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DEMONSTRATION OF NONPOINT POLLUTION ABATEMENT THROUGH IMPROVED STREET CLEANING PRACTICES

by

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components requires a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solving, and involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources; for the preservation and treatment of public drinking water supplies; and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a vital communications link between the researcher and the user community.

A detailed evaluation of various street cleaning programs can be used by those concerned with urban runoff control to estimate how adequately street cleaning can help meet local control objectives. This report presents the results of many street cleaning tests conducted in San Jose, California. These tests were influenced by normal conditions that can affect the effectiveness of street cleaning programs, including street surface condition, nature of street surface particulates, and parked cars. The effects of these variables are quantified and can be used by planners in many parts of the country. Other aspects of street cleaning and urban runoff were also studied and are presented in this report. These include street surface contaminant accumulation rates, runoff analyses, cost and effectiveness of alternative control measures, decision analyses to select control measures, and roadside airborne particulate concentrations.

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ABSTRACT

This final report presents the results and conclusions from the EPA-sponsored demonstration study of nonpoint pollution abatement through improved street cleaning practices. An important aspect of the study was the development of sampling procedures to test street cleaning equipment performance in real-world conditions. These sampling and experimental design procedures are described in detail and can be used by others to directly determine both street surface contaminant accumulation rates and street cleaning performance using other equipment in their own service areas.

The report describes accumulation rate characteristics of the various pollutants associated with street dirt. The results of performance tests for street cleaning equipment and the factors that are thought to affect this performance are also presented. These data are used to draw conclusions about elements that must be considered in designing an effective street cleaning program.

The study of urban runoff yielded information on runoff flow characteristics, concentrations and total mass yields of monitored pollutants in the runoff, and street dirt removal capabilities and effects on deposition in the sewerage for various kinds of storms. Estimated runoff control effectiveness by various street cleaning programs are also given. These data are summarized here, and urban runoff water quality is compared with recommended water quality criteria and the quality of treated sanitary wastewater.

Cost and labor effectiveness of street cleaning, runoff treatment, and combined runoff and wastewater treatment are also presented. In addition, the results of a special study of airborne dust losses from street surfaces are presented.

A comprehensive bibliography is also included for those who want further information about street cleaning practices and urban runoff characteristics.

This is the first study in a series of projects being conducted in San Jose, California, to evaluate the effects of urban runoff on a receiving water, to determine the source areas of the problem pollutants, and to select the most appropriate mixture of control measures.

This final report is submitted in fulfillment of Grant No. S-804432 by the City of San Jose under the sponsorship of the U.S. Environmental Protection Agency. Woodward-Clyde Consultants participated in this study under a subcontract with the City of San Jose. This project began in September 1976 and was completed in August 1978.

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TABLE 0-1. METRIC CONVERSION TABLE

To Convert	Multiply by	To Obtain
acre	0.405	hectares (ha)
cubic feet per second (cfs)	0.0283	cubic meters per second (m^3/sec)
cubic yard (yd^3)	0.765	cubic meters (m^3)
dollars per pound ($/lb)	0.454	dollars per kilogram ($/kg)
feet (ft.)	0.305	meters (m)
gallons (gal.)	3.79	liters (l)
gallons per curb-mile (gal/curb-mile)	6.10	liters per curb-kilometer (l/curb-km)
inch (in.)	2.54	centimeter (cm)
man-hours per pound (man-hrs/lb)	0.454	man-hours per kilogram (man-hrs/kg)
mile (mi)	1.61	kilometer (km)
miles per hour (mph)	1.61	kilometers per hour (km/hr)
pounds (lbs)	0.454	kilograms (kg)
pounds per curb-mile (lb/curb-mile)	3.55	kilograms per curb-kilometer (kg/curb-km)
pounds per hour (lb/hr)	0.454	kilograms per hour (kg/hr)
pounds per square inch (psi)	0.0703	kilograms per square centimeter (kg/cm^2)
pounds per vehicle-mile (lb/veh-mi)	3.55	kilograms per vehicle-kilometer (kg/veh-km)
pounds per year (lb/yr)	0.454	kilograms per year (kg/yr)
square feet (ft^2)	0.0929	square meters (m^2)
square mile (mi^2)	2.59	square kilometers (km^2)
ton	0.908	tonne (t)
tons per acre per year (tons/acre/yr)	0.446	tonne per hectare per year (t/ha/yr)
tons per cubic yard ($tons/yd^3$)	0.843	tonne per cubic meter (t/m^3)

ACKNOWLEDGMENTS

The Public Works Department of the City of San Jose was the grantee of this project, with Woodward-Clyde Consultants (WCC) acting as consulting engineers for the city.

Sincere gratitude goes to Mr. Anthony N. Tafuri and Mr. Richard Field, both of the Storm and Combined Sewer Section (Edison, New Jersey) of the U.S. EPA Municipal Environmental Research Laboratory, Cincinnati, Ohio, for their valuable guidance and assistance during this project. Mr. James D. Sartor, Vice President, was the project sponsor for Woodward-Clyde Consultants.

The San Jose Public Works Department Operations Division staff participated in this project under the direction of Mr. Richard Blackburn, project manager and Chief Assistant Director of Public Works. Mr. David Pasquinelli acted as project engineer for the city. Special thanks are extended to Mr. J. Michael Sartor, who as project coordinator helped the city staff work efficiently with the staff of WCC. Mr. Michael Sartor was assisted by Mr. William Dotzler and Mr. Greg Rodriques. Mr. Thomas McGee, a private consultant, also provided valuable field and laboratory assistance.

The San Jose Department of Public Works Street and Sewer Maintenance Division staff participated in this project under the direction of Mr. Steven Seward, Superintendent. The Street Sanitation Section was of considerable help in supplying needed street cleaning equipment and operators. The cooperation of Mr. Stan Jacklich, Mr. Joe Padilla, and sweeper operators Messrs. Ernie Gomez, Vince Lopez, and Carlos Vargas was greatly appreciated.

The staff of the Vehicle Maintenance Division of the San Jose Department of Public Works was extremely helpful in determining street cleaner program costs and in keeping the testing equipment in good operating condition. The division is directed by Mr. Fred Wright, Superintendent. Special thanks are also extended to Mr. Jim Albanese.

Two street cleaner manufacturing companies were vital to the success of this project and must be acknowledged. Food Machinery Company (FMC) donated the use of one of their street cleaners and an operator. The help of Mr. Patrick Carroll, Mr. Bill Williams, and Mr. Clifford McNamara of FMC was appreciated. Newark Brush Company, manufacturer, and GCS Inc., distributor, enabled a different street cleaner to be used in the project. Thanks are extended to Dr. John Horton of Newark Brush Company and Mr. Dick Moore and Mr. Don Loper of GCS Inc.

SECTION 1

INTRODUCTION

Past research, notably that conducted for the U.S. Environmental Protection Agency (EPA), by the American Public Works Association (Sullivan 1969), and by the URS Research Company (Sartor and Boyd 1972; Pitt and Amy 1973; Amy *et al*. 1974), has clearly revealed the water pollution potential of street surface contaminants. These projects present strong evidence relating contaminated streets with the contamination of receiving waters. A paper presented at the American Water Works Association annual conference in Boston in 1974 (Pitt and Field 1974) using data from these reports compared the relative importance of untreated nonpoint urban storm runoff with treated sanitary wastewater in their potential effects on receiving waters. Reductions in runoff pollutants could be accomplished by treating the runoff and/or reducing the quantities of pollutants contaminating the runoff.

Although it is clear that pollutants in street dirt have a significant effect on the quality of urban runoff and its effect on receiving water, there are many questions that remain to be answered about the nature of this cause and effect relationship. This project attempted to answer some of these questions and to develop more specific information that was needed in order to select effective control measures.

This study was designed to measure street cleaning equipment effectiveness in removing pollutants from the street surface in a real-world situation. It must be emphasized that the purpose of the project was not to compare specific types of equipment. Rather, it was to determine the range in capabilities of current street cleaning equipment in order to gain information about the general cost and effectiveness of street cleaning programs in removing street surface pollutants.

The study also determined pollutant accumulation rates of street dirt in test areas with different characteristics. Because the pollution characteristics of street dirt are known to vary as a function of particle size (Sartor and Boyd 1972; Pitt and Amy 1973), specific concentrations of various pollutants in different particle size groups were examined. In addition, the effectiveness of street cleaning equipment in removing different particle sizes from the street, and bulk densities for various particle sizes were also examined. These data demonstrate the potential quantity of pollutants that may be affected by street cleaning, the relationship of the pollutants to street dirt particle size, and the way various particle sizes may settle out in a water column (in the sewerage or in a treatment process).

Another area of concern is the transport of particulates in sewerage systems and the associated mass balance relationships. In a combined sewerage system, the sanitary sewage flow velocities are much less during dry weather than during wet weather, when the additional urban storm runoff adds to the flow volumes. During dry weather, primary sanitary solids can settle out in the sewerage, to be flushed out during the high flows of wet weather. This increased concentration of solids can greatly add to the pollution load at the beginning of a storm (Burgess and Niple, Ltd. 1969; Pisano and Queiriroz, 1977). Storms with low runoff volumes may remove large quantities of road surface particulates and transport them to the sewerage system. These particutates may settle out in the sewerage system and be available for flushing during periods of larger flows. Stormwater management techniques utilizing in-line storage can also cause large quantities of solids to build up in the system (Lager and Smith 1974; Pisano and Queiriroz 1977). Some data are available on the buildup and transport of these solids in combined and separated sanitary sewerage systems. Comparisons of the amounts of pollutants in the street dirt and in the runoff from monitored storms provided information concerning deposition characteristics in the sewerage and the relative quantity of pollutants in the runoff originating in land-use areas other than the street surface.

Metcalf and Eddy (Lager and Smith 1974), in a study conducted for the EPA, summarized the technology available for the treatment and management of urban runoff and costs and effectiveness of treatment. Unfortunately, comparable data for street cleaning programs have not been available. Some information on typical street cleaner performance is available from earlier EPA-sponsored studies, but these limited data are based on idealized strip test conditions. Street cleaning performance data, which were used to make cost and labor effectiveness comparisons with alternative control measures, were obtained from tests in real-world conditions.

This study also examined resuspended street surface particulates. Estimates of air pollutant emissions for EPA air quality regions, statewide areas, and specific air basins are very important for continuing air quality control planning. Most utility, industrial, and residential activities (including unpaved roads) have received attention as particulate air pollutant sources. Research by Roberts (1973), MWRI (Cowherd, et al. 1977) and PEDCo (1977) indicates that paved roads should also be considered as important particulate air pollutant sources. Dust from the atmosphere, soil from erosion, and vehicular deposits on paved street surfaces can be disturbed by wind and traffic, causing particulate emissions. Street cleaning may be an effective means of removing these particulates before they can be blown into the air.

Very little quantitative information about particulate emissions from paved street surfaces is available. As part of an overall program to determine the behavior of radioactive fallout, the Nuclear Regulatory Commission has funded continuing studies of particulate residence times in the atmosphere, airborne particulate deposition rates, and resuspension of settled particulates. Some particle resuspension studies have included research of particle resuspension from asphalt streets caused by traffic. Their results and theories are useful, but these studies consider only particles that have settled onto the street surface from the atmosphere. This study examined losses from the total particulate loading on the street surface, including both losses washed into the street through erosion, and tracked onto the street by vehicles.

It is expected that this study will have a two-fold benefit. First, the data obtained will fill significant gaps in current knowledge about the role of street dirt in causing water and air pollution, and to effect its control. Second, the carefully developed experimental design and sampling procedures for various portions of the study can be used by others wishing to obtain specific information about street dirt characteristics and its effects on air and water quality in their own cities.

SECTION 2

CONCLUSIONS

The conclusions presented here summarize the information that has been collected and analyzed as part of this current research. The effect these conclusions may have on a specific city's street cleaning program is expected to vary widely, depending on conditions in that city. For this reason, the study does not yield a set of specific, how-to instructions or generically applicable street cleaning guidelines. Rather, it indicates the type of information that must be considered in designing effective control measures. For more detailed information on results and a description of the analytical structure of the study, the reader is referred to Sections 3 through 6.

SAMPLING TECHNIQUES

One important aspect of the study was the development of sampling techniques that can be used to directly monitor changes in street surface loadings for different test areas over a long period. These sampling procedures (see Appendix A) can easily be used by a city's public works department to determine the specific loading conditions and street cleaning performance necessary. The sampling equipment can be rented if it is not available within the department. With these procedures, street surface loading conditions over a large area can be sampled in a relatively short time. The experimental design procedures (see Appendix B) can be used to determine the number of subsamples required for specific project objectives and study area conditions.

STREET CLEANING EQUIPMENT TESTS

The major element of the demonstration project was an evaluation of the effectiveness of several types of street cleaning equipment currently available under varying real-world conditions. This portion of the study investigated accumulation rates of street dirt in the various test areas, the effect of particle size on pollution concentrations and equipment performance. The study pointed out a number of elements that should be considered in designing an effective pollution abatement program.

One of these elements is the accumulation rate characteristics of street dirt. Tables 2-1 and 2-2 summarize the observed accumulation rate conditions. The study showed that accumulation rates vary widely in different test areas depending on street surface conditions, land use, and activities within the area. Street dirt loading was also found to increase more rapidly immediately after street cleaning, and then level off somewhat after several days. This loading pattern is expected to be due to wind and vehicle-caused turbulence

TABLE 2-1. AVERAGE TOTAL SOLIDS ACCUMULATION RATE

Test Area	Loading Immediately After Cleaning (lb/curb-mile)	Accumulation Rate for Period of Time Since Last Cleaned (lb/curb-mile/day)		
		0 → 2 days	2 → 10 days	10 → 30 days
Keyes-good asphalt	290	17	13	11
Keyes-oil and screens	1800	20	19	16
Tropicana-good asphalt	130	17	13	11
Downtown-good asphalt	170	10	9	9
Downtown-poor asphalt	780	20	20	20

TABLE 2-2. ANNUAL AVERAGE ACCUMULATION RATES FOR VARIOUS POLLUTANTS* (lb/curb-mile/year)

Test Area	Total Solids	Chemical Oxygen Demand	Kjeldahl Nitrogen	Ortho-Phosphates	Lead	Zinc	Chromium	Copper	Cadmium
Keyes-Good Asphalt	4000	440	8.4	0.62	20	2.0	1.5	2.5	0.009
Keyes-Oil and Screens	5800	470	8.6	0.37	7.3	1.4	2.0	2.9	0.008
Tropicana-Good Asphalt	4000	440	8.4	0.62	20	2.0	1.5	2.5	0.009
Downtown-Good Asphalt	3300	440	6.2	0.47	20	2.8	1.8	3.5	0.01
Downtown-Poor Asphalt	7700	880	18	1.1	15	3.7	3.5	7.3	0.02

*The overall annual average accumulation rate for mercury was 0.0015 lb/curb-mile/year, and for asbestos was 3.7×10^{12} fibers/curb-mile/year.

suspending the particles in the air, thus causing increased air pollution. These characteristics should be considered in developing optimum street cleaning schedules.

