resources (WDNR) and the U.S. Geological Survey (USGS) was to determine the contaminant loads for representative sources in the study areas. Measured contaminant concentrations and simulated runoff volumes were used to determine source-area loads. An attempt was made to collect runoff samples from every rain for a 2-month period beginning in May 1991. Source-area loads were based on all sampled runoff. These contaminant loads were used to identify the critical source areas.

Simple sampling devices were positioned to isolate runoff from each source area. All sampling equipment, except the roof samplers, was installed below the ground so that the runoff would enter the sample bottle by gravity. Samples were collected from all the source areas at the same time. The samples were analyzed for dissolved phosphorus, total phosphorus, total solids, suspended solids, dissolved and total recoverable cadmium, chromium, copper, lead, and zinc, hardness, and fecal coliform bacteria. Laboratory analyses were done at Wisconsin's State Laboratory of Hygiene in Madison, Wisconsin using EPA-approved procedures.

Runoff volumes were estimated using an urban nonpoint-source model called Source Load and Management Model (SLAMM), (Pitt and Voorhees, 1989). SLAMM was used to estimate runoff volumes for 14 types of source areas. Urban planners use the model to simulate stormwater contaminant loads and to evaluate the effects of best-management practices. Results from the study also were used to continue calibration of the model (Voorhees, 1992).

Stage data and water-quality samples were collected at the storm-sewer outfall for each area studied. Outfall and source-area data collection were done concurrently. Automatic water-quality sampling equipment was programmed to collect flow composite samples. Data collection at the outfalls was done to check the accuracy of the simulated runoff volumes and the source-area loads.

Contaminant loads were calculated by multiplying the geometric means of the concentrations in runoff from all the monitored storms times the simulated runoff volumes. The geometric means were used instead of average concentrations because it is believed that urban runoff concentrations are distributed log-normally, as shown in the Nationwide Urban Runoff Project (U.S. Environmental Protection Agency, 1983). Geometric means also provided values that could be used to calculate loads in locations outside the study areas.

Following are more detailed descriptions of the study areas, sampling sites, sampling equipment, sample processing procedures, and source-area runoff volume estimates.

TABLE 1. Study-Area Characteristics

	Study Area (1)	
Characteristic	Monroe	Syene
Drainage Area, hectares	94.4	46.4
Residential Area, %	97	-
Commercial Area, %	3	-
Industrial Area, %	-	100
Age of Development, years (2)	40	17
Roofs with Galvanized Rain Gutters, % (3)	30	--
Street Covered by Tree Canopy, % (3)	35	<1
Soil Type (4)	silt loam	silt loam
Hydrologic Soil Type (5)	B	B
Average Slope, % (6)	2.2	.39
Street Sweeping Schedule: (7)		
Arterials, per month	4	1
Collectors, per month	1	1
Feeders, per month	1	-
Traffic Volume: (7)		
Arterials, cars per day	20,000	19,800
Collectors, cars per day	2,850 to 7,300	500 to 2,150
Feeders, cars per day	100 to 400	-

1) Single dash indicates source area is not in the study area; double dash indicates insufficient data.
2) Dane County Register of Deeds.
3) Visual observation in study area.
4) Dane County soil survey maps prepared by the U.S. Soil Conservation Service.
5) U.S. Soil Conservation Service classification.
6) Estimation from USGS topographic map.
7) City of Madison Department of Highways.

Description of Study Areas

Madison, Wisconsin, is a medium-sized city with a population of 190,262 (Wisconsin Legislative Reference Bureau, 1990). It has a moderate climate with an annual precipitation of more than 76.2 centimetres (cm). On average, 7.62 cm of rain falls each month from May to October. The ground usually is frozen from late November until early April, with an average February frost depth of 34.3 cm.

Two areas about 8-kilometres (km) apart were selected for study on the west side of the city. One of these, the Monroe area, consists of mostly residential land use and a small commercial area. Part of one church and a school also are included. The other study area is Syene which is all industrial park (TABLE 1). Some characteristics of the two areas, such as the slope, are very different, but they share the same wide range in traffic volumes.

TABLE 2. Size of Each Source Area by Land Use (1)

Source Area	Monroe Area				Syene Area	
	Residential		Commercial		Industrial	
	Hectares	Percent	Hectares	Percent	Hectares	Percent
Feeder Streets	8.1	8.8	-	-	-	-
Collector Streets	4.7	5.1	.3	10.7	2.9	6.3
Arterial Streets	-	-	.6	21.4	.5	1.1
Lawns	61.1	66.7	-	-	17.7	38.4
Driveways	4.8	5.2	-	-	.3	.7
Roofs	11.7	12.8	.6	21.4	9.6	20.8
Parking Lots	-	-	1.3	46.4	15.1	32.8
Sidewalks	1.2	1.3	<.1	.1	-	-
Total (2)	91.6	99.9	2.8	100.0	115.6	100.1

1) Single dash indicates source area is not in the study area.
2) Percentage totals do not add to 100 percent due to rounding.

Sizes of the source areas were determined by digitizing aerial photographs onto an ARC/INFO geographic information system (TABLE 2). Distributions of the source areas were typical for the three land uses. The amount of each impervious area directly connected to storm sewers was determined by observation (TABLE 3).

TABLE 3 Percentage of Impervious Source Areas Directly Connected to Storm Sewers (1)

Source Area	Study Area	
	Monroe (%)	Syene (%)
Streets	100	100
Driveways	75	90
Roofs:		
Residential	2	-
Commercial	100	-
Industrial	-	72
Parking Lots	100	81
Sidewalks	50	-

1) Single dash indicates source area is not in the study area.

Sampling Sites

Multiple sampling sites were located in each source area (Figs. 1 and 2). Street sampling sites were selected to represent a wide range of traffic volumes. A total of 46 sites were located in the source areas (TABLE 4). Samples from the same source area were composited to make up 12 sample sets for the Monroe area and 6 sample sets for the Syene area. Samples from lawns were composited to separate high-maintenance lawns from low-maintenance lawns. Samples from residential roofs were divided into those with aluminium rain gutters and those with galvanized rain gutters.

TABLE 4 Number of Sampling Sites in the Monroe and Syene Areas

Area	Land Use	Source Area	Number of Sampling Locations	Number of Samples Analyzed Separately
Monroe:	Residential	Feeder Streets	6	2
		Collector Streets	3	1
		Lawns	6	2
		Driveways	4	1
		Residential Roofs	6	3
	Commercial	Arterial Streets	4	1
		Parking Lots	1	1
		Flat Roofs	2	1
Syene:	Industrial	Collector Streets	4	1
		Arterial Streets	4	1
		Parking Lots	3	3
		Flat Roofs	3	1
		Total Number of Sampling Sites:	46	