Table 2-3 shows the median particle size of street surface particulates (before street cleaning) for the five study areas. The areas with better quality street surfaces had more of the smaller sized particles present. The median particle size of street dirt was also found to increase with time between cleaning and decrease with cleaning. Other tests also showed that street cleaning equipment picks up larger particles more effectively than smaller particles. As a result, the small particles tend to increase in abundance with time. Most of the monitored pollutants showed increases in concentration as particle size decreased. Thus, street cleaning equipment effectiveness at removing pollutants in the smaller particle sizes must be considered. It is important to note that street cleaning can remove important amounts of pollutants: this is because they also occur in the larger particle sizes that compose a greater amount of the total solids on the street than do the smaller particle sizes. The analysis of particle size and pollution concentrations

TABLE 2-3. MEDIAN PARTICLE SIZES OF STREET SURFACE PARTICULATES

Test Area	Median particle size (μ) (before street cleaning)
Keyes-good asphalt	200
Keyes-oil and screens	330
Tropicana-good asphalt	150
Downtown-good asphalt	155
Downtown-poor asphalt	230

makes it possible to assess removal capabilities for the various pollutants, thus enabling design of control procedures to achieve specific pollutant removal goals.

An important conclusion derived from the street cleaning equipment tests showed that different test area conditions affected performance more than differences in equipment type. Table 2-4 shows average street cleaning effectiveness values for the different test areas. When the test area was held constant, cleaning frequency and the number of passes affected performance more than differences in equipment. Smoother (asphalt) streets were found to be easier to keep clean than streets with oil and screens surfaces or those in poor condition. The street surface loading values after cleaning were always

TABLE 2-4. AVERAGE REMOVAL EFFECTIVENESS FOR STREET CLEANERS

	Total Solids			Amount Removed Per Pass (lb/curb-mile)							
Test Area	Average Loading Before Cleaning	Percent Removal	Amount Removed Per Pass (lb/curb-mile)	Chemical Oxygen Demand	Kjeldahl Nitrogen	Ortho-Phosphates	Lead	Zinc	Chromium	Copper	Cadmium
Keyes-Good Asphalt	400	33	130	16	0.28	0.018	0.81	0.079	0.051	0.081	0.00030
Keyes-Oil & Screens	2000	9	170	12	0.14	0.0089	0.15	0.066	0.071	0.13	0.00024
Tropicana-Good Asphalt	200	43	100	9.7	0.21	0.017	0.40	0.049	0.039	0.072	0.00027
Downtown-Good Asphalt	240	34	83	11	0.16	0.012	0.49	0.072	0.047	0.093	0.0023
Downtown-Poor Asphalt	1400	40	540	61	0.3	0.079	1.0	0.27	0.24	0.50	0.0015

lower on the asphalt streets in good condition. These findings reinforce the view that street cleaning programs should vary for different service area conditions.

Results of the study showed that the pounds-per-curb-mile* unit is a much more effective pollutant removal measurement than the percentage-of-initial-loading-removed unit. Because of the wide variations in street dirt loadings in different areas, the percentage of removal method cannot give a measurement of the actual number of pounds of pollutants removed in a given time. Such information is required in order to make meaningful cost and labor effectiveness estimates. Figure 2-1 relates the annual total solids removal with the street cleaning frequency for different street surface conditions. Pollutant removal per unit effort decreases with increasing numbers of passes per year.

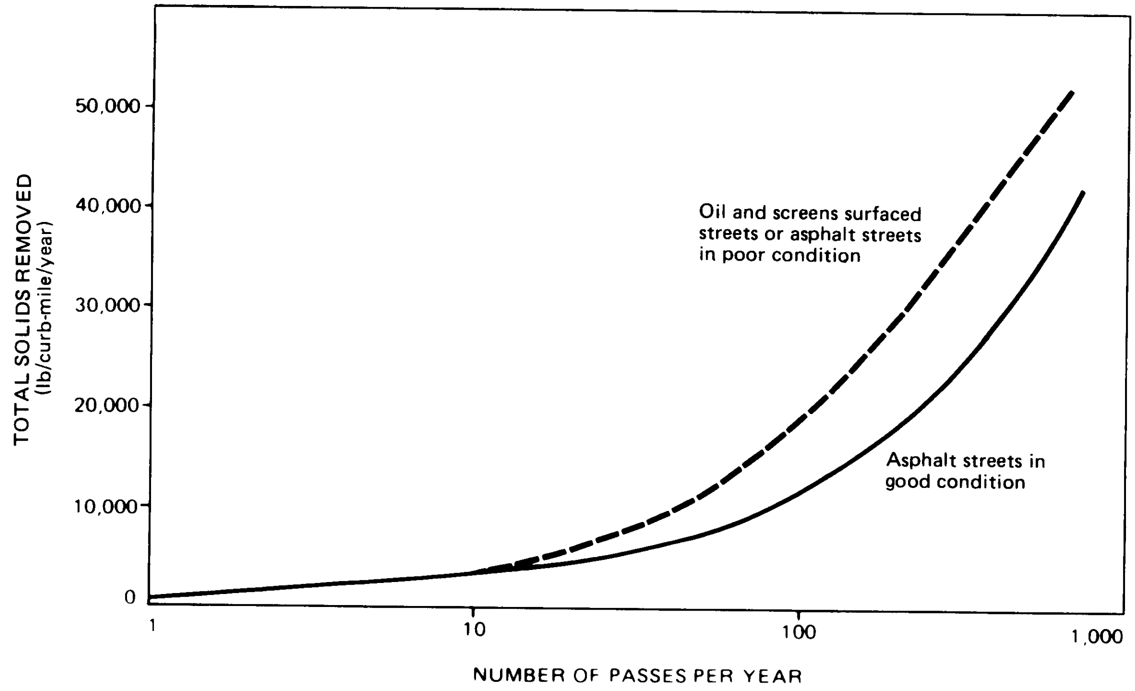

Figure 2-1. Annual amount removed as a function of the number of passes per year.

A model was also developed that describes the effects of parked cars on street cleaning equipment performance, based on the distribution of particulates across the street for different parking conditions (Tables 2-5 and 2-6). The need for parking controls was found to be dependent on street surface condition and parking characteristics.

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*See Metric Conversion Table 0-1.

TABLE 2-5. AVERAGE TOTAL SOLIDS LOADING DISTRIBUTION ACROSS THE STREET

Test Area	Distance to Median Loading Value (ft.)	Distance to 90% of Loading Towards Curb (ft.)
Keyes-good asphalt	6.5	14
Keyes-oil and screens	1.5	6.7
Tropicana-good asphalt	1.0	3.8

TABLE 2-6. EFFECTS OF PARKED CARS ON CLEANING EFFECTIVENESS

	Percent Total Street Surface Solids Removal for the Following Parking and Street Conditions					
	Smooth Streets				Oil and Screened Streets	
Parking Regulations	Light	Moderate	Extensive Day/Night	Extensive 24 hr.	Light	Extensive
With parking prohibition during street cleaning*	48	44	28	15	15	7
No parking restrictions during street cleaning**	36	20	23	43	13	7

*The street cleaner always operates next to the curb with 100% effective parking prohibitions.
**The street cleaner operates along the curb, except when going around parked cars.

PARTICULATE ROUTING AND POLLUTANT MASS FLOW CHARACTERISTICS OF URBAN RUNOFF

This portion of the study examined overall urban runoff flow characteristics for the study areas, sampled the runoff to determine pollution concentrations, investigated the pollutant removal effects and deposition patterns in the sewerage for various storms, and compared runoff water quality with recommended water quality criteria and sanitary wastewater effluent. Table 2-7 summarizes the observed runoff water quality during this study.

The urban runoff flows were measured so that pollutant mass yields could be calculated from the concentration values monitored in the sampling program. These estimates indicated the potential effect urban runoff may have on receiv-

TABLE 2-7. OBSERVED RUNOFF WATER QUALITY CONCENTRATIONS

Parameter, Units*	Number of Analyses	Minimum	Maximum	Average
Common Parameters and Major Ions				
pH, pH units	88	6.0	7.6	6.7
Oxidation Reduction Potential, mV	39	40	150	120
Temperature, °C	11	14	17	16
Calcium	5	2.8	19	13
Magnesium	5	1.4	6.2	4.0
Sodium	5	<0.002	0.04	0.01
Potassium	5	1.5	3.5	2.7
Bicarbonate	5	<1	150	54
Carbonate	5	<0.001	0.005	0.019
Sulfate	5	6.3	27	18
Chloride	5	3.9	18	12
Solids:				
Total Solids	20	110	450	310
Total Dissolved Solids	20	22	376	150
Suspended Solids	20	15	845	240
Volatile Suspended Solids	10	5	200	38
Turbidity, NTU**	88	4.8	130	49
Specific Conductance, µmhos/cm	88	20	660	160
Oxygen and Oxygen Demanding Parameters:				
Dissolved Oxygen	11	5.4	13	8.0
Biochemical Oxygen (5-day)	13	17	30	24
Chemical Oxygen Demand	13	53	520	200
Nutrients:				
Kjeldahl Nitrogen	13	2	25	7
Nitrate	5	0.3	1.5	0.7
Orthophosphate	13	0.2	18	2.4
Total Organic Carbon	5	19	290	110
Heavy Metals:				
Lead	11	0.10	1.5	0.4
Zinc	11	0.06	0.55	0.18
Copper	11	0.01	0.09	0.03
Chromium	11	0.005	0.04	0.02
Cadium	11	<0.002	0.006	<0.002
Mercury	11	<0.0001	0.0006	<0.0001

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*mg/l unless otherwise noted
**Nephelometric turbidity units

ing waters. The general hydrographic information from the study may also be useful in verifying simple urban runoff models.

The runoff sampling program yielded several important conclusions. BOD values were of particular interest because BOD can cause immediate and important oxygen demands on receiving waters. Determining the actual rate of this demand is important in determining the actual effect of BOD on receiving waters and in designing effective control procedures. The study showed an unexpectd increase by a factor of 2 or more (from about 30 mg/l to about 100 mg/l) in BOD values during the 10- to 20-day incubation period of the tests. Sanitary wastewater BOD values typically increase by a factor of only about 0.5 during the same time period. This apparent increase in BOD may be caused by inadequacies in the standard BOD bottle test, or it may indicate that the long-term effects of BOD from urban runoff on receiving waters may be more important than short-term effects.

The relative strengths of pollutants in the runoff were compared with concentrations in the street dirt samples to determine the extent to which street dirt was responsible for these pollutants. The study showed that monitored heavy metal concentrations were much smaller in the runoff than in the street dirt, and organics and nutrient concentrations were much larger. These data indicate that street activity is probably responsible for most of the heavy metal yields, while runoff and erosion from off-street areas during storms is probably responsible for most of the organic and nutrient yields. Thus, if organics and nutrients must be significantly reduced in the runoff, street cleaning alone may not be sufficient.

The pollutant removal capabilities of various storms were studied because of their effect on the loadings remaining on the streets after storms, and the flow and deposition patterns of solids in the sewarage. The monitored storms had a much smaller removal effect in the oil and screens test area than in the test areas with asphalt streets. Interestingly, the first storm (which had a much greater intensity than the other two storms monitored) showed smaller relative removals, probably because larger amounts of eroded material were washed onto the streets. The two less intense storms were capable of almost completely removing street surface particulate material from the asphalt streets without causing large amounts of erosion. Comparisons of the street loading removal values with runoff yields measured at the outfall showed that the two less intense storms deposited more material in the sewerage than did the first storm, with its high runoff volume and flow velocity.

Frequent street cleaning on smooth asphalt streets (once or twice per day) can remove up to 50 percent of the total solids and heavy metal yields of urban runoff. Typical street cleaning programs (once or twice a month) remove less than 5 percent of the total solids and heavy metals in the runoff. Organics and nutrients in the runoff cannot be effectively controlled by intensive street cleaning--typically much less than 10 percent removal, even for daily cleaning.

The comparison of runoff pollutant concentrations with recommended water quality criteria (Table 2-8) showed that the heavy metals--cadmium chromium, lead, copper, mercury, and zinc--as well as phosphates, BOD, suspended sol-

TABLE 2-8. RECOMMENDED BENEFICIAL USE CRITERIA EXCEEDED BY RUNOFF

Beneficial Use	Parameters Exceeding Recommended Criteria
Livestock	lead*
Wildlife	none
Aquatic life	chromium, cadmium*, lead*, mercury*, biochemical oxygen demand, turbidity, suspended solids
Marine life	phosphates*, cadmium, copper, zinc
Recreation	phosphates*
Public Fresh-water Supply	cadmium, lead*
Irrigation	cadmium

*The maximum observed value was >10 times the minimum recommended criteria

ids, and turbidity exceeded some recommended water quality criteria. That does not necessarily mean that a problem exists. However, a problem may arise for these parameters and they should be investigated further in receiving waters. The study showed that aquatic life beneficial uses can be adversely affected by more pollutants than other beneficial uses.

Table 2-9 compares observed runoff water quality with treated secondary sanitary wastewater effluent water quality. The concentrations of many pollutants in the runoff samples were greater than in secondary treated sanitary wastewater effluent. Annual yield comparisons showed that the yields for lead, chromium and suspended solids were greater in the street surface portion of the runoff than in the treated secondary effluent. Thus, urban runoff may cause some greater short- and long-term receiving water pollution problems than the treated sanitary wastewater effluent. Street cleaning and/or runoff treatment may be a more effective control measure than further improvement in treated sanitary wastewater effluent quality for some of the parameters.

COST AND SELECTION OF CONTROL MEASURES

This portion of the study assessed the cost and labor effectiveness of various nonpoint pollution control measures: street cleaning, runoff treatment, erosion control, and combined runoff and wastewater treatment.

San Jose's street cleaning costs for the study period (1976-1977) averaged about $14 per curb-mile cleaned and required about 0.9 man-hours per curb-mile cleaned. The cost and labor requirement analyses of street cleaning showed several important factors. First, street cleaning is labor-intensive* in re-

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*The majority (about 75 percent) of San Jose's street cleaning costs were for labor.

TABLE 2-9. COMPARISON OF RUNOFF WATER QUALITY TO TREATED SECONDARY WASTEWATER EFFLUENT WATER QUALITY

Runoff parameters that exceed the corresponding treated secondary sanitary wastewater effluent parameters for the following conditions:

Average Runoff Concentrations	Peak Runoff Concentrations	Annual Runoff Yield***
Biochemical oxygen demand	Biochemical oxygen demand	Suspended solids
Chemical oxygen demand	Chemical oxygen demand*	Lead*
Suspended solids	Suspended solids*	Chromium
Total organic carbon	Total organic carbon	
Turbidity	Turbidity	
Lead*	Lead**	
Zinc	Zinc	
Cadmium	Cadmium*	
Chromium	Chromium	
	Copper	

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* The runoff condition is >10 times the sanitary wastewater effluent condition.
** The runoff condition is >100 times the sanitary wastewater effluent condition.
*** The runoff annual yield only represented the street surface portion of the total runoff.

lation to other control methods--a charcteristic that must be considered socially beneficial. Second, maintenance costs composed about 30 percent of total program costs in this study. The remaining 70 percent were for capital and operational costs. Thus, equipment replacement for reducing costs would achieve a maximum cost savings of much less than 30 percent. Other costs are constant and would not vary significantly for different types of currently available street cleaning equipment. Figure 2-2 shows that the cost to remove a pound of street dirt increases with increasing numbers of cleaning passes in a year. A cost increase of about tenfold over typical street cleaning program costs may be necessary to realize substantial improvements in urban runoff water quality (greater than 25 percent removal of total solids and heavy metals). Increased street cleaning costs would benefit areas not affected by other typical urban runoff control measures such as air quality, public safety, and litter.

When all costs for the various control measures were considered, per unit pollutant removal costs for street cleaning (Table 2-10) were found to be significantly less than those for separate runoff treatment costs. The study indicated that combined sewage and runoff treatment costs for the facility considered were somewhat less than for special runoff facilities. However, costs of heavy metal runoff treatment could not be considered because of a lack of

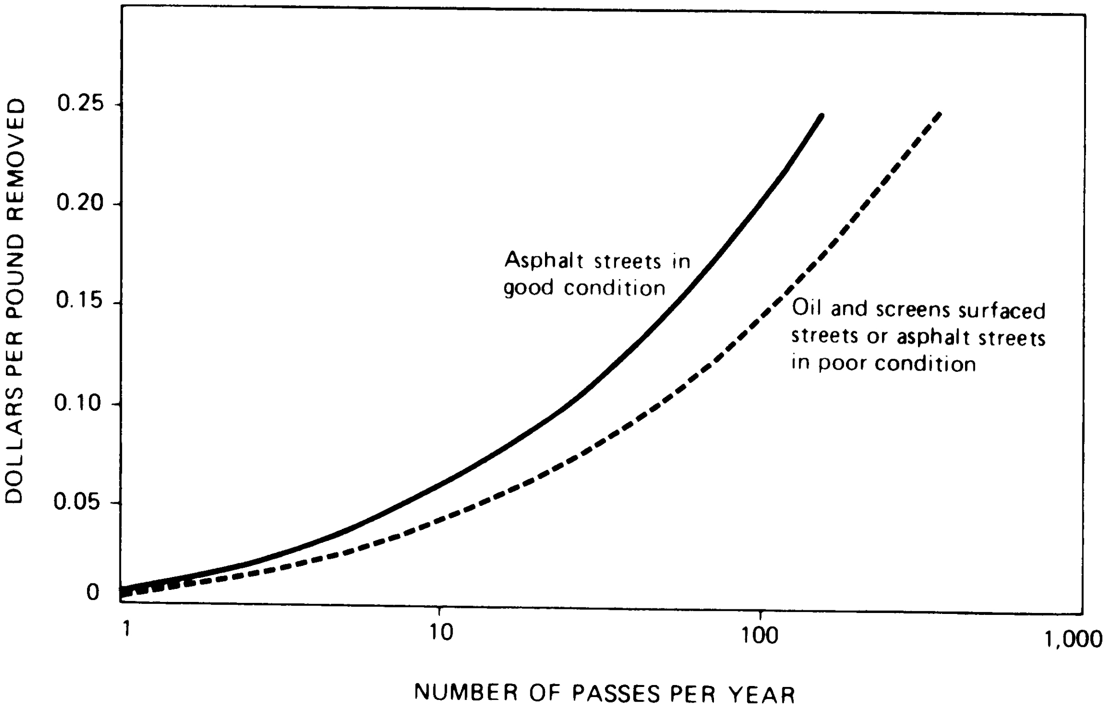

Figure 2-2. Costs to remove a pound of street dirt as a function of the number of passes per year.

TABLE 2-10. COSTS TO REMOVE VARIOUS STREET SURFACE CONTAMINANTS BY THE STREET CLEANING PROGRAMS TESTED ($/pound removed)

Parameters	Minimum	Maximum	Average*
Total Solids	0.03	0.17	0.11
Suspended Solids**	0.05	0.33	0.21
Chemical Oxygen Demand	0.23	1.4	1.0
Biochemical Oxygen Demand**	0.46	2.9	2.0
Orthophosphate	180	1600	920
Kjeldahl Nitrogen	11	100	63
Lead	14	93	38
Zinc	52	290	180
Chromium	58	360	240
Copper	28	190	130
Cadmium	6100	58,000	34,000

*These values are averaged for the different test areas.
**Estimates.

data. Costs to remove heavy metals from runoff are expected to be much greater than the street cleaning costs. It should be added that other control measures affect only water quality, while street cleaning has multiple benefits and can also improve air quality, aesthetic conditions, and public safety.

DUST LOSSES FROM STREET SURFACES TO THE AIR

This portion of the study investigated dust (fugitive particulate) concentration increases and emissions from street surfaces. Various influencing factors such as traffic density, weather conditions, and street surface conditions were also monitored. The loading of particulates on the street surface is believed to be an important factor in the level of these emissions, and improved street cleaning may play an important role in their control. Downwind roadside particulate concentrations were found to be about 10 percent greater than upwind concentrations (on a number basis). About 80 percent of the concentration increases, by number, were associated with particles in the 0.5 to 1.0 micron size range, but about 90 percent of the particle concentration increases, by weight, were associated with particles greater than 10 microns. The study showed that street surface particulate accumulation rates decrease with the passage of time after street cleaning or a significant rain. It is thought that this decrease is caused by particulate losses to the air. Differences between initial street surface particulate accumulation rates and the lower rates observed several days after street cleaning were used to estimate dust losses. These calculations showed that about one week after street cleaning, approximately 4 to 6 lb/curb-mile per day of particulates were lost to the air. This loss rate corresponds to an automobile use emission rate of about 0.66 to 18 grams per vehicle-mile. This rate increases for longer cleaning intervals and varies widely for different conditions.

Dust levels in the cabs of street cleaning equipment were also investigated with and without the use of the water spray. The study showed that, for a state-of-the-art four-wheel mechanical street cleaner, the water spray was very effective in controlling dust inside the cab and in the immediate vicinity of the street cleaner. The spray, however, did not significantly reduce the total high dust levels in the area immediately behind the street cleaner.

SECTION 3

STREET CLEANING EQUIPMENT TESTS

SUMMARY

The objectives of the study of street cleaning equipment performance were:

- To determine the accumulation rate of street surface particulates between each street cleaner test.
- To determine the characteristics of street dirt in relation to particle size and concentrations of specific pollutants.
- To investigate various street cleaning practices under actual field conditions (including various street surface conditions, residual particulate loading, traffic density, parked car, and climatic conditions) in order to determine the range of possible cleaning performances offered by current types of street cleaning equipment.

Accumulation Rates

The accumulation rate characteristics of street surface contaminants must be known in order (1) to understand the magnitude of the problem a street cleaning program must address, and (2) to determine the most effective control methods. This study showed that the accumulation rates varied widely from test area to test area. These variations are thought to be due to street surface conditions and to land-use patterns and activities within the test area (e.g., vacant lots, commercial development, pedestrian and automobile traffic, and parking). Such variations should be considered in scheduling street cleaning programs for different types of areas.

The study also showed that the median particle size of street surface contaminants increased with time between street cleaning, then decreased with cleaning. These data also show that street cleaning equipment picks up large particles much more effectively than small particles. Thus the small particles, which have higher concentrations of pollutants, tend to build up on the street surface.

The loading was found to increase more rapidly immediately after the street was cleaned; accumulating rates decreased as the number of days after street cleaning increased, probably because wind and automobile-related air turbulence suspend the particles in the air. This should be considered in establishing optimum street cleaning frequencies. It should be remembered that although longer periods between street cleaning may not result in similarly increased loadings, they could cause greater road-side airborne particulate concentrations (see Section 6).

Effects of Particle Size

Because street cleaning equipment performance varies with particle size, analyses based on particle size groupings were necessary to determine street cleaning performance for specific pollutants. Almost all of the monitored pollutants showed increases in concentration as particle size decreased. Street cleaning equipment was also found to be more effective at removing larger, aesthetic-related particles than at removing smaller particles that have generally higher pollutant concentrations. It is important to note, however, that street cleaning equipment can remove important quantities of these pollutants under many conditions. Typically, a much greater quantity of the total solids on the street is of the larger particle sizes. Even though concentrations of the monitored pollutants are not as high in the larger particle sizes, important amounts are found in them because of their greater quantity. Assessemnts of removal capability for various pollutants can indicate what mix of control measures should be used to achieve specific goals.

Equipment Performance

The equipment performance tests showed that the differences in test areas affected the initial (before cleaning) and residual (after cleaning) loadings much more than differences in equipment type. Furthermore, within any one test area, the cleaning frequency and number of passes influenced before and after loadings much more than differences in equipment type. It was found that smoother streets (asphalt) can be maintained in a much cleaner condition than rougher-surfaced (oil and screens) streets or streets in poor condition. Street cleaning programs should, therefore, vary for different street surface conditions.

Because of the variability in initial loadings in different areas, it is important to measure cleaning effectiveness on a pounds-removed-per-curb-mile basis rather than on a percentage-of-initial-loading-removed basis. For example, removing a small percentage of the initial loading in a dirty industrial area could remove more pollutants than removing a high percentage of the initial loading in a clean commercial area. The pounds-removed-per-curb-mile value is necessary in designing a program to meet a goal of removing a certain number of pounds of pollutant in a given time. This measurement also makes it possible to compare the unit costs ($/lb* removed) and unit labor (man-hr/lb* removed) requirements of street cleaning with these values for alternative control measures.

STRUCTURE OF THE STUDY

Several street cleaning programs using various types of equipment and levels of effort were evaluated. This evaluation was the major element of

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*See Metric Conversion Table 0-1.

the demonstration project. The following types of street cleaning equipment were studied under various operating conditions and cleaning frequencies:

- four-wheel mechanical street cleaner
- state-of-the-art mechanical four-wheel street cleaner
- vacuum-assisted street cleaner

The purpose of this project was not to compare these specific types of street cleaning equipment, but to determine the range and capabilities of street cleaning equipment in general. These specific pieces of street cleaning equipment were selected for study because they represent three different generic types and because they were readily available for testing. It must be stressed that the performance as measured in these tests may not be an accurate indication of the ability of this equipment under other operating conditions. The scope and intent of this project was to demonstrate the range of possible cleaning effectiveness of different types of street cleaning equipment under a variety of real-world operating conditions. The available resources for the project required that the study be conducted in one city with a limited selection of available equipment.

Street cleaning equipment performance is thought to be very sensitive to operator and maintenance skill. The equipment must be adjusted adequately and maintained and operated in a manner to optimize debris removal and minimize costs. The operators and maintenance personnel used during these tests were supplied by the manufacturers and by the city of San Jose's Public Works Department. They were all well trained and skilled and operated the test equipment in an optimum and recommended manner.

Eight potential study areas were considered within the city of San Jose. Three were selected as being representative of the variety of conditions found in San Jose and many other cities: the Tropicana study area, the Keyes Street study area, and a Downtown study area. The selection criteria and more specific information about the study areas are found in Appendix C.

Because of variable street surface conditions, the Downtown and Keyes Street study areas were divided into two test areas, while the Tropicana study area was best treated as a single test area. Thus a total of five test areas were used in the initial field activities:

- Tropicana - good asphalt street surface test area
- Keyes Street - good asphalt street surface test area
- Keyes Street - oil and screens street surface test area
- Downtown - good asphalt street surface test area
- Downtown - poor asphalt street surface test area

Figure 3-1 shows the San Francisco Bay Area and the general location of the city of San Jose. Figure 3-2 shows the three study areas selected and their location within the city of San Jose.