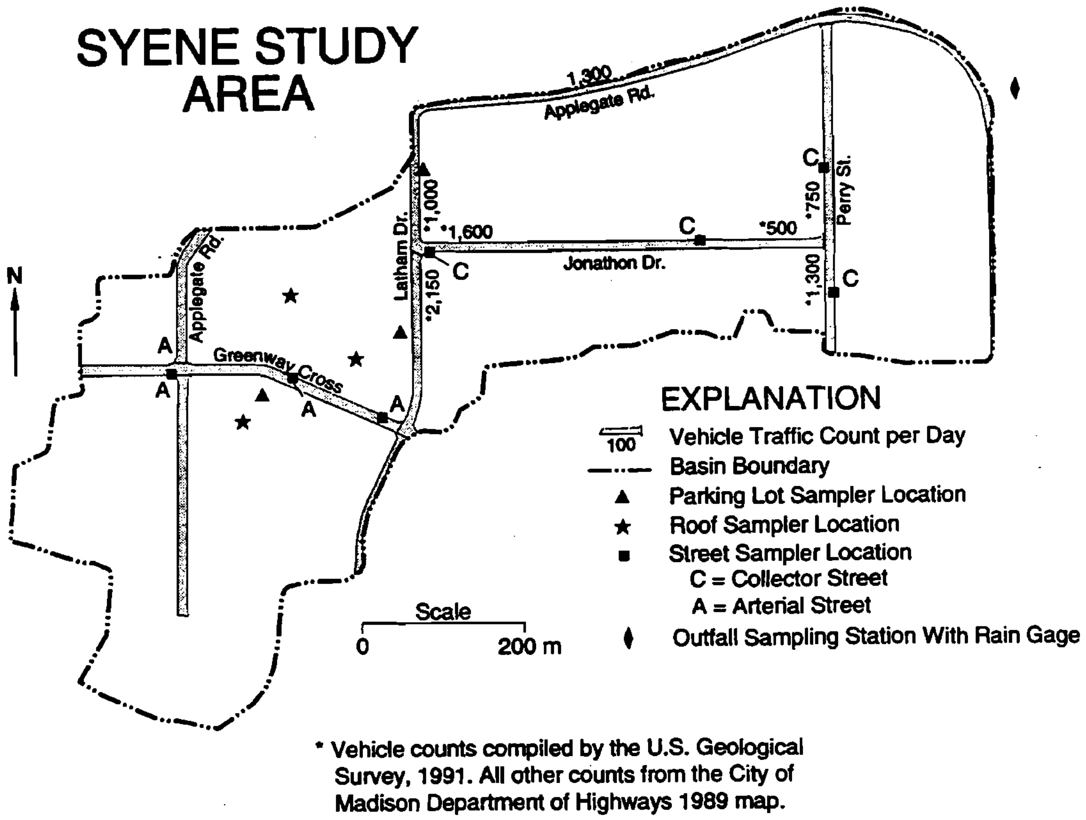

Fig. 1. Location of Syene sampling sites and vehicle traffic counts.

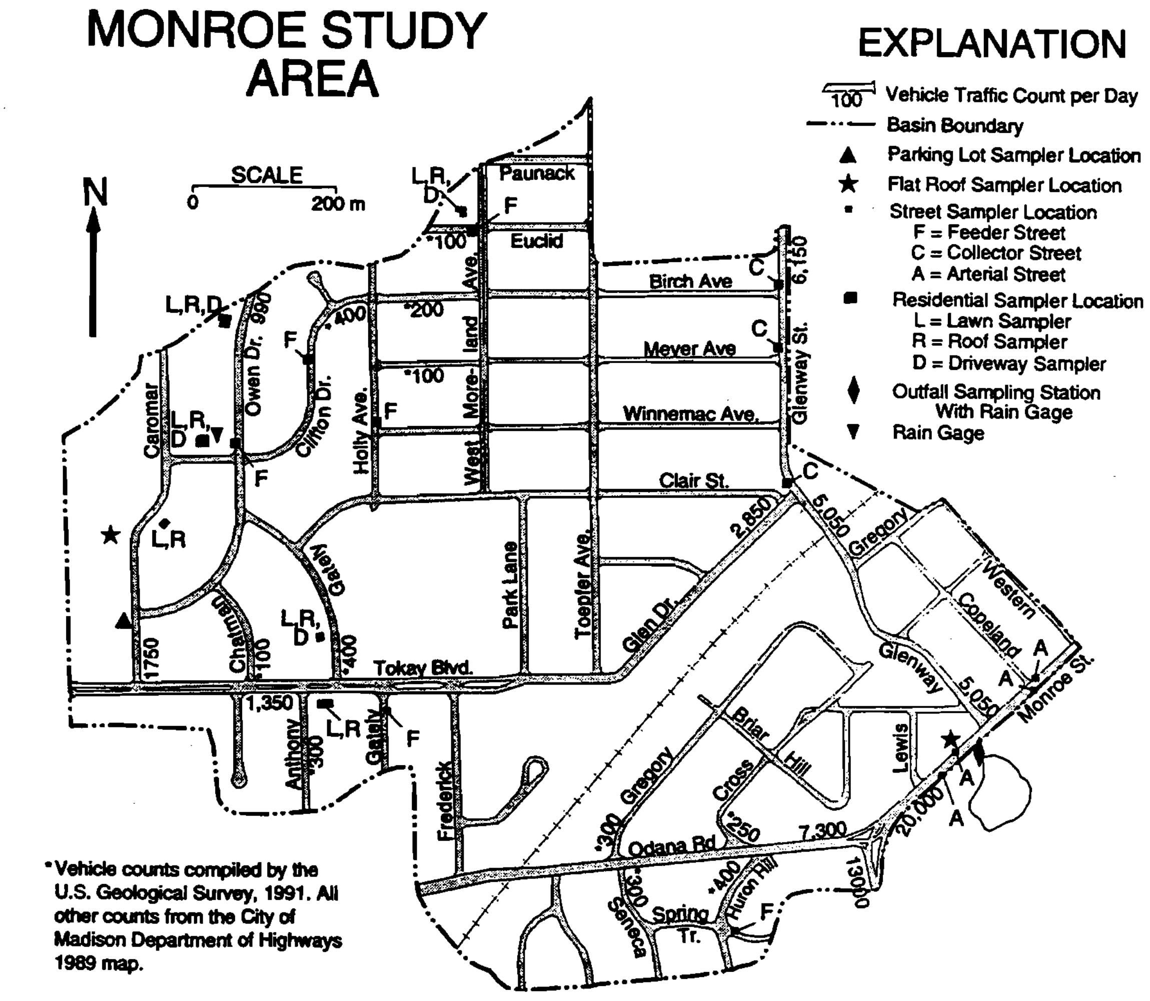

Fig. 2. Location of Monroe sampling sites and vehicle traffic counts.

Sampling Equipment

A different piece of sampling equipment was designed for each type of source area. Samplers were designed not to interfere with any activities within the source area and therefore were left in place between storms. Clean sample bottles were placed in each sampler just before each storm and removed as quickly as possible after runoff had stopped. The following is a brief description of each type of sampler.

Street samplers. The street sampler consisted of a 10.2-cm inside-diameter PVC pipe cut to a length of 19.1 cm (Fig. 3). A 0.946-litre (l) sampling bottle fit inside the pipe. A PVC coupling was cut in half and glued to the top of the pipe. A cap for the coupling was made using a 2.54-cm thick piece of PVC. A lathe was used to give the cap a concave shape and a groove for an O-ring.

The street sampler was installed in a 15.2-cm diameter hole drilled about 0.92-meter (m) from the curb. The hole was made deep enough so that the top of the sampler cap was flush with the street pavement. Quick-set grout held the street sampler in place.

Runoff water entered the sampler through a 1.59-cm hole located in the centre of the concave side of a cap. The sampling-bottle cap was attached to the underside of the PVC cap with glue.

Driveway samplers. Runoff water from driveways was diverted into a nearby sampler by using a flat piece of clear plastic glued to the driveway. The sampler consisted of a 0.946-l glass bottle placed in a 10.2-cm diameter protective PVC sleeve located in the ground along side the driveway. A 1.27-cm diameter silicon tube carried the runoff to the sampler. An indentation in the bottom of the sampler cap and a groove at the top of the PVC pipe allowed the silicon tubing to reach the sample bottle when the sampler cap was in place.