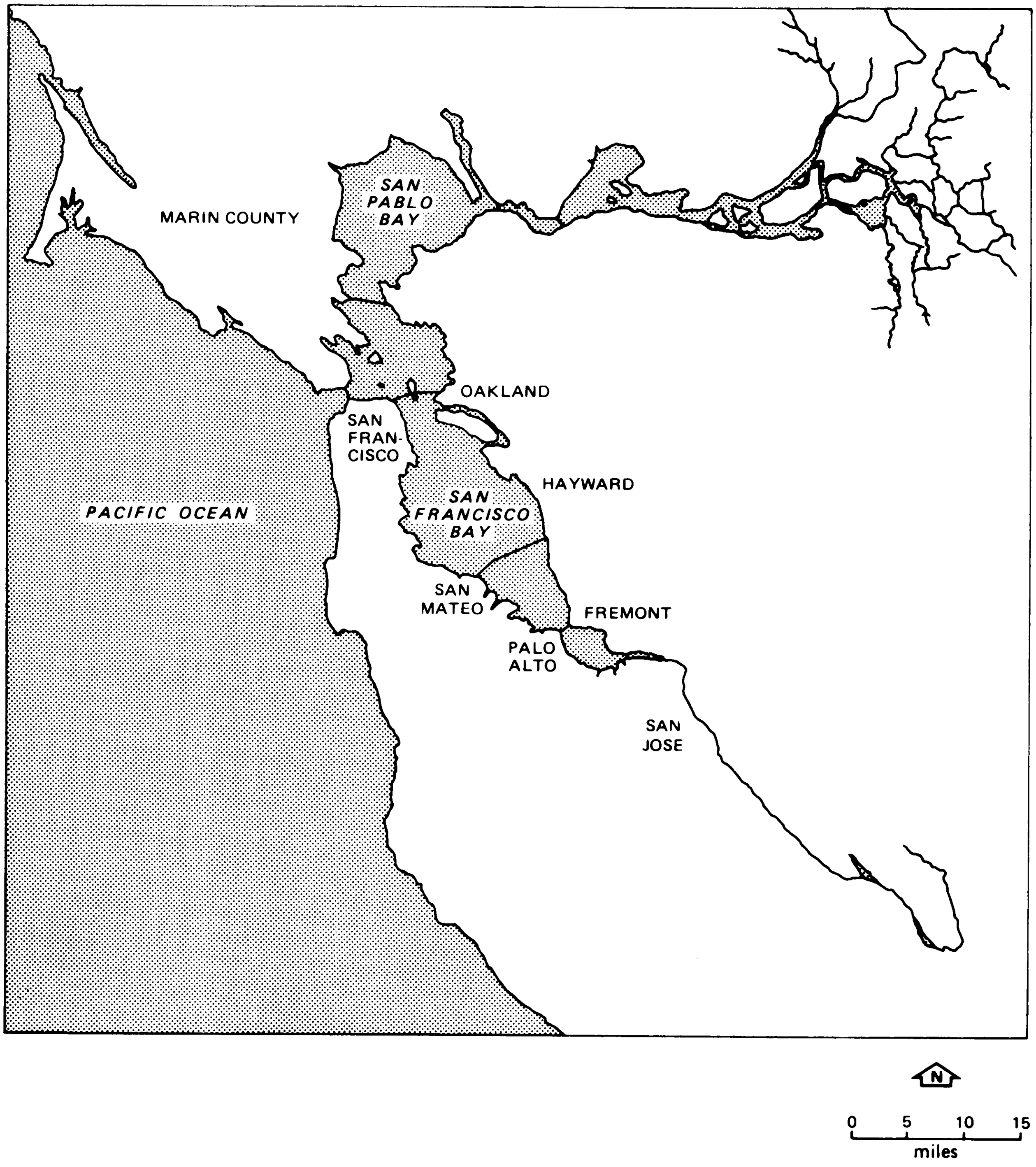

Figure 3-1. San Francisco Bay Area showing the general location of the City of San Jose.

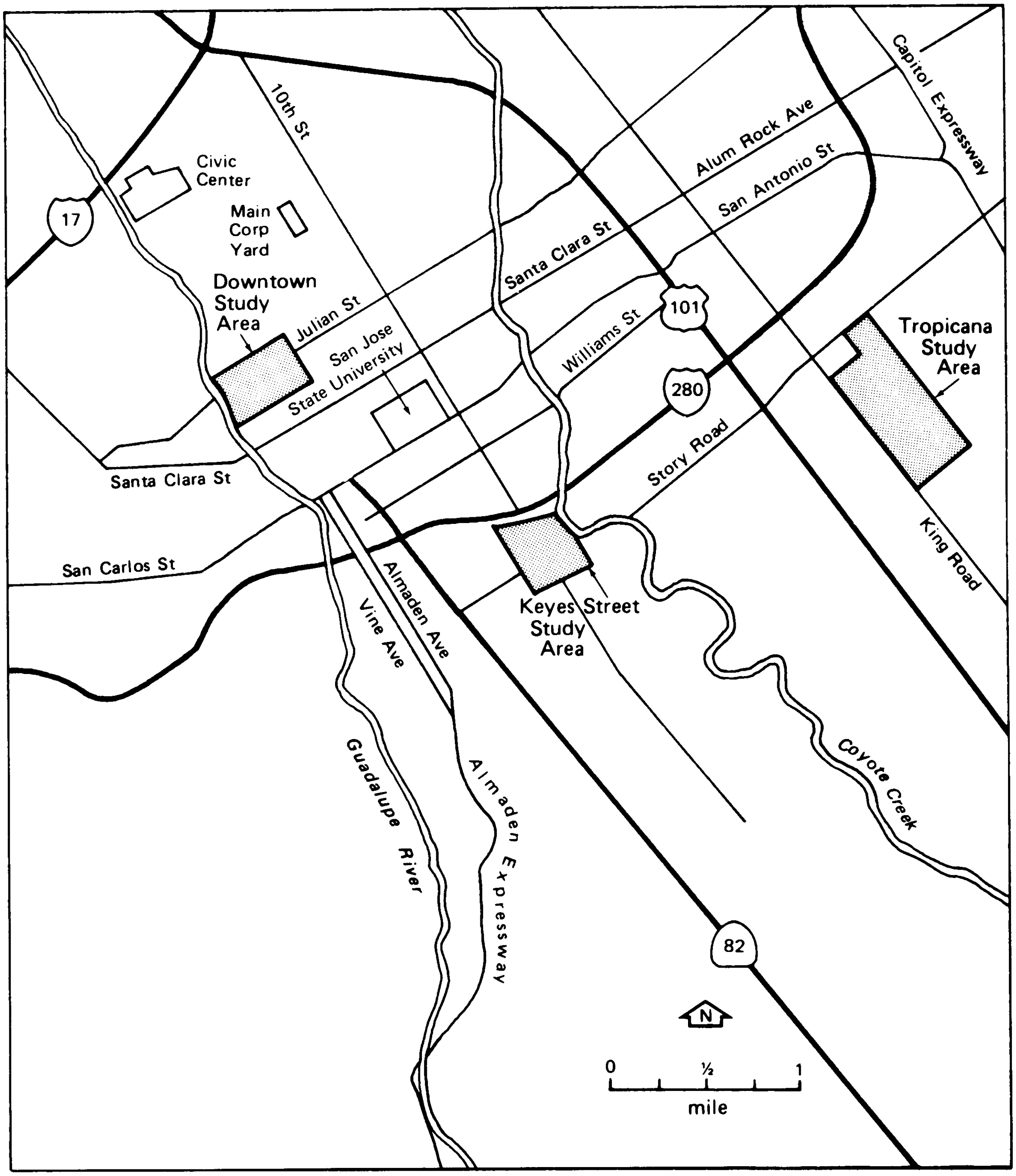

Figure 3-2. Map showing the location of the three study areas.

The cleaning frequencies used in this study ranged from two passes every day to one pass every seven weeks. Each piece of equipment was evaluated in the field during two different seven-week periods: once in the first and once in the second phase (with the exception of the vacuum-assisted street cleaner). The first two weeks of each seven weeks of equipment evaluation used daily cleaning. A single pass was made every weekday during the first week and two passes were made each weekday during the other week. The last five weeks of each test period used weekly cleaning intervals. Equipment was rotated through the different testing areas at the end of each cleaning period.The test schedule is shown in Table 3-1. One hundred sixty-three cleaning passes were conducted, and about 20,000 samples were collected during the demonstration project in the test areas. This schedule allowed the different characteristics and long-term seasonal differences in the test areas to be included in the evaluation of the range of equipment effectiveness.

In addition to cleaning the specific test area, an adjacent buffer zone up to three times the size of the test area was also cleaned in order to reduce potential edge effects (tracking of particulates into the test areas from the adjacent areas, which were usually significantly dirtier or cleaner).

The long-term and frequent sampling in the test areas made it possible to directly measure accumulation rates of street surface contaminants. Street surface samples were collected within a few hours before and after street cleaning by the procedures described in Appendix A. The idealized loading pattern resulting from sampling at these intervals, a sawtooth pattern depicting the deposition and removal of street surface particulates, is illustrated in Figure 3-3. The accumulation rate can be determined by calculating the angle of the slope between adjacent sampling periods. The two factors affecting the accumulation rate are the deposition rate and the removal rate.* The deposition rate

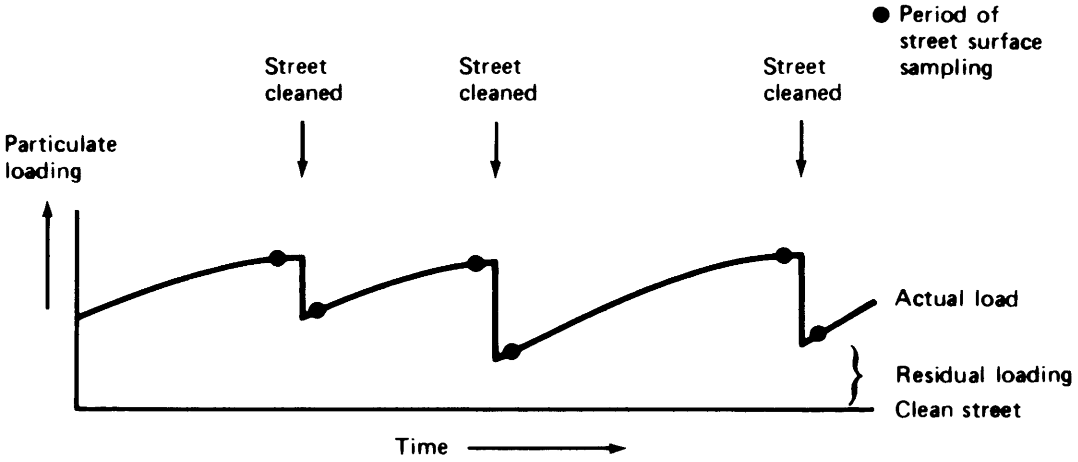

Figure 3-3. Sawtooth pattern associated with deposition and removal of particulates.

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*Accumulation rate = deposition rate - removal rate.

TABLE 3-1. STREET CLEANING SCHEDULE FOR SAN JOSE STUDY AREAS

5-Day Work Week	Equipment Type and Number of Passes per Week		
	Downtown	Keyes	Tropicana
12/13 → 12/17/76	A-5		
12/20 → 12/24			A-10
12/27 → 12/31		A-1	
1/3 → 1/7/77		A-1	
1/10 → 1/14		A-1	
1/17 → 1/21		A-1	
1/24 → 1/28			
1/31 → 2/4		B-10	
2/7 → 2/11			B-5
2/14 → 2/18		B-1	
2/21 → 2/25		B-1	
2/28 → 3/4		B-1	
3/7 → 3/11		B-1	
3/14 → 3/18		B-1	
3/21 → 3/25			
3/28 → 4/1			C-5
4/4 → 4/8		C-10	
4/11 → 4/15			C-1
4/18 → 4/22			C-1
4/25 → 4/29			C-1
5/2 → 5/6			C-1
5/9 → 5/13			C-1
5/16 → 5/20			
5/23 → 5/27			
5/20 → 6/3			
6/6 → 6/10			A-5
6/13 → 6/17			
6/20 → 6/24		A-10	
6/27 → 7/1		A-1	A-1
7/4 → 7/8		A-1	A-1
7/11 → 7/15		A-1	A-1
7/18 → 7/22		A-1	A-1
7/25 → 7/29		A-1	A-1
8/1 → 8/5			
8/8 → 8/12		B-5	
8/15 → 8/19			B-10
8/22 → 8/26		B-1	B-1
8/29 → 9/2		B-1	B-1
9/5 → 9/9		B-1	B-1
9/12 → 9/16		B-1	B-1
9/19 → 9/23		B-1	B-1

Notes: A = 4-wheel mechanical street cleaner
B = state-of-the-art 4-wheel mechanical street cleaner
C = 4-wheel vacuum-assisted mechanical street cleaner

is a function of the characteristics of the area, such as climate, land use, traffic, and street surface conditions. Removal can occur by street cleaning or naturally by winds or rains.

The data collected in these test areas were also used to identify the range of performances that may be expected from currently available street cleaning equipment. Differences of removal values (lb/curb-mile removed) instead of percentage removals (percentage of initial loading removed) for the various test conditions are used as a more meaningful measure of equipment performance.

ANALYTICAL PROGRAM

The design of the sampling program required decisions as to the method of sample collection (see Appendix A) and the extent of sampling (see Appendix B). Because the objectives of this project were unique, new procedures had to be carefully developed so that the sampling program could yield sufficient information. The following elements summarize the particulate sample analysis program:

- Estimates of the volume of the hopper contents in the street cleaning equipment were made after each test; the hopper contents were also sampled and analyzed for particle size distributions.
- All samples (accumulation, hopper, across-the-street, driving lane, and before and after tests) were sieved for particle size analyses by using a 0.25-in. wire screen; Tyler screens numbered 10 (2000 μ) 20 (850 μ) 30 (600 μ) 60 (250 μ) 140 (106 μ) and 325 (45 μ); and the pan.*
- The bulk density of each of the above sieved samples was determined.
- The loading (lb/curb-mile) of each particle size was calculated for accumulation and test samples; the percentage of sample in each size was also calculated for accumulation, hopper, and test samples.
- The before and after test samples for each size, each test area, and each equipment test phase were combined for the following analyses:**

  Lead (Pb)
  Zinc (Zn)
  Chromium (Cr)
  Copper (Cu)
  Cadmium (Cd)
  Chemical oxygen demand (COD)
  Kjeldahl nitrogen
  Total orthophosphates (Ortho PO_4)
  Mercury (Hg) (16 analyses only)
  Asbestos (8 analyses only)

---

*The pan collects all of the material passing through the finest screen.

**Approximately 8 sizes x 3 test areas x 5 equipment test phases = 120 samples.

CONCENTRATIONS OF STREET SURFACE CONTAMINANTS AS A FUNCTION OF PARTICLE SIZE

Previous studies (Sartor and Boyd 1972; Pitt and Amy 1973) have demonstrated the importance of chemical analyses of different particle sizes instead of the total sample. The chemical character of each size is relatively constant (within a specific test area and time frame), but the percentage composition of the different sizes can vary significantly. Therefore, analyses of different sizes can vary significantly, and analyses of different particle sizes yield more useful information than total sample analyses.

Each collected sample was divided into eight particle sizes:
(<45 μ; 45 → 106 μ; 106 → 250 μ; 250 → 600 μ;
600 → 850 μ; 850 → 2000 μ; 2000 → 6370 μ; and >6370μ).
All of the samples collected in each test area for each equipment type were combined for chemical analyses by particle size. These chemical analyses were used to calculate total pollutant loadings for all of the samples collected.

Tables E-1 through E-5 of Appendix E present all the particle size pollutant concentration data obtained during the project, while Figures E-1 through E-10 graphically summarize pollutant concentrations for the first test phase. Figures are presented for chemical oxygen demand (COD), total orthophosphates (Ortho PO_4), Kjeldahl nitrogen, lead (Pb), zinc (Zn), chromium (Cr), copper (Cu), and cadmium (Cd) for each of the five test areas and for eight particle sizes, plus a weighted average for most of the samples. The weighted average is based on the total calculated loadings for each test area and parameter. Figures E-9 and E-10 present mercury and asbestos concentrations as a function of particle size for all test areas combined.

The pollutant strengths are presented as milligrams of pollutant per kilogram of total solids (equivalent to ppm), except for asbestos, which is expressed as fibers per gram of total solids. Almost all of the parameters for all of the test areas show higher concentrations with decreasing particle size. Mercury, cadmium, zinc, lead, Kjeldahl nitrogen, and total orthophosphates show the highest concentrations with smaller particle sizes, while copper and chromium show the lowest concentrations with the smallest particle size. The asbestos information presented is subject to wide variation because of the small number of fibers counted in each sample aliquot. The lengths of the fibers observed ranged from 5 to 250 microns in length. Generally, the smallest particle sizes had the shortest observed maximum fiber lengths.

Figure 3-4 shows the particle size distribution for each test area. This figure is based on the "initial" loading samples (samples collected immediately before the streets were cleaned) to minimize the effects of street cleaning on the particle size distribution. The average median particle sizes ranged from about 150 μ to 400 μ, with asphalt streets in good condition having the smallest median particle sizes and the poor condition asphalt streets and oil and screens surfaced streets having the largest particle sizes.

Only the oil and screens test area had significantly different pollutant strengths associated with the different particle sizes than the other test areas. The oil and screens pollutant concentrations are generally less (by about half) than the concentrations from the other test areas. This reduction is due to large quantities of street wear products "diluting" the pollutants originating

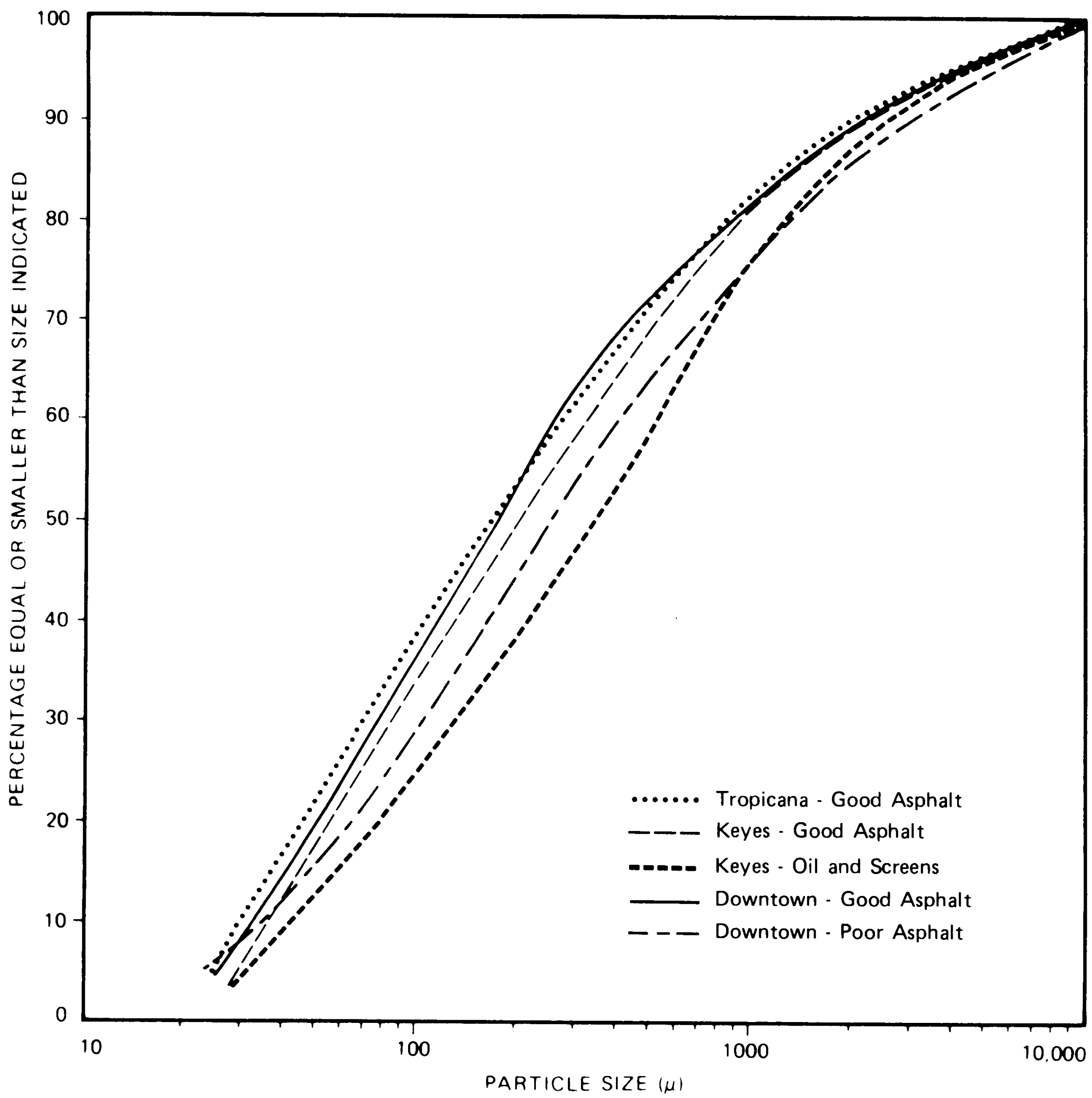

Figure 3-4. Particle size distribution of "initial" loading samples.

from other source areas (such as vehicle wear products and local erosion). None of the different test periods had significantly different pollutant strengths. The pollutant strengths observed were all within the range of strengths reported in previous investigations, as shown on Table 3-2. This particle size information was used to determine the accumulation rates and street cleaning equipment performance for the different pollutants.

TABLE 3-2. AVERAGE NATIONWIDE POLLUTANT STRENGTHS ASSOCIATED WITH STREET SURFACE PARTICULATES

Parameter (ppm[a] except as noted)	Mean Strength	Minimum Strength	Maximum Strength	Standard Deviation	Ratio of Standard Deviation to Mean
BOD$_5$ (b)	70,000[e]	8500[e]	270,000[e]	80,000[e]	1.1
COD (b)	140,000	17,000	530,000	160,000	1.1
Ortho PO$_4$ (b)	1300	14	6700	1400	1.1
Total PO$_4$ (b)	2900	210	5400	f	-
NO$_3$ (b)	800	20	16,000	2600	3.3
NH$_4$ (b)	2600	600	5400	f	-
Kjeldahl N (b)	3000	450	13,000	3100	1.0
Cd (b)	3.4	0	25	3.6	1.1
Cr (b)	210	3	760	110	0.52
Cu (b)	100	8	290	100	1.0
Fe (b)	22,000	2200	72,000	11,000	0.50
Pb (b)	1800	0	10,000	2,000	1.1
Mn (b)	420	100	1600	220	0.52
Ni (b)	35	0	170	38	1.1
Sr (b)	21	0	110	21	1.0
Zn (b)	370	21	1100	210	0.57
Total coliforms (no./gram (d)	2.5×10^6	1.2×10^4	8.6×10^7	g	-
Fecal coliforms (no./gram) (d)	1.7×10^5	6.0	1.7×10^7	g	-
Asbestos (fibers/gram) (c)	160,000	0	770,000	180,000	1.1
Rubber (c)	4600	500	11,000	2,600	0.57
p, p-DDD (d)	0.082	0.0002	0.27	0.080	0.98
p, p-DDT (d)	0.075	0.0004	0.38	0.12	1.6
Dieldrin (d)	0.028	0.003	0.074	0.028	1.0
Endrin (d)	0.00028	0	0.0022	0.00073	2.6
Lindane (d)	0.0022	0	0.019	0.0063	2.9
Methoxychlor (d)	0.50	0	3.1	1.1	2.2
Methyl parathion (d)	0.0024	0	0.022	0.0073	3.0
PCBs (d)	0.77	0.07	2.3	0.76	1.0

[a] ppm = microgram of pollutant per gram of total dry solids; the mean total solids (b) accumulation was 150 lb/curb-mile/day, with a range of 3 to 2700 and a standard deviation of 370 lb/curb-mile/day.

[b] Amy, et al. (1974) - a compilation of the results of many studies

[c] Shaheen (1975)

[d] Sartor and Boyd (1972)

[e] BOD = 1/2 COD (see Colston, 1974)

[f] Few samples (less than 10)

[g] Very large variance.

These data indicate that a control measure (such as conventional street cleaning methods) that is most effective in removing large particle sizes may be unable to remove enough of those pollutants found in the less abundant, smaller particle sizes. Therefore, it may be difficult to meet objectives unless extra effort is expended. However, street cleaning may remove important amounts of these pollutants because they are also found in the more abundant larger particle sizes. The effectiveness of street cleaning, therefore, depends on the specific service area characteristics and program objectives.

DETERMINATION OF ACCUMULATION RATES OF STREET SURFACE CONTAMINANTS

This portion of the study was aimed at determining specific accumulation rates in the test areas. This information must be known before an effective street cleaning program can be designed. The rainfall pattern during the time of the study was examined and those periods in which rains had caused significant natural removal of street surface contaminants were eliminated from analyses. In order to determine accumulation rates of different pollutants, the samples were analyzed on a particle size basis as described above. This procedure was essential because different particle sizes have different concentrations of pollutants. Equipment performance also varies with particle size, which affects the overall amount of various pollutants that can be removed by street cleaning.

Sources of Street Surface Contaminants

Most of the street surface contaminants (by weight) are a function of the local geological conditions, with added fractions resulting from motor vehicle emissions and wear. For smooth streets in good repair, minor contributions are made by wear of the street surfaces. The specific make-up of street surface contaminants is a function of many site conditions and varies widely.

Table 3-3 presents chemical analyses for some possible street comtaminants. Most of the materials listed are high in volatile solids. Brake linings contribute extremely high concentrations of lead, chromium, copper, and nickel. Rubber has high concentrations of lead and zinc. Asphalt pavement has a high concentration of nickel. Cigarettes have high concentrations of lead, chromium, copper, nickel and zinc (Shaheen 1975).

Usually, most street surface particulates are the products of erosion of local soils. Nitrogen and phosphorus are contributed by local plants and soils and are carried onto the street surface by rain, wind, and traffic. Potentially adverse quantities of polychlorinated biphenyls (PCBs) have also been shown to originate from local soils (Shaheen 1975).

Although a small percentage (by weight) of the street surface pollutants results from wear and emissions from motor vehicles, the toxicity of these contaminants increases their importance. Deposits of grease, petroleum, and n-paraffin can result from spills or leaks of vehicle lubricants, antifreeze, or hydraulic fluids. Phosphorus and zinc, used as oil additives, can also be deposited from spills. Lead deposits can be deposited from spills or leaks, or combustion of leaded fuels, and (along with zinc) from tire wear. Asbestos can be deposited from wear of the clutch, brake linings, and tires. Copper, nickel, and chromium can be deposited from wear of metal from platings; bearings, and other moving parts. Roadway abrasion is another source of street pollutants, although studies show that such contributions, for smooth streets in good repair, are insignificant compared to contributions due to traffic activities and erosion of local soil (Shaheen 1975).

Chlorides are deposited primarily from deicing compounds with some additional chlorides resulting from roadway abrasion and local soils. Chloride accumulation in regions with snow is probably traffic-dependent because of the application of more deicing material on well-traveled streets.

TABLE 3-3. ANALYSIS OF POSSIBLE STREET SURFACE CONTAMINANTS

Material	Tot. Vol. Solids (mg/g)	BOD[a] (mg/g)	COD (mg/g)	Grease (mg/g)	Petroleum (mg/g)	n-Paraffins (mg/g)
Gasoline	1000	150	680	1.3	1.3	1.3
Lubricating Grease	970	140	-	750	670	570
Motor Oil	1000	140	220	990	940	850
Transmission Fluid	1000	100	200	990	940	880
Antifreeze	990	38	1100	140	70	6.1
Undercoating	1000	90	310	960	180	120
Asphalt Pavement	64	1.2	86	21	15	9
Concrete	71	1.4	64	2.7	1.3	1
Rubber	990	27	2000	190	100	56
Diesel Fuel	1000	80	400	390	310	210
Brake Linings	290	17	420	31	8.3	7.6
Brake Fluid	1000	26	2400	880	33	19
Cigarettes	860	85	780	30	21	2.7
Salt[b]	75	-	-	0	0	0
Cinders	0.0	-	59	1.3	1.2	1.2
Area Soil[c]	-	-	-	-	-	-

Material	Lead (μg/g)	Mercury (μg/g)	Chromium (μg/g)	Copper (μg/g)	Nickel (μg/g)	Zinc (μg/g)
Gasoline	660	<0.05	15	4	10	10
Lubricating Grease	<2	<0.05	<2	<1	<1	160
Motor Oil	9	<0.05	<2	3	17	1100
Transmission Fluid	8	<0.05	<2	<1	21	240
Antifreeze	6	<0.05	<2	76	16	14
Undercoating	120	<0.05	<2	1	480	110
Asphalt Pavement	100	<0.05	360	50	1200	160
Concrete	450	<0.05	93	99	260	420
Rubber	1100	<0.05	180	250	170	620
Diesel Fuel	12	<0.05	15	8	8	12
Brake Linings	1100	<0.05	2200	31,000	7500	120
Brake Fluid	7	<0.05	19	5	31	15
Cigarettes	490	<0.05	71	720	190	560
Salt	2	<0.05	2	2	9	1
Cinders	<2	<0.05	<2	3	4	7
Area Soil	<2	<0.05	36	23	25	27
Detection Limit	2	0.05	2	1	1	0.01

Source: Shaheen 1975

[a] BOD determinations were made on "pure" materials using a seed of unacclimated sewage organisms.