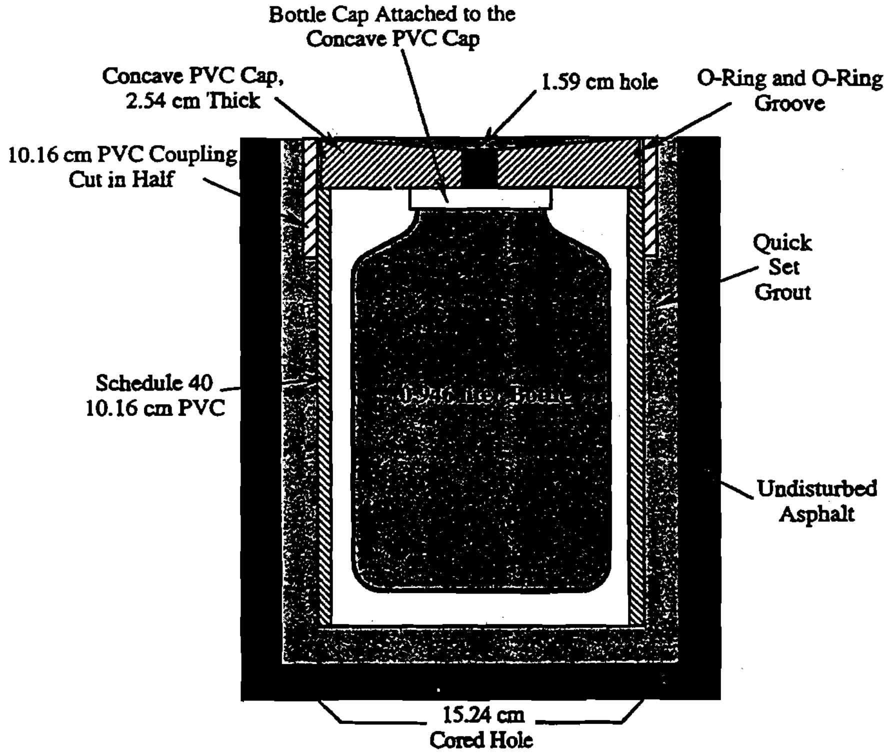

Fig. 3. Diagram of a street sampler.

Lawn samplers. Lawn samples were collected from a sloping surface. A lawn sampler used two, 1.22-m pieces of 1.27-cm diameter PVC pipe placed flush with the surface of the ground, with an angle of about 150 degrees between the two pipes. Runoff entered the pipes through 7.62-cm slits cut along the entire length of each pipe. Each pipe was wrapped with fibreglass screen to prevent the entry of insects and large debris. Clothes pin anchors held the pipes in place.

Water from the pipes flowed into a sampler fitted with a special cap. The sampler consisted of a 0.946-l glass bottle placed in a 10.2-cm diameter protective PVC sleeve. The cap had two grooves to accommodate the silicon tubing used to deliver the water from the lawn-sampler pipes.

Roof samplers. Roof samplers were designed to divert a small portion of the water in the gutter downspout to a sample bottle. A 0.64-cm diameter vinyl tube was attached to the inside of the downspout using wire or clothes pins. The tubes were placed in that part of the downspout that carried the largest volume of flow. Each tube went into a 3.785-l glass bottle placed in a 25.4-cm diameter PVC protective sleeve. A piece of 0.64-cm thick PVC sheet covered the protective sleeve.

Parking-lot samplers. Parking-lot samplers were designed to capture a small portion of the runoff entering a storm-sewer inlet. A portion of the inlet flow was diverted to a sample bottle using a trough made of a 1.27-cm diameter PVC pipe cut in half. The trough was held in place with stainless-steel band clamps attached to the inlet grating. A 0.64-cm inside diameter vinyl tube brought the water from the trough to a hole in the cap of a sampling bottle.

A 9.5-l glass sampling bottle was hung from the side of the storm-sewer inlet. The hanger system was made of vinyl-coated wire and a plastic hook.

Storm-sewer outfall samplers. An automated sampling station was located at the storm-sewer outfall in the Monroe and Syene areas. Both stations collected flow data, rainfall data, and water-quality samples. An effort was made to collect flow composite samples for each storm during the sampling period.

Campbell Scientific CR10 data loggers were programmed to control data and sample collection. The data loggers recorded water stage and rainfall pulses, computed instantaneous discharge and activated the samplers. Flow weighted water-quality samples were taken by an ISCO 3700 refrigerated sampler which was activated by the CR10 after a predetermined runoff volume was exceeded.

The instantaneous discharge was calculated differently for each automated sampling station. A velocity probe and stage-sensing equipment was used to calculate instantaneous discharge at the Monroe station. The flow-sensing equipment was in a box culvert that discharged water to a wet detention basin. Total runoff volumes for each storm were calculated at the Monroe station using a V-notch weir at the outlet of the wet detention basin.

The Manning formula and stage-sensing equipment were used to calculate instantaneous discharge at the Syene station. Discharge was measured in a 1.37-m pipe. To cover a wider range of storms, two ISCO samplers were installed at the Syene station. Total runoff volumes for each storm were calculated by summing the instantaneous discharges.

Sample-Processing Procedures

All equipment was cleaned carefully after each use. A Teflon-coated churn splitter was used to composite and split the samples. Some of the samples were filtered for dissolved constituents. A millipore filter unit was used with a 0.7-micrometer quartz pre-filter and a 0.45-micrometer membrane filter. Processed samples were delivered immediately to the laboratory for analysis. Contaminant concentration data were stored in the USGS QWDATA and EPA's STORET data bases.

Source-Area Volumes

Version 5.1 of SLAMM was used to estimate the runoff volumes from each source area. Documentation for the model and the parameter files are available from the WDNR. Runoff volumes estimated by the model were calibrated with data from several different urban runoff studies (Pitt, 1987; Voorhees, 1992).

Input data to SLAMM included individual rainfall characteristics, source-area characteristics, and descriptions of best-management practices. The rainfall parameter file required rainfall depth and the start and end times for each storm. Source-area characteristics needed by the model were surface area, street length, hydrologic soil type, amount of connected imperviousness, building density, presence of alleys, roof pitch, pavement texture, and parking density. Street sweeping, considered a best-management practice for the model, was the only best-management practice used in the two areas that were studied.

RESULTS AND DISCUSSION

All of the source-area samplers worked reasonably well. At least seven samples were collected from most source areas to produce a total of 151 samples. Most runoff from rainfall occurring between May 5 through July 7, 1991 was sampled.

The design of the samplers was not only appropriate for the collection of sheet-flow samples, but the samplers also proved to be unobtrusive and very durable. Homeowners with lawn samplers could still cut their grass. The roof samplers did not interfere with the operation of the downspouts. Parking-lot and street samplers did not affect the flow of traffic, and large traffic volumes did not damage the street samplers.

Samples from 10 rainfall events were collected for the Monroe area and samples from 9 rainfall events were collected for the Syene area. Monroe rainfall depths were calculated by averaging data from 2-rainfall gages in the Monroe area. Syene rainfall depths were obtained from 1-rainfall gage in the Syene area. One-half of the rainfall events were small, with a total rainfall depth of 0.17 inch or less (TABLE 5). Three larger rainfalls with depths between 0.40 and 0.84 inch were recorded for each area. Total rainfall for May and June was 15.11 cm, 82% of the normal of 18.36 cm (National Oceanic and Atmospheric Administration, 1991).