[b] Results are on a dry weight basis. Salt as received contained 3.7% water, assayed 93.2% sodium chloride, and contained less than 0.005% cyanide.

[c] Soils from the Washington, D.C. area contained a magnetic fraction of from 8.9% to 12.5%, less than 0.05 mg rubber per gram, less than 3 x 10^5 asbestos fibers per gram, 50 to 100 mg/g volatile solids and 15 to 80 mg/g COD.

Other categories of pollutant sources occur which are specific to a particular area and on-going activities. For example, iron oxides are associated with welding operations; strontium, used in the production of flares and fireworks, would probably be found on the streets in greater quantities around holiday times or at the scenes of traffic accidents.

Appendix G and Section 4 discuss the relative contributions of the street surface loadings to the total storm runoff yields. A current project (Source-Area Contributions for Urban Runoff, Grant No. R805418) currently being conducted in San Jose will result in additional information on this subject.

Long-Term Loading Variations

Figures D-1 through D-5 of Appendix D present the rainfall history in the study areas by time during the testing period.

The runoff monitoring program is discussed in Section 4 of this report. During the testing phase of this study, significant rains occurred on a total of 11 days, while measurable rains occurred on a total of 36 days.

A significant rain is one that is expected to remove a large portion of the street surface contaminants present before the storm. However, these rains can also add material to the street surface during the rain through erosion of adjacent areas. A significant rain is defined as having a total rainfall of about 0.2 in. or greater within about one day (irrespective of traffic conditions), or a peak instantaneous rainfall intensity of 0.5 in. per hour with little or no traffic, or an average intensity of 0.1 in. per hour or greater with moderate to heavy traffic. Rains and traffic conditions meeting one of these sets of criteria are believed to be capable of imparting enough energy to the street surface to loosen street surface contaminants and to supply enough water to flush these contaminants along the street surface and gutters to storm sewerage inlets. Enough water may not be available to carry the particulates through the storm sewerage and out the outfall. This would result in deposition of solids in the sewerage (see Section 4). Rainfall intensity and removal effectiveness relationships were studied by Sartor and Boyd (1972) and discussed by others (including Pitt and Field 1977).

Figures D-6 through D-22 of Appendix D present total street surface particulate loadings and median particle sizes as a function of time. These figures show a sawtooth pattern similiar to that shown in Figure 3-3 for the total solids loading conditions over much of the study period. Some unexplained decreases in loadings are also periodically shown. It is thought that these decreases in loadings may be caused by high winds. Significant rains in some cases cause a decrease in street surface loadings, while they cause an increase in others. Increases are thought to be caused by erosion. The median particle size of street surface particulates also decreases with street cleaning and increases with time until recleaned. The median particle size can decrease either with removal of larger particles or with an increase in the quantities of smaller particles. Decreases in median particle sizes were caused by the removal of larger particle sizes during street cleaning operations. A more detailed discussion of street cleaning performance as a function of particle size is given later in this section.

Accumulation Rates of Specific Pollutants

As described previously, all of the test and accumulation samples were separated by particle size. Samples of each particle size category for each test area and equipment type were then analyzed for the various pollutants.

Figure 3-5 shows computer assisted curves of total solids street loadings as a function of time since last cleaned. All measured street surface loading values (by particle size) and associated time periods since last cleaned were grouped by test area and season, and computer analyzed to identify the best fitting curves. Loading values that were affected by rains were eliminated from the analyses. First, second and third order polynomial curves, with and without logarithmic (natural) data transformations, were used. The data showed considerable spread, with correlation coefficient (r^2) values for the curves used ranging from 0.35 to 0.9 (a correlation coefficient of 1.0 corresponds to a "perfect fit" curve). Seasonal differences were not definitive because of fewer resultant data points per curve and larger variations. Figure 3-5 is highly influenced by the residual loading values, which are generally the "cleanest" the streets can be, and are usually the loading values immediately after street cleaning; however, streets after certain rains can be cleaner.

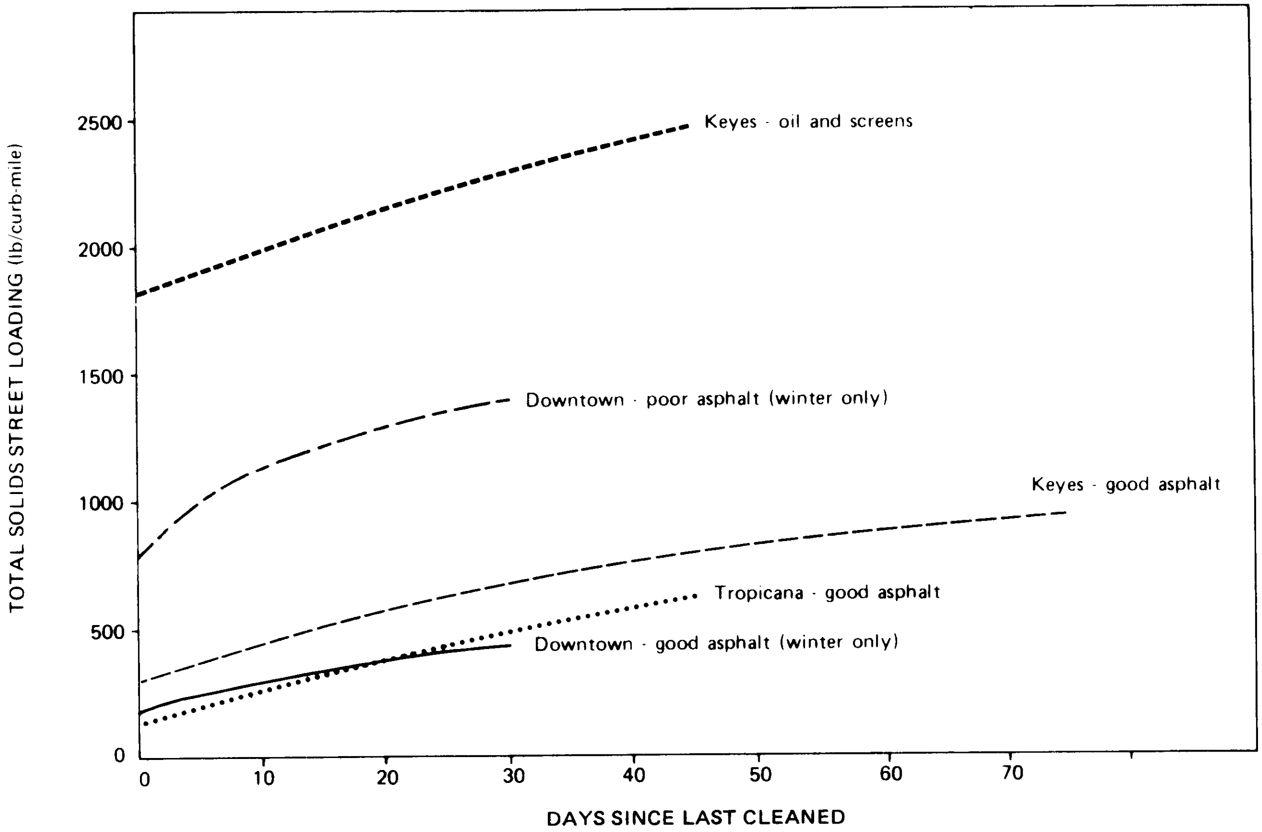

Figure 3-5. Total solids accumulation since last cleaned (all seasons combined).

The resulting loadings were quite different for each test area. The accumulation rates for the different test areas were much more similar than the loading values. The good condition "asphalt" test areas had the smallest loading values at any one time, while the oil and screens test area and poor condition asphalt test area had the largest loadings. No radical leveling off of the loadings occurred, although the rate of loading gains decreased with time. Table 3-4 presents calculated annual average accumulation rates for the various pollutants and for each test area.

TABLE 3-4. ANNUAL STREET SURFACE POLLUTANT ACCUMULATIONS (lb/curb-mile/year)

Study Area	Total Solids	Chemical Oxygen Demand	Kjeldahl Nitrogen	Ortho-Phosphates	Lead	Zinc	Chromium	Copper	Cadmium
Keyes and Tropicana - good asphalt	4000	440	8.4	0.62	20	2.0	1.5	2.5	0.009
Keyes-oil and screens	5800	470	6.6	0.37	7.3	1.4	2.0	2.9	0.008
Downtown-good asphalt	3300	440	6.2	0.47	20	2.8	1.8	3.5	0.01
Downtown-poor asphalt	7700	880	18	1.1	15	3.7	3.5	7.3	0.02

Table 3-5 shows calculated street surface pollutant loadings for the different test areas and for different times since last cleaned. Table 3-6 compares the loading values at any time with the initial loading values. The Tropicana test area is seen to change in relative loading values much more than for the other test areas. The oil and screens test area had smaller relative increases in street surface loadings with time. Changes in cleaning frequencies would, therefore, not affect street loadings in the oil and screens test area as much as for the other test areas.

Calculations were made to average the slopes (the change of street surface particulate loadings as a function of time) of each particle size to determine accumulation rates of each pollutant for each test area and equipment test phase. These calculated pollutant accumulation rates are shown in Table 3-7, which presents the accumulation rates expressed as pounds of pollutant per curb-mile per day for each of the five test areas. The values are divided into several accumulation time periods: 0 to 2.0, 2.1 to 4.0, 4.1 to 10.0, 10.1 to 20.0, 20.1 to 30.0, 30.1 to 45.0, 45.1 to 60.0 and 60.1 to 75.0 days. Accumulation rates measured over a period of time near to the street cleaning date were greater than accumulation rates measured over an accumulation period further from the day of street cleaning. This would be portrayed with a sawtooth pattern of accumulation in which loading values tend to level off with time. Differences in accumulation rates were found between the different test areas, but the range in average accumulation rates only varied by about 2 to 1 in most cases.

TABLE 3-5. STREET SURFACE POLLUTANT LOADINGS FOR VARIOUS TIMES SINCE LAST CLEANED (lb/curb-mile)

Study Area and Days Since Last Cleaned	Total Solids	Chemical Oxygen Demand	Kjeldahl Nitrogen	Ortho-Phosphates	Lead	Zinc	Chromium	Copper	Cadmium
Keyes-good asphalt									
0 days	290	32	0.62	0.044	2.0	0.20	0.12	0.17	0.00076
2	320	36	0.69	0.049	2.2	0.22	0.13	0.19	0.00083
4	350	39	0.74	0.053	2.3	0.23	0.14	0.21	0.00089
10	430	48	0.91	0.065	2.7	0.27	0.17	0.26	0.0011
20	550	61	1.2	0.083	3.2	0.33	0.21	0.33	0.0013
30	650	72	1.4	0.099	3.7	0.38	0.25	0.40	0.0016
45	790	87	1.7	0.13	4.5	0.46	0.31	0.49	0.0020
60	900	100	1.9	0.15	5.1	0.52	0.35	0.56	0.0023
75	980	110	2.1	0.16	5.4	0.38	0.38	0.61	0.0025
Keyes-oil and screens									
0	1800	120	2.0	0.11	3.0	0.51	0.68	0.83	0.0028
2	1800	120	2.0	0.11	3.1	0.52	0.69	0.85	0.0029
4	1900	130	2.1	0.12	3.1	0.53	0.71	0.87	0.0029
10	2000	130	2.2	0.12	3.2	0.55	0.74	0.92	0.0031
20	2100	150	2.4	0.13	3.4	0.59	0.80	1.0	0.0033
30	2300	160	2.5	0.14	3.6	0.63	0.85	1.1	0.0035
45	2400	170	2.7	0.15	3.8	0.66	0.90	1.2	0.0037
Tropicana-good asphalt									
0	130	13	0.28	0.024	0.50	0.12	0.044	0.078	0.00038
2	160	17	0.35	0.029	0.66	0.14	0.056	0.098	0.00045
4	190	20	0.40	0.033	0.79	0.15	0.066	0.12	0.00051
10	270	29	0.57	0.045	1.2	0.19	0.094	0.17	0.00068
20	390	42	0.81	0.063	1.7	0.25	0.14	0.24	0.00096
30	490	53	1.0	0.079	2.2	0.30	0.18	0.31	0.0012
45	630	68	1.3	0.11	3.0	0.38	0.23	0.39	0.0016
60	740	81	1.6	0.13	3.6	0.44	0.27	0.47	0.0019
75	820	89	1.7	0.14	3.9	0.48	0.30	0.52	0.0021
Downtown-good asphalt									
0	170	23	0.32	0.025	1.0	0.15	0.094	0.18	0.0051
2	190	25	0.35	0.028	1.1	0.17	0.10	0.20	0.0056
4	210	28	0.39	0.030	1.2	0.18	0.11	0.22	0.0062
10	260	35	0.49	0.038	1.5	0.23	0.14	0.28	0.0078
20	350	47	0.66	0.051	2.1	0.31	0.19	0.37	0.011
30	440	59	0.83	0.064	2.6	0.38	0.24	0.47	0.013
Downtown-poor asphalt									
0	780	89	1.8	0.11	1.5	0.37	0.35	0.74	0.0021
2	820	94	1.9	0.12	1.6	0.39	0.37	0.78	0.0022
4	860	99	2.0	0.12	1.7	0.41	0.39	0.82	0.0023
10	990	110	2.3	0.14	1.9	0.47	0.45	0.94	0.0027
20	1200	140	2.8	0.17	2.3	0.57	0.54	1.1	0.0032
30	1400	160	3.3	0.20	2.7	0.67	0.64	1.3	0.0038

TABLE 3-6. RATIO OF POLLUTANT LOADING VALUES AT VARIOUS TIMES SINCE LAST CLEANED TO RESIDUAL LOADING VALUES

	Days Since Last Cleaned								
Study Area	0	2	4	10	20	30	45	60	75
Keyes-good asphalt	1.0	1.1	1.2	1.5	1.9	2.2	2.7	3.1	3.4
Keyes-oil and screens	1.0	1.0	1.0	1.1	1.2	1.3	1.4	-	-
Tropicana-good asphalt	1.0	1.3	1.5	2.1	3.0	3.8	4.8	5.7	6.3
Downtown-good asphalt	1.0	1.1	1.2	1.5	2.1	2.6	-	-	-
Downtown-poor asphalt	1.0	1.1	1.1	1.3	1.5	1.8	-	-	-

TABLE 3-7. POLLUTANT ACCUMULATION RATES FOR DIFFERENT PERIODS SINCE LAST CLEANED (lb/curb-mile/day)*

Study Areas and Accumulation Periods	Total Solids	Chemical Oxygen Demand	Kjeldahl Nitrogen	Ortho-Phosphates	Lead	Zinc	Chromium	Copper	Cadmimum	Median Particle Size (μ)
Keyes-oil and screens										
0 → 2 days	20	1.50	0.021	0.00140	0.024	0.0047	0.0068	0.0098	0.000024	990
2 → 4 days	20	1.50	0.021	0.00140	0.024	0.0047	0.0068	0.0098	0.000024	700
4 → 10 days	17	1.40	0.019	0.00100	0.021	0.0041	0.0059	0.0083	0.000030	1,100
10 → 20 days	16	1.30	0.017	0.00100	0.018	0.0037	0.0054	0.0078	0.000022	1,100
20 → 30 days	15	1.20	0.016	0.00089	0.018	0.0036	0.0050	0.0073	0.000021	1,000
30 → 45 days	10	0.82	0.011	0.00060	0.012	0.0024	0.0034	0.0051	0.000014	1,200
Average	16	1.30	0.018	0.00100	0.020	0.0039	0.0056	0.0080	0.000023	1,000
Keyes & Tropicana-good asphalt										
0 → 2 days	17.0	1.90	0.034	0.0026	0.080	0.0084	0.0060	0.0100	0.000035	330
2 → 4 days	13.0	1.50	0.028	0.0020	0.065	0.0067	0.0048	0.0086	0.000028	320
4 → 10 days	13.0	1.50	0.028	0.0020	0.065	0.0067	0.0048	0.0086	0.000028	340
10 → 20 days	12.0	1.30	0.024	0.0018	0.054	0.0060	0.0043	0.0072	0.000028	310
20 → 30 days	10.0	1.10	0.022	0.0016	0.052	0.0054	0.0039	0.0067	0.000028	330
30 → 45 days	9.1	1.00	0.019	0.0018	0.047	0.0048	0.0035	0.0059	0.000023	330
45 → 60 days	7.9	0.85	0.017	0.0013	0.040	0.0040	0.0030	0.0050	0.000019	320
60 → 75 days	5.0	0.54	0.011	0.0081	0.025	0.0027	0.0019	0.0031	0.000014	320
Average	11.0	1.20	0.023	0.0017	0.054	0.0056	0.0040	0.0069	0.000025	330
Downtown-good asphalt average	9	1.2	0.017	0.0013	0.054	0.0078	0.0050	0.0096	0.00027	250
Downtown-poor asphalt average	21	2.4	0.049	0.0031	0.041	0.010	0.0095	0.020	0.000056	330

* Note:	weighted concentration	daily average accumulation rate	average annual accumulations
Mercury	0.33 ppm	4.0×10^{-6} lb/curb-mi/day	0.0015 lb/curb-mi/year
Asbestos	1.8×10^{6} fibers/gram	1×10^{10} fibers/curb-mi/day	3.7×10^{12} fibers/curb-mi/year

The median particle sizes of the accumulating solids for the asphalt test areas all were about the same (250 to 350μ), while the particle sizes associated with the accumulating solids in the oil and screens test area were much larger (about 1000μ). In addition, these particle sizes do not change with accumulation time for the asphalt streets, but appear to increase with time for oil and screens surfaced streets. The larger sizes for the oil and screens accumulating solids are caused by wear of the surfacing material itself (which is comprised of small-sized gravel). The sizes of the accumulating solids on the asphalt streets are generally smaller than the sizes of the total street dirt loadings (indicating a build-up of the finer particle sizes on the asphalt streets), while the sizes of the accumulating solids on the oil and screens surfaced streets are larger than the sizes of the total street dirt loadings.

It is interesting to note that the overall pollutant accumulation rates in the oil and screens test area are about the same or slightly smaller than for any of the other test areas, yet the oil and screens test area always had the greatest street surface loadings observed. Because of the increased surface roughness and generally larger particle sizes in the oil and screens test area, a large quantity of loose material could stay on the street surface and not be removed significantly by rainfall (see Section 4). The smoother asphalt streets in the Tropicana and Downtown-good asphalt test areas had accumulation rates that were about equal and had generally larger increases in street surface loadings with time. The Downtown-poor asphalt street surface test area had the largest accumulation rates of any of the test areas. These large rates are thought to be caused by the poor condition of the streets and the character of the area, which cause a greater erosion of the street surface and accumulation of material from outside the street environment. Street cleaning performance is closely related to the accumulation rates and the initial contaminant loading values on the streets before street cleaning, and is discussed in later sections.

GENERAL DESCRIPTION OF STREET CLEANING EQUIPMENT

Motorized street cleaners are designed to loosen dirt and debris from the street surface, transport it onto a moving conveyor, and deposit it temporarily in a storage hopper. The most common design (mechanical street cleaner) uses a rotating gutter broom to remove the particles from the gutter area and place them in the path of a large cylindrical broom which rotates to carry the material onto a conveyor belt and into the hopper. This type of street cleaner uses a water spray to control dust. This street cleaner is available in several forms, including self-dumping street cleaners and three- or four-wheel street cleaners. Three-wheel street cleaners are generally more maneuverable, but four-wheel street cleaners usually travel at higher road speeds when not cleaning.

Vacuum assisted mechanical street cleaners have been in use in Europe for many years and in limited use in this country for some time. Vacuum assisted street cleaners use gutter and main pickup brooms for loosening and moving street dirt and debris into the path of a vacuum intake, which places the debris in the hopper. The vacuum system also replaces the conveyor system. All material picked up by the vacuum nozzle is saturated with water on entry and passed into a vacuum chamber where the water-laden dust and dirt settle out.

Another type of street cleaner uses a regenerative air system. Using recycled air, these street cleaners "blast" the dirt and debris from the road surface into the hopper. Air is then vented through a dust separation system.

Some small, industrial-type vacuum street cleaners do not use main pickup brooms, but use the vacuum system to directly clean the street. These small street cleaners are most useful for cleaning parking lots, although they are also used to clean factory floors and sidewalks. They are of limited use on city streets.

When the hopper of a street cleaner is filled, the material may be taken by the street cleaner to a storage or disposal site. More commonly, it is simply dropped in a convenient place along the street cleaning route (preferably an inconspicuous side street or vacant lot). The dirt and debris are later collected by truck crews, usually with a front-end loader. The majority of street cleaners dump their hoppers from the bottom, however, some manufacturers make street cleaners with a hopper that swings up on arms and can dump directly into a truck or debris box. This eliminates the need for a separate pickup crew and decreases the chances of storage-pile losses.

The operating speed of most street cleaners falls in the range of 4 to 8 mph.* This is a normal speed for street cleaning operations in residential and commercial areas where a street cleaner must maneuver around cars blocking access to the curb. Several manufacturers offer four-wheel street cleaners that can travel at speeds up to 50 mph when not cleaning. Auxiliary engines or special power-takeoff transmissions provide additional speed and power to brooms and elevators. They allow the operator to vary the cleaner speed as required for street conditions (traffic, debris types, loading, etc.) while maintaining an effective broom rotational speed.

Street flushing, as typically conducted, merely displaces dirt and debris from the street surface to the gutter. Flushers do not remove potential pollutants from the air and water environments. The volume of water used is usually insufficient to transport the accumulated litter to the nearest drain. If the water volume were sufficient to transport the material to the drain (several thousand gallons per curb-mile*), it would probably be deposited in the catchbasin or the sewerage. If the debris did reach the receiving water in separated sewerage systems, the debris would probably cause a more severe water pollution problem than if they were washed off the streets during a rain storm, when larger receiving water flows occur for dilution. Adequate flushing in combined sewerage systems could move the street surface pollutants into the sewerage and toward the treatment facility. Most public works agencies use flushers for aesthetic purposes or for quickly moving material out of travel lanes. A street flusher consists of a water supply tank mounted on a truck or trailer, a gasoline engine drive pump or power takeoff for supplying pressure, and three or more nozzles for spraying the water in several directions. The large nozzles on the flusher are individually controlled. They are usually placed so that one is pointed across the path of the flusher, and one on each side is pointed toward the gutter. This arrangement makes it possible to flush an

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*See Metric Conversion Table 0-1.

entire street in one pass and provides flexibility in operation. The capacity of the water carried on typical street flushers varies from 800 to 3500 gallons.* The nozzle pressure of the water is usually between 30 and 55 psi.* The volume of water delivered must be proportional to the speed of the vehicle and the pumps must be capable of supplying sufficient water at suitable pressures.

Machine street cleaning may be assisted by manual cleaning in areas that machines cannot reach, although machine cleaning accounts for the majority of street cleaning activities in most communities. Manual cleaning is primarily used to clean those streets where cars prevent the effective use of mechanical equipment. It is most often used in business districts where the emphasis is on keeping litter under control. Manual methods are also useful in supporting mechanical operations. A manual crew can follow a street cleaner and clean out catchbasin inlets, sweep up missed debris, and assist in transferring debris from the street cleaner to trucks.

Typical Street Cleaning Programs and Operating Conditions

Information from two APWA questionnaires--one sent to more than 400 cities in 1973 and a follow-up questionnaire sent to more than 200 cities in 1975, concerning street cleaning operations in a recent project (APWA 1973 and 1975) --can be used to define current cleaning programs. Other data sources (Scott 1970; Laird and Scott 1971; Mainstem 1973; APWA 1945) can also be used to describe typical street cleaning programs. The results of these surveys are presented in the following discussion. These survey results should not be considered a goal for any cleaning program, but only an indication of the norm. Part of Section 5 discusses procedures for the determination of a street cleaning program. Because of varying objectives and conditions, some cities will need much more intensive street cleaning programs than other cities.

General City Characteristics

Table 3-8 presents the areas and the total street miles for cities with various population ranges (APWA 1973). Obviously, as the population increases, the size of the city increases. About 0.5 square miles* and about 3 street-miles* are required for each 1000 people. These values may be substantially larger for small cities (those with much fewer than 10,000 people).

Table 3-9 shows the street grades for cities throughout the country (APWA 1973). Most streets are flat with grades of less than 2 percent; however, some cities only have flat grades on one percent of their streets. Of the cities that responded, only 11 percent of the streets had grades greater than 6 percent; but 50 percent of all of the streets of some cities had 6 percent grades. Street cleaning equipment must be more powerful if the street grades are steeper. The specific routes may be selected on a topographic basis to minimize the number of street cleaners with large horsepower engines.

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*See Metric Conversion Table 0-1.

TABLE 3-8. AREA AND STREET MILES FOR NATIONWIDE CITIES

Population Range	Area (mi^2)		Street miles	
	Average	Range	Average	Range
<10,000	5.6	2 → 11	51	25 → 74
10,000 → 25,000	13	3 → 73	120	30 → 600
25,000 → 50,000	15	1 → 120	130	4 → 1600
50,000 → 100,000	34	3 → 550	220	12 → 1400
100,000 → 250,000	47	8 → 120	440	18 → 1300
250,000 → 500,000	110	21 → 520	830	270 → 1600
500,000 → 1,000,000	420	46 → 3500	1900	860 → 4400
>1,000,000	220	52 → 460	2600	-- --
Overall	47	1 → 3500	310	4 → 4400

Source: APWA 1973

TABLE 3-9. STREET TOPOGRAPHY CONDITIONS FOR NATIONWIDE CITIES

Grade Range	Percent of Streets in Grade Range	
	Average	Range
0 → 2% grade	57	1.0 → 100
2 → 6% grade	33	1.0 → 100
>6% grade	10	0.5 → 50

Source: APWA 1973

General Street Cleaning Program Characteristics

Table 3-10 shows the numbers of street cleaners that were operating in 1969 and 1970 based on street-miles and population groups (Scott 1970; Laird and Scott 1971). About 20 cleaners were used for every 1000 street-miles. The average street was cleaned about once every month, assuming an average cleaner usage of about 25 curb-miles per day with some of the equipment not operating because of repairs.

TABLE 3-10. NUMBER OF STREET CLEANERS FOR NATIONWIDE CITIES

City Population	Cleaners per 1000 street miles[a]		Average Number of (Cleaners per 100,000 people[b])
	Average	Range	
<25,000	32	6.9 → 220	9.6
25,000 → 50,000	18	6.3 → 40	5.4
50,000 → 100,000	21	6.7 → 78	5.8
100,000 → 250,000	15	3.0 → 43	4.2
250,000 → 500,000	18	4.4 → 87	3.7
500,000 or more	14	2.6 → 28	2.7

Sources: [a]Laird and Scott 1971
[b]Scott 1970

From 3 to 10 cleaners were available for every 100,000 people. Based on these values, 7200 street cleaners were available in the U.S. in 1970 (Scott 1970). Only about 35 percent of the cities had parking regulations to enhance the street cleaning efforts (Scott 1970).

One of the major complaints about street cleaning operations concerns interim storage of collected materials on streets. An average of 6 hours interim storage was reported by the cities responding and the storage duration ranged from 5 minutes to 3 days (APWA 1973).

Operator training and operator performance are assumed to be directly related, but only 43 percent of the cities that responded had a formal operator training program. The average initial training period was 54 hours per operator with subsequent training of about 30 hours per operator per year (APWA 1975).

Many cities with severe winter snow conditions do not conduct street cleaning operations all year long. Most of the cities (56 percent) conducted their street cleaning operations the whole year, but three percent cleaned streets during only 3 or 4 months of the year (APWA 1975).

Public works departments removed, on the average, about 260 pounds per person per year from the streets in 1973 (APWA 1975). Since street refuse has a bulk density of about 1 ton per cubic yard*, this would be equal to about 25 million cubic yards or 25 million tons* of material per year for a

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*See Metric Conversion Table 0-1.

city of 100,000 people. Therefore the ultimate disposal of this material is an important aspect of a complete street cleaning program.

Cleaning Equipment

Ninety-six percent of the estimated 7200 street cleaners operating in the U.S. in 1969 and 1970 were manufactured by one of three companies (Scott 1970). This percentage is thought to have decreased since 1970, because of the rise in the number of equipment manufacturers. Eighty-seven percent of the cleaners were gasoline operated (Scott 1970).