TABLE 5 Rainfall Depths, Intensity, and Duration for Sampled Storms in the Monroe and Syene Areas (1)

Monroe Area					Syene Area				
Beginning Rain Date	Rainfall Depth (cm)	Rainfall Duration (hr)	Rainfall Intensity (cm/hr)	Interevent Duration (days)	Beginning Rain Date	Rainfall Depth (cm)	Rainfall Duration (hr)	Rainfall Intensity (cm/hr)	Interevent Duration (days)
05/05/91	2.13	12.84	0.17	5.80	05/05/91	1.52	4.92	0.31	5.76
05/17/91	.25	3.91	.06	9.35	05/17/91	.18	1.44	.12	9.35
05/21/91	.15	.50	.30	3.09	05/21/91	.38	.31	1.22	3.09
05/25/91	.25	1.08	.24	3.92	05/25/91	.10	.48	.21	1.38
05/30/91	.30	.17	1.81	4.32	05/30/91	.13	.24	.53	6.40
05/30/91	.28	.12	2.33	.25	06/10/91	.86	1.73	.50	9.16
06/10/91	.76	1.90	.40	9.12	06/12/91	1.02	.62	1.63	1.40
06/12/91	1.40	2.16	.65	1.38	07/01/91	.43	3.19	.14	9.76
07/01/91	.69	3.43	.20	9.79	07/07/91	1.96	.38	5.09	5.91
07/07/91	1.70	1.61	1.06	5.91					

1) A rainfall event is defined as having a dry period of at least 6 hours followed by a minimum rainfall depth of 0.10 cm during the next 6-hour period; cm = centimeter; hr = hour.

Although it was hoped to collect a composite sample from each runoff, the source-area samplers appeared to collect primarily a first-flush sample. If a composite sample had been collected, the sampler would not have been completely full at the end of each runoff. The source-area samplers were usually full. Contaminant concentrations analyzed in the samples probably were larger than the concentrations would have been had a composite sample been collected.

For seven rainfall events, samples were collected at both the source areas and the storm-sewer outfalls (TABLE 5). Samples for three storms at the Monroe outfall were not collected, and one storm was monitored at the outfall but not in the source areas. Outfall samples were not collected for two storms in the Syene area. Malfunctions in the flow-recording equipment and power failures were the principal reasons samples were missed at the outfall sampling stations.

Before determination of critical source areas, it was necessary to do a number of calculations with the concentration data. Runoff volumes from source areas needed for load calculations were estimated by using SLAMM. Accuracy of the source-area loads and the simulated volumes were checked by comparing them with the loads and volumes measured at the two storm-sewer outfalls.

Source-Area Concentrations

Sampling summary. Between 7 and 10 samples were collected from all the source-area samplers except the lawn and the commercial parking-lot samplers. Between 3 and 7 samples were collected from each lawn sampler and five samples were collected from the commercial parking-lot sampler. Eight samples were collected from the Monroe storm-sewer outfall, and nine samples were collected from the Syene storm-sewer outfall.

The source-area samplers were very reliable. When the roof and parking-lot samplers failed, it was because inlet tubes became clogged with vegetative material or other debris. The fact that not every rainfall produced lawn runoff, reduced the number of lawn samples. Only rainfall with relatively large intensities and long duration appeared to produce enough runoff to fill most of the six lawn samplers. The two storms for which most of the lawn samplers collected runoff had rainfall amounts of 1.40 and 1.70 cm and intensities of 0.66 and 1.04 cm per hour respectively. Only one or none of the lawn samplers worked for five of the rainfall events with the smallest rainfall amounts and/or intensities. Two lawn samplers worked for storms with rainfall amounts of 0.69 and 0.76 cm and intensities of 0.20 and 0.41 cm per hour, respectively.

All of the contaminants were analyzed for most of the samples. However, a funding shortage prevented the last five roof samples from being analyzed for three of the heavy metals--cadmium, chromium, and lead. The same three metals were not analyzed for any of the lawn samples. Also, all the dissolved-zinc concentrations were discarded because filter blanks showed that the filtering procedure had contaminated the samples with zinc.

Manipulation of concentration data. Concentration data had to be manipulated in three ways before the geometric means could be determined for each source area. First, censored concentrations designated as being less than the detection level were replaced with numerical values. Second, the concentration data were consolidated, as much as possible, for source areas with multiple concentration values for each runoff. Third, runoff concentration values were assigned to sidewalks, commercial collector streets, and industrial lawns, which were not monitored as part of the study.

A numerical value of one-half the detection level was substituted for censored concentration values. Using numerical replacements for censored values can introduce a bias and result in an erroneous estimate of the mean (Travis and Land, 1990); however, it would be unreasonable with the relatively small data set from this study to circumvent this problem by using a log-normal probability distribution to determine the geometric means. The possibility of some error in the mean should not mask the relative importance of each source area.

Five of the constituents had censored values replaced with numerical values; these were dissolved cadmium, total recoverable cadmium, total recoverable chromium, dissolved copper, and fecal coliform bacteria. The number of censored concentrations did not exceed 3 out of 10 samples for most of the source areas. Replacement values for dissolved cadmium, total recoverable cadmium, and total recoverable chromium were assigned to runoff from all of the land uses except roof tops. Censored dissolved-copper concentrations were replaced in runoff from all the source areas except industrial roof tops. A large percentage of the roof-top samples had censored concentrations for the four metals.

Most of the dissolved-lead and chromium concentrations were censored for all the source areas. No attempt was made to replace any of these censored concentrations with numerical values. Because of the large percentage of censored data, it was decided to eliminate these two constituents from the load calculations. For the same reason dissolved cadmium, total recoverable cadmium, and total recoverable chromium also were eliminated from the load calculations for runoff from roof tops, and dissolved-copper loads were not calculated for runoff from industrial roof tops.

Sampling sites for some source areas in the Monroe and Syene areas were grouped to produce more than one concentration value for each runoff. The groups for the Monroe area included (1) high- and low-maintenance lawns, (2) residential roofs with and without galvanized rain gutters, and (3) streets with different traffic volumes (TABLE 6). Streets and parking lots in the Syene area were grouped by traffic volume. As expected, the groups within a source area had very different concentrations of at least one contaminant. For example, the geometric mean zinc concentration of 246 g/l for runoff from roof tops with galvanized gutters was larger than the mean of 88 g/l observed for runoff from roof tops with aluminium gutters. Groups based on traffic volume had very different concentrations for all contaminants.

TABLE. 6 Source Areas Combined to Produce Geometric Mean Contaminant Concentrations Used For Load Computations

Source Areas Combined to Form		Resulting Source Area
Two Feeder Streets	=>	Residential Feeder Streets
High-Maintenance Lawn + Low-Maintenance Lawn	=>	Residential Lawns
Two Aluminum-Gutter Roofs + One Galvanized-Gutter Roofs	=>	Residential Roofs
Parking Lots: Large Traffic + Medium Traffic + Small Traffic Volumes	=>	Industrial Parking Lots

Although it was intended that different groups be used to provide a more accurate load value for each source area, it was decided to use one concentration value for runoff from lawns, residential roofs, residential feeder streets, and industrial parking lots. A shortage of monitored storms was one reason the groups were combined for lawns and industrial parking lots. Only three storms were monitored for low-maintenance lawns, and four storms were monitored for one of the industrial parking lots. A more important reason to combine the groups for these four source areas was that the surface area for each group represented within the source area was unknown. Without the surface area, a runoff volume could not determined for each group.

Concentration data for feeder, collector, and arterial streets in the Monroe area and concentration data for collector and arterial streets in the Syene area were not combined because surface areas were available for each street. These surface areas were determined in ARC/INFO after being classified as feeder, collector or arterial based on city vehicle counts. Recent vehicle counts were available for all the arterial and collector streets in the study area. Vehicle counts were not available for most of the residential feeder streets. However, feeder streets could be identified easily because of their low vehicle counts and their location in the residential area.

It is important to note that the copper and lead concentrations for one of the residential-roof groups were not used to determine the average concentrations. Vent-stack flashing made of copper produced unusually large copper and lead concentrations in the roof runoff. Total recoverable copper and lead had geometric mean concentrations of 32 and 40 g/l, respectively, for runoff from roofs with copper flashing, whereas runoff from roofs with galvanized flashing had total recoverable copper and lead concentrations of 5 and 8 g/l, respectively.

Contaminant concentrations measured in runoff from residential driveways were used for calculating loads in runoff from residential and commercial sidewalks. Loads were calculated for industrial lawns by using the concentrations measured in runoff from residential lawns. Concentrations in runoff from the residential collector streets were used for the commercial collector streets. These substitutions were necessary to do a complete mass balance for each area.

Geometric means. Geometric mean concentrations were calculated for all the source areas (TABLE 7). The wide range in concentrations around the geometric mean indicates that concentrations can be quite variable for some source areas (Figs. 4 and 5). Only runoff from roof tops stands out as having a small range in concentration values for all the contaminants except dissolved copper, zinc, and fecal coliform bacteria. Despite this variability, geometric mean concentrations appear to be different between some of the source areas.

Runoff from streets seems to have the largest mean concentration for all the contaminants except for total recoverable zinc in runoff from industrial roofs and phosphorus in runoff from residential lawns. The industrial-roof mean total recoverable zinc mean concentration of 1,155 g/l was 2 to 20 times larger than runoff from the other source areas. Roofs runoff usually had the smallest mean contaminant concentration among the source areas for each land use. Runoff from lawns had the largest total and dissolved phosphorus concentrations. Total phosphorus concentrations in runoff from lawns were about 2 to 18 times larger than the concentrations in runoff from other residential source areas.

TABLE 7 Geometric Mean Concentrations of Contaminants in Runoff from Source-Areas and Storm-sewer Outfalls (1)

Contaminant	Feeder Streets	Collector Streets	Arterial Streets	Lawns	Drive-ways	Roofs	Parking Lots	Out-fall
				Residential Source Areas				
Total Solids (mg/L)	796	493	-	600	306	91	-	369
Suspended Solids (mg/L)	662	326	-	397	173	27	-	262
Total Phosphorus (mg/L)	1.31	1.07	-	2.67	1.16	.15	-	.66
Disolv. Phosphorus (mg/L)	.37	.31	-	1.45	.49	.06	-	.27
Disolv. Cadmium (µg/L)	.5	.3	-	--	.5	--	-	.3
Disolv. Copper (µg/L)	9	24	-	6	9	10	-	5
Total Rec. Cadmium (µg/L)	.8	1.4	-	--	.5	--	-	.4
Total Rec. Chromium (µg/L)	5	12	-	--	2	--	-	5
Total Rec. Copper (µg/L)	24	56	-	13	17	15	-	16
Total Rec. Lead (µg/L)	33	55	-	--	17	21	-	32
Total Rec. Zinc (µg/L)	220	339	-	59	107	149	-	203
Fecal Coliform (cfu/100 mL)	92,061	56,554	-	42,093	34,294	294	-	175,106
				Commercial Source Areas				
Total Solids (mg/L)	-	---	373	-	-	112	127	---
Suspended Solids (mg/L)	-	---	232	-	-	15	58	---
Total Phosphorus (mg/L)	-	---	.47	-	-	.20	.19	---
Disolv. Phosphorus (mg/L)	-	---	.10	-	-	.08	.05	---
Disolv. Cadmium (µg/L)	-	---	.9	-	-	--	.4	---
Disolv. Copper (µg/L)	-	---	18	-	-	6	9	---
Total Rec. Cadmium (µg/L)	-	---	1.8	-	-	--	.6	---
Total Rec. Chromium (µg/L)	-	---	16	-	-	--	5	---
Total Rec. Copper (µg/L)	-	---	46	-	-	9	15	---
Total Rec. Lead (µg/L)	-	---	50	-	-	9	22	---
Total Rec. Zinc (µg/L)	-	---	508	-	-	330	178	---
Fecal Coliform (cfu/100 mL)	-	---	9,627	-	-	1,117	1,758	---
				Industrial Source Areas				
Total Solids (mg/L)	-	958	879	---	-	78	531	267
Suspended Solids (mg/L)	-	763	690	---	-	41	312	146
Total Phosphorus (mg/L)	-	1.50	.94	---	-	.11	.39	.34
Disolv. Phosphorus (mg/L)	-	.51	.20	---	-	.02	.05	.14
Disolv. Cadmium (µg/L)	-	.4	.6	---	-	--	.3	.2
Disolv. Copper (µg/L)	-	18	14	---	-	--	15	10
Total Rec. Cadmium (µg/L)	-	3.3	2.5	---	-	--	1.0	1.0
Total Rec. Chromium (µg/L)	-	15	23	---	-	--	12	6
Total Rec. Copper (µg/L)	-	76	74	---	-	6	41	28
Total Rec. Lead (µg/L)	-	86	60	---	-	8	38	25
Total Rec. Zinc (µg/L)	-	479	575	---	-	1,155	304	265
Fecal Coliform (cfu/100 mL)	-	8,338	4,587	---	-	144	2,705	5,114

1) Single dash indicates source area is not in the land use; double dash indicates insufficient data; triple dash indicates values are shared with those above for the same source area; Rec = recoverable; Disolv. = dissolved.

The relatively large concentrations of zinc in roof runoff indicate that galvanized roofing materials were a source of the zinc. One-third of the residential roofs had galvanized downspouts. Roofing materials also might be a source of copper and lead in the runoff from residential roofs. Concentrations of dissolved copper and total recoverable copper and lead were slightly larger in the residential roof runoff than in runoff from driveways and lawns.

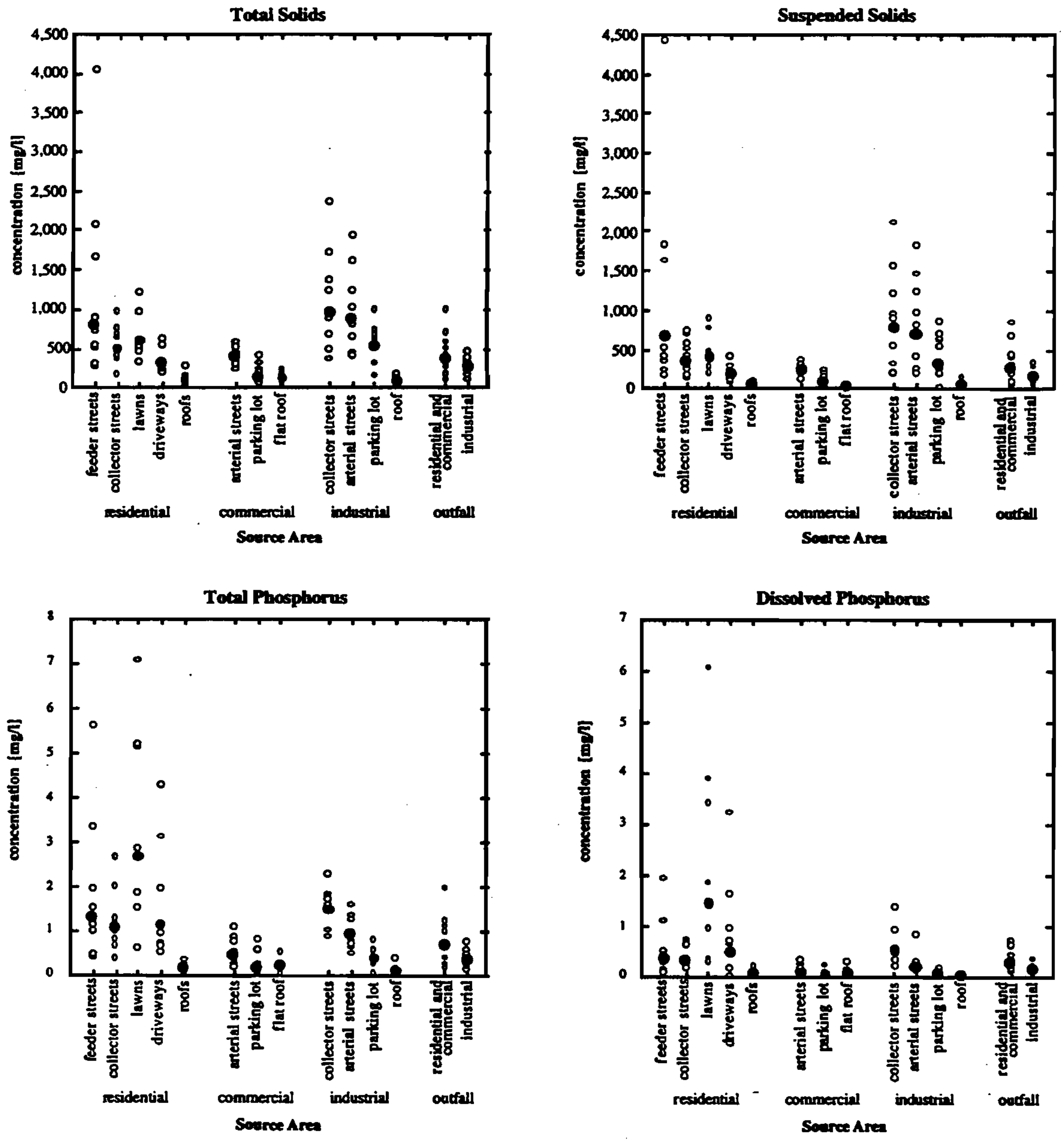

Fig. 4. Distribution of selected contaminant concentrations in stormwater runoff by source area, (black dot represents the geometric mean of the data, white dot represents discrete contaminant concentration).

Fecal coliform bacteria counts appear to be larger in runoff from residential areas than from commercial and industrial areas. Only the bacteria counts in runoff from the roofs are similar among the land uses. The counts are also larger in runoff from the Monroe outfall than from the Syene outfall. If wildlife and pets are the main source of the bacteria, the larger numbers of wildlife and pets in residential areas could certainly be a reason the counts were larger in runoff from these areas. Wildlife habitat is very limited in the industrial and commercial areas. For example, 35 percent of the street surface is covered by tree canopy in the residential area, whereas there is no tree canopy in the other land-use areas.

The geometric mean concentrations of total recoverable zinc in runoff from all the source areas were large enough to exceed the Wisconsin Acute Toxicity Criteria for warmwater sport fisheries 57.39 µg/L respectively (Wisconsin Department of Natural Resources, 1989). Concentrations of total recoverable copper in runoff from all source areas except industrial and residential roofs exceeded the acute toxicity criteria of 8.63 µg/L. The geometric means of the copper and zinc concentrations in runoff from both outfalls also exceeded the acute toxicity criteria. Wisconsin's recreational-use bacteria standard of 400 colony forming units/100 ml was greatly exceeded by runoff from all the source areas except roofs.

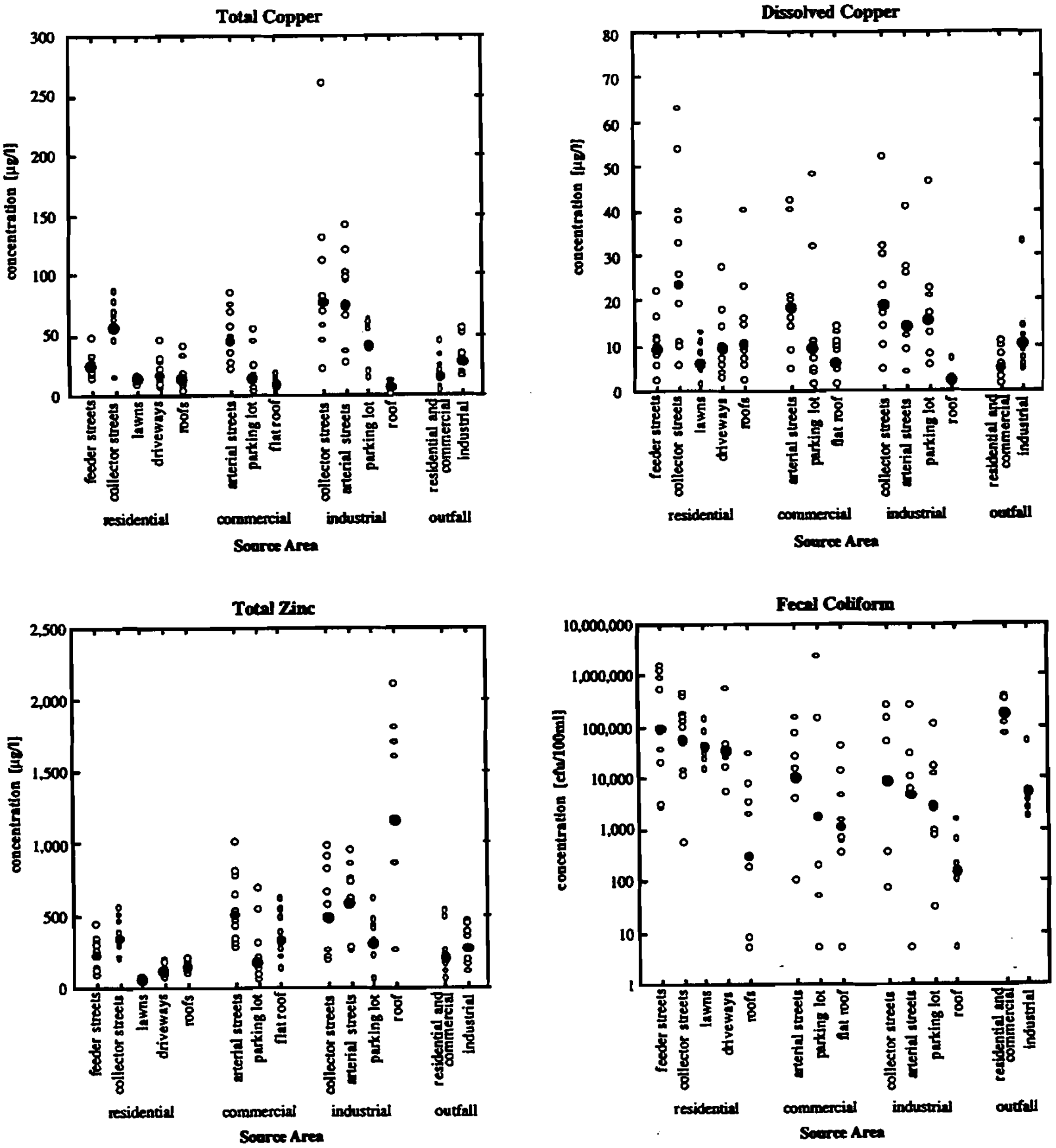

Fig. 5. Distribution of selected contaminant concentrations in stormwater runoff by source area, (black dot represents the geometric mean of the data, white dot represents discrete contaminant concentration).

Runoff Volumes

Accuracy of volumes. Before using SLAMM to estimate the runoff volumes for each source area, the model was verified by comparing model-simulation volumes to volumes measured at the two outfalls. Simulated runoff volumes for eight rainfall events at both the Monroe and Syene outfall areas were determined. The sum of the measured runoff volumes was 19% less and 16% more than the simulated values at the Monroe and Syene outfall areas, respectively.

SLAMM was very sensitive to the hydrological soil type selected for the areas. Soil maps for the Syene area indicated that the hydrological soil group is A/B, but the model substantially underestimated the runoff volumes for this soil group. The soil hydrologic group was changed to C/D because much of the native topsoil indicated by the soil maps had been removed. This change doubled the estimated runoff volume.

Source-area volumes. Runoff volumes were simulated for all storms with source-area contaminant concentrations--10 storms for the Monroe area and 9 for the Syene area (TABLE 5). Model output for each source area included individual storm runoff volumes and totals for all storms. Total runoff volumes (TABLE 8) for each source area were used to calculate the source-area loads.

TABLE 8 Simulated Runoff Volumes Contributed by Each Source Area (1)

	Percent runoff volumes for the following Source Areas								Total
Land Use	Feeder Streets	Collector Streets	Arterial Streets	Lawns	Drive-ways	Roofs	Parking Lots	Side-walks	Volume (cubic m)
	Based on Monitored Rainfall, May 5-July 7,1991								
Residential	38	22	-	7	21	3	-	9	10,285
Commercial	-	9	20	-	-	19	51	1	1,757
Industrial	-	8	1	12	--	28	51	--	14,787
	Based on 4 Years of Rainfall: 1985, 1986, 1990 and 1991 (2)								
Residential	34	20	-	18	17	4	-	7	96,219
Commercial	-	10	21	-	-	20	49	1	13,628

1) Single dash indicates source area is not in the land use; double dash indicates source area contributes less than 1% of the runoff volume; m = meter.
2) Total volume represents an annual average volume for the 4 years of data.

Source areas with the largest amount of connected impervious area produced most of the runoff. Residential streets and roofs had about the same amount of area, but the streets produced most of the runoff from the residential land use. Streets were 100% connected, and the roofs were only 2% connected. Because the impervious source areas in the commercial and industrial land uses were largely connected, the volume of runoff coming from each impervious source area was more closely related to the size of its area. For example, industrial parking lots had the greatest amount of area and also produced the largest volume of runoff.

Lawns had the largest amount of area in the residential and industrial land use, but produced a relatively small runoff volume. Obviously, infiltration of the rainfall greatly diminishes the runoff from lawns. Volumes of runoff from lawns would be expected to increase with larger and more intense rain. A second model simulation was done for the residential and commercial land uses using four years (1985-86 and 1990-91) of rainfall records from a rain gage in the nearby Brewery Creek watershed.

Many larger and more intense rains were represented by the 4 years of rainfall record. Rainfall amounts ranged from 0.15 to 7.06 cm. Runoff volumes from residential lawns changed from 7% to 18% for the longer rainfall record (TABLE 8). An increase in the contribution from lawns only slightly decreased the percent volume of runoff coming from streets, but the lawn contribution was similar to that of driveways. No changes were observed in runoff volumes from the source areas in the commercial land use. This was expected because the commercial land use has no pervious areas.

Contaminant Loads

Contaminant loads were determined for all the source areas using the geometric mean concentrations and the runoff volumes just described. Residential and commercial source-area loads were based on 10 runoff samplings, and industrial source-area loads were based on nine. Dissolved cadmium and total recoverable cadmium, chromium, and lead were not included in the load computations for residential and industrial areas because their geometric mean concentrations were not available for lawn.

Accuracy of loads;. Before using the geometric-mean source area loads to identify critical source areas, their accuracy was checked using two different methods. First they were compared to loads calculated using the concentrations in runoff from each storm multiplied times the runoff volume for each storm. Then, all the individual runoff loads were added together and compared to the geometric-mean source area loads. The load results were similar.

The second check compared the geometric-mean source area loads to measured loads at the storm-sewer outfalls. Because the runoff volumes already had been compared, this was more of a check of the accuracy of the concentrations. Not all the runoff monitored in the source areas was monitored at the outfalls because of equipment failure, so the source-area loads were the sum of individual storms that had outfall data. Six storm loads were summed for the Monroe area, and seven storm loads were summed for the Syene area (TABLE 9). Source-area loads from both the residential and commercial land uses were compared to the Monroe area outfall loads.

TABLE 9 Comparison of Measured and Simulated Contaminant Loads for Monroe and Syene Areas (1)

	Monroe Area			Syene Area		
Contaminant	Measured (grams)	Simulated (grams)	Difference (%)	Measured (grams)	Simulated (grams)	Difference (%)
Total Solids	3,474,681	3,957,285	14	2,748,739	4,453,327	62
Suspended Solids	2,715,502	3,011,355	11	1,834,571	3,525,367	92
Total Phosphorus	5,717	8,754	53	3,579	6,492	81
Dissolved Phosphorus	2,278	3,771	66	1,376	2,435	77
Dissolved Copper	38.9	76.5	97	68.6	71.9	5
Total Rec. Copper	146	213	46	202	228	13
Total Rec. Zinc	1,322	1,978	50	2,084	3,650	75

1) Ratio of difference between measured and simulated loads; Rec. = recoverable.

Although comparison of calculated and measured outfall loads was a good way to test the reasonableness of the source-area loads, the potential problem with contaminant delivery made it difficult to understand how much of the error was due to sampling design. Delivery might have been a problem because the sum of the source-area loads was always larger than the measured loads. If some of each contaminant is not transported to the end of the pipe, the source-area loads certainly would overestimate the outfall loads. Some kind of delivery function is needed to reduce the error between the simulated and measured outfall loads.

The sampling approach certainly played some role in the larger simulated loads. For example, the source-area samplers collected primarily a first-flush sample, especially the street samplers, which would produce a larger concentration than a composite sample. The two outfall samplers collected composite samples.

Source-area loads. A wide range in the percentage of the contaminant loads contributed by each source area was observed for each land use (TABLE 10). Runoff from streets in the residential land use usually had the largest contaminant loads. Phosphorus loads differed somewhat from this trend because runoff from lawns and driveways had loads similar to runoff from the collector streets. Although runoff volumes from lawns were small, phosphorus loads were relatively large because of the high concentrations. Runoff from residential roofs had the smallest contaminant loads, although the percentage contribution of metals was similar to runoff from lawns.

Runoff from parking lots and arterial streets in the commercial land use had the largest contaminant loads. Their percentage contribution was similar for most of the contaminants. Although commercial parking lots contributed more than twice the runoff volume of arterial streets, the geometric mean concentrations for runoff from the arterial streets were more than twice as large as the mean concentrations in runoff from parking lots. Runoff from collector streets had the largest load of fecal coliform bacteria and matched runoff from parking lots and arterial streets in phosphorus loads. The much larger mean concentrations of bacteria and phosphorus found in runoff from collector streets made their loads larger than would be expected with the relatively small runoff volumes. Runoff from sidewalks contributed the smallest contaminant loads.

TABLE 10 Critical Source Areas and Contaminant-Load Percentages Contributed By Each Source Area in Residential, Commercial, and Industrial Land Uses (1)

Contaminant	Feeder Streets	Collector Streets	Arterial Streets	Lawns	Drive-ways	Roofs	Parking Lots	Side-walks	Total Load
				Residential Source Areas (2)					
Total Solids	***56***	***20***	-	7	12	--	-	5	5,664 kg
Suspended Solids	***62***	***18***	-	7	9	--	-	4	4,182 kg
Total Phosphorus	***39***	***19***	-	14	***20***	--	-	8	13,109 g
Dissolved Phosphorus	***31***	15	-	***22***	***23***	--	-	9	4,717 g
Dissolved Copper	***29***	***44***	-	3	16	2	-	6	125 g
Total Rec. Copper	***33***	***45***	-	3	13	1	-	5	288 g
Total Rec. Zinc	***42***	***38***	-	2	11	2	-	5	2,061 g
Fecal Coliform (3)	***57***	***21***	-	5	12	--	-	5	$6{,}287 \times 10^9$
				Commercial Source Areas (2)					
Total Solids	-	***22***	***35***	-	-	10	***31***	2	367 kg
Suspended Solids	-	***27***	***41***	-	-	3	***27***	2	194 kg
Total Phosphorus	-	***29***	***27***	-	-	11	***28***	5	597 g
Dissolved Phosphorus	-	***30***	***20***	-	-	16	***27***	7	169 g
Dissolved Copper	-	***19***	***31***	-	-	10	***39***	1	20.4 g
Total Rec. Copper	-	***22***	***38***	-	-	7	***32***	1	41.1 g
Total Rec. Zinc	-	11	***34***	-	-	***22***	***32***	1	503 g
Fecal Coliform (3)	-	***60***	***22***	-	-	3	10	5	153×10^9
				Industrial Source Areas (2)					
Total Solids	-	***17***	3	15	-	5	***60***	-	6,707 kg
Suspended Solids	-	***21***	4	16	-	4	***55***	-	4,274 kg
Total Phosphorus	-	17	2	***47***	-	5	***29***	-	10,063 g
Dissolved Phosphorus	-	***17***	1	***69***	-	2	11	-	3,690 g
Dissolved Copper	-	***14***	2	6	-	5	***73***	-	158 g
Total Rec. Copper	-	***19***	3	5	-	6	***67***	-	467 g
Total Rec. Zinc	-	7	2	1	-	***60***	***30***	-	7,784 g
Fecal Coliform (3)	-	9	1	***70***	-	1	***19***	-	$1{,}058 \times 10^9$

1) Critical source areas are highlighted in bold, italicized print. A critical source area is defined as a source area that has combined loads contributing at least 75% of the total load for a land use. Rec. = recoverable. kg = kilogram; g = gram.
2) Single dash indicates source area is not in the land use; double dash indicates less than 1% of load.
3) Units for fecal coliform bacteria are colony-forming units (cfu).

Runoff in three different source areas in the industrial land use had at least one contaminant with the largest contaminant load. Runoff from parking lots had the largest loads of solids, dissolved copper, and total recoverable copper. Phosphorus and fecal-coliform loads were largest in runoff from lawns. The small runoff volumes from lawns were not as important as the large phosphorus concentrations and bacteria counts.

Runoff from industrial roofs contributed most of the total recoverable zinc load. Zinc concentrations in roof runoff were about four times the levels in parking-lot runoff, but the roof runoff volume was only one-half the parking-lot runoff volumes. Small runoff volumes from the arterial streets produced the smallest contaminant loads.

Although contaminant loads were a function of both concentration and runoff volumes, their magnitudes were not always a good indicator of commercial and industrial source areas with the largest and smallest loads. Commercial and industrial source areas with the largest and smallest runoff loads were not always the same source areas with the largest and smallest concentrations and runoff volumes. However, the residential source areas with the largest and smallest runoff loads usually had the largest and smallest concentrations and runoff volumes.

Critical Source Areas

Critical source areas were identified as the fewest number of source areas that together could contribute about 75% or more of the contaminant load from a land use. Streets were a critical source area for most contaminants in each land use (TABLE 10). Parking lots were another critical source area for all but two of the contaminants in the runoff from commercial and industrial land uses.

Some of the contaminants had one critical source area with a much larger contribution than the others. For example, suspended solids loads in runoff from residential feeder streets were much larger than the loads in runoff from residential collector streets. Also, total recoverable copper loads in runoff from industrial parking lots were much larger than in runoff from industrial collector streets. Seven of the contaminants had at least one example of one source area contributing at least 50% of the contaminant load.

Critical source areas and their contaminant loads were somewhat unique to the two areas. Loads for each critical source area or the critical source areas themselves might change for the same land uses in other urban drainage areas. Source-area characteristics that greatly affected the source-area loads included the size of the source area, the percentage of connected imperviousness, the type of roofing materials, the traffic volume, and the hydrologic soil type. All of these could change to some degree from one urban drainage area to another.

CONCLUSIONS

Source-area contaminant loads were determined from samples obtained by simple sampling devices and from discharge estimates of an urban runoff model. SLAMM worked well as an urban runoff model used to simulate source-area runoff volumes, for this study.

Streets will probably be a critical source area in every land use. The majority of the runoff loads for many contaminants may be from streets in residential and commercial land uses. Parking lots are probably another critical source area for commercial and industrial land uses. Most of the solids and copper loads in runoff from industrial land uses probably come from parking lots, whereas industrial roofs are probably the most important critical source area for zinc. Contaminant loads in runoff from lawns, especially phosphorus, may become critical if rainfall results in significant runoff.

Identification of critical source areas will focus attention on the most important sources of each contaminant and it could reduce the amount of area needing best-management practices. This is especially true for residential and industrial land uses in the two areas that were studied. Only two out of the six source areas in the residential land use and two out of five in the industrial land use are needed to decrease most contaminant loads by 75%. Only 14% of the residential area would need to be managed to control 75% or more of the loads for all the contaminants except phosphorus. Between 39 and 53% of the industrial area needs to be managed to control 75% or more of the loads for all the contaminants except bacteria and phosphorus.

About 77% of the area in the commercial land use would have to be managed to control at least 75% of the loads for all contaminants except fecal coliform bacteria. A disproportionate contaminant load is not found in a single source area of the commercial land use because there are no lawns and there is about an equal amount of parking-lot and street area. Lawns occupied large areas in the other land uses but produced only a small amount of the contaminant load. Only 33% of the area would need to be managed to control at least 75% of the bacteria load.

Selection of best-management practices for streets and parking lots is probably the most cost effective way of controlling contaminant loads in runoff from the two areas studied. If a sweeping technique could be found that would remove a majority of the contaminants from pavement surfaces, street sweeping could be used for both the streets and parking lots. It would be essential to sweep parking lots to substantially reduce the contaminant load in runoff from industrial land uses. Structural practices, such as infiltration devices, also might be modified for parking lots in both the commercial and industrial land uses.

Critical source areas could also be used when formulating pollution prevention plans. Removal of galvanized roofing materials from roofs probably would reduce the zinc load, especially in runoff from industrial land uses. A decrease in the amount of fertilizers applied to lawns probably would decrease the amount of phosphorus coming from residential and industrial land uses. If more were known about the sources of the contaminants washed off streets and parking lots, pollution prevention could become an important best-management practice for those two source areas.

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