Sixty-six percent of all streets were cleaned by mechanical cleaners. Twenty-five percent were cleaned by vacuum assisted mechanical cleaners or by regenerative air street cleaners. The remaining streets were cleaned by flushers only, or by a combination of equipment types (APWA 1973).

The reported operating speeds of mechanical and vacuum cleaners averaged about 6 mph (they ranged from 2 to 25 mph). Flushers operated at a somewhat faster speed, averaging 8 mph (APWA 1973). A faster street cleaner speed usually results in less efficient removal of street dirt, but the relationship of speed to removal efficiency for flushers is not known. Manufacturers usually recommend an operating speed of 5 mph for mechanical and vacuum cleaners and 15 mph for flushers. It is thought that cities operate their flushers at speeds slower than recommended by the manufacturers because of public safety considerations.

The most common street cleaner hopper sizes were 3 and 4 cubic yards, with only 4 percent either smaller than 2.5 cubic yards or equal to or larger than 5 cubic yards (Scott 1970). The average reported volume of debris picked up during one machine's shift was about 15 cubic yards (APWA 1973). Therefore, about four or five loads were dumped during each shift.

General Street Cleaning Equipment Performance

All street cleaning equipment currently used can efficiently remove litter (larger than 0.25 in.) from the street cleaner path. The following general discussion concerns the removal of smaller particles (less than 0.25 in.) as measured in several previously conducted controlled tests. Information presented later in this section about the San Jose test results concerns all particle sizes. Most of the equipment used in these tests was in good maintenance and operated under recommended conditions although some were quite different than those currently available. Departures from recommended operating conditions may result in lower or higher removal rates.

Past test results have shown direct relationships between cleaning efficiency, particle size, and street surface particulate loading. Tables 3-11 and 3-12 show the cleaning effectiveness of vacuumized street cleaners (Clark and Cobbin 1963) and mechanical street cleaners (Sartor and Boyd 1972) for various particle sizes and total particulate loading conditions. These values were determined by examining data that were collected under several hundred controlled and in-situ tests. Actual cleaning efficiency may vary substantially from these values because of site-specific variables. It was found that street surface loading strongly influences the removal efficiency. Results from this San Jose demonstration

TABLE 3-11. REMOVAL EFFICIENCIES FOR VACUUMIZED STREET CLEANER AT DIFFERENT INITIAL PARTICULATE LOADINGS AND FOR VARIOUS EQUIPMENT PASSES (%)*

Size Range	Street Surface Loading and Number of Passes								
	20 → 200/curb-mi			200 → 1,000 lb/curb-mi			1,000 → 10,000 lb/ curb-mi		
	1 pass	2	3	1	2	3	1	2	3
44→74μ	3	6	9	20	36	49	70	91	97
74→177μ	50	75	88	60	84	94	75	94	99
177→300μ	50	75	88	60	84	94	80	96	99
300→500μ	60	84	94	65	88	96	70	91	94
750→1,000μ	50	75	88	60	84	94	70	91	97

Source: Clark and Cobbin 1963
*From cleaner path (0 to 8 ft. from curb), not total street loading.

TABLE 3-12. MECHANICAL STREET CLEANER EFFICIENCIES FOR VARIOUS EQUIPMENT PASSES (%)

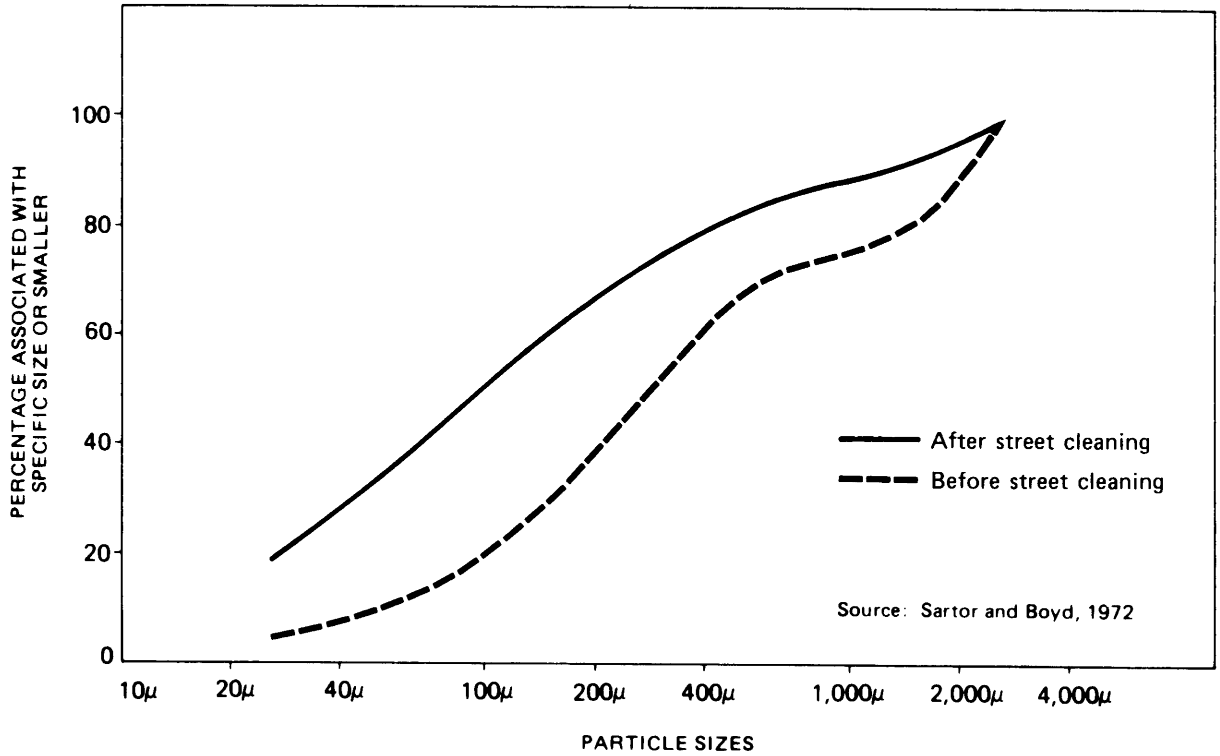
	180 → 1800 lb/curb-mile		
Size Range	1 pass	2 passes	3 passes
<43	15	28	39
43 104	20	36	49
104 → 246μ	50	75	88
246 → 840μ	60	84	94
840 → 2000μ	65	88	96
2000μ → 6370μ	80	96	99

Source: Sartor and Boyd 1972

study also showed strong influences resulting from street surface conditions. Without exception, higher loadings resulted in better removal percentages. In a nationwide study (Sartor and Boyd 1972), city-averaged street surface particulate loadings ranged from about 300 to 6000 lb/curb-mile, with an average of 1500 lb/curb-mile. Therefore, it is expected that identical equipment will perform differently in different cities and different sections of cities because of differences in loadings.

Calculations were also made to show the effects of multiple passes by the same equipment (see results in Tables 3-11 and 3-12). With multiple passes, larger particles (and litter) are removed more effectively than smaller particles, thus changing the particle size distribution. Figure 3-6 compares street surface particle-size distributions before and after a single pass with mechanical street cleaners (averaging results from four tests in separate cities, from Sartor and Boyd 1972). Before cleaning, the median dust and dirt particle size (smaller than 0.25 in.) is seen to be about 300 µ and the median particle size after cleaning is reduced to about 100 µ. This modification in particle size distribution and its effects on street cleaning efficiency can change the removal rates for the various pollutants.

Data concerning flushers, regenerative air cleaners, and combinations of equipment are scarce. Limited testing from in situ tests has demonstrated overall



Source: Sartor and Boyd, 1972

Figure 3-6. Particle (<0.25 inch) size distribution before and after sweeping tests (Atlanta, Tulsa, Phoenix, and Scottsdale tests combined).

particle removal rates of 30 percent for a single pass of a conventional flusher and 80 percent for a mechanical street cleaner followed by a flusher (Sartor and Boyd 1972). Conventional flusher operations do not remove the various pollutants from the street, they only move the particles to the curb. If sufficient water was used to flush the particulates to the storm drainage system, the pollutants would be discharged to the receiving waters, possibly during low flow conditions. Large fractions of some pollutants can only be removed by wet processes (Sartor and Boyd 1972; Pitt and Amy 1973). Pollutants with more than 20 percent in the flushed fraction included: NO_2, NO_3, PO_4, fecal coliform bacteria, fecal strep bacteria, chloride, Kjeldahl N, and BOD. Therefore, in order to remove more than 80 percent of these pollutants from the cleaner path, it is expected that some type of effective wetting/flushing must be used. No data are available concerning removal rates as a function of particle size for flushers, manual cleaning, or regenerative air cleaner units.

When the size distributions for pollutants existing on the street are known, it is possible to estimate their removal rates. Many of the pollutants have greater concentrations associated with the smaller particle sizes. Table 3-13 lists the mass-weighted median particle sizes for various street surface pollutants as measured during two previous EPA sponsored research projects (Sartor and Boyd 1972; Pitt and Amy 1973). These small particle sizes are not as efficiently removed by typical street cleaning equipment as are larger particle sizes.

Table 3-14 shows calculated removal efficiencies of various street cleaning programs for various pollutants. Phosphates are the most difficult to remove by any of the listed programs; lead and iron are the easiest to remove. The total solids (smaller than 0.25 in.) are removed at efficiencies ranging from 40 percent to 50 percent under normal conditions; but a mechanical street cleaner followed by a flusher may remove about 80 percent of the solids of the material in the street cleaner path.

If the equipment is not operated under recommended conditions, the removal rates are expected to change. As an example, the following conclusions are based on data from the Newark Brush Co. (Horton 1968). This study related broom type, broom strike, brush speed, and vehicle speed to total solids removal for mechanical street cleaners:

- Sweeping pattern (a measure of the pressure against the street surface) and broom speed are critical factors in removing road debris.
- A worn broom sweeps all types of debris better than a new one.
- Crimped wire and fiber brooms were more efficient than plastic or plastic-wire mixtures.
- The sweeping pattern contributes greatly to cleaning efficiency; small patterns leave uncleaned streaks in depressions on irregular road surfaces (Figure 3-7).
- At faster travelling speeds, proportionally higher broom rotation speeds should be employed (Figures 3-8 and 3-9).

These tests were conducted with a single-engine street cleaner. Except for the several gear ratios, higher broom speeds resulted from higher engine speeds. These higher forward speeds may decrease cleaning effectiveness by reducing broom-pavement contact. Thus, it is desirable to have an auxiliary speed control to maintain a constant optimum broom speed. To maintain a high cleaning efficiency, the data in Figures 3-7, 3-8 and 3-9 support a preference for a street cleaner speed of about 4 mph with a fast broom rotational speed at high pressure. For the ranges shown, brush speed and pattern are more important than forward speed.

TABLE 3-13 MEDIAN PARTICLE SIZE FOR VARIOUS STREET SURFACE CONTAMINANTS

Parameter	Approximate Median Particle Size (μ)
Total Solids	220
BOD_5	120
COD	42
PO_4	36
Kjeldahl - N	120
All Pesticides Combined	140
Cd	61
Sr	160
Cu	120
Ni	230
Cr	220
Zn	190
Mn	290
Pb	200
Fe	320

Sources: Sartor and Boyd, 1972
Pitt and Amy, 1974

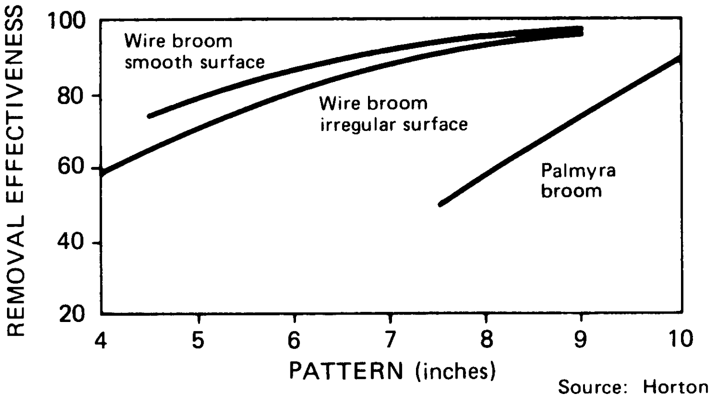
TABLE 3-14. REMOVAL EFFICIENCIES FROM CLEANER PATH FOR VARIOUS STREET CLEANING PROGRAMS* (%)

Sreet Cleaning Program and Street Surface Loading Conditions	Total Solids	BOD_5	COD	KN	PO_4	Pesticides	Cd	Sr	Cu	Ni	Cr	Zn	Mn	Pb	Fe
Vacuum Street Cleaner 1 pass; 20 → 200 lb/curb mile total solids	31	24	16	26	8	33	23	27	30	37	34	34	37	40	40
2 passes	45	35	22	37	12	50	34	35	45	54	53	52	56	59	59
3 passes	53	41	27	45	14	59	40	48	52	63	60	59	65	70	68
Vacuum Street Cleaner 1 pass; 200 → 1,000 lb/curb mile total solids	37	29	21	31	12	40	30	34	36	43	42	41	45	49	59
2 passes	51	42	29	46	17	59	43	48	49	59	60	59	63	68	68
3 passes	58	47	35	51	20	67	50	53	59	68	66	67	70	76	75
Vacuum Street Cleaner 1 pass; 1000 → 10,000 lb/curb mile total solids	48	38	33	43	20	57	45	44	49	55	53	55	58	62	63
2 passes	60	50	42	54	25	72	57	55	63	70	68	69	72	79	77
3 passes	63	52	44	57	26	75	60	58	66	73	72	73	76	83	82
Mechanical Street Cleaner 1 pass; 180 → 1800 lb/curb mile total solids	54	40	31	40	20	40	28	40	38	45	44	43	47	44	49
2 passes	75	58	48	58	35	60	45	59	58	65	64	64	64	65	71
3 passes	85	69	59	69	46	72	57	70	69	76	75	75	79	77	82
Flusher	30	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)	(a)
Mechanical Street Cleaner followed by a flusher	80	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)	(b)

(a) 15 → 40 percent estimated
(b) 35 → 100 percent estimated

*These removal values assume all the pollutants would lie within the cleaner path (0 to 8 ft. from the curb)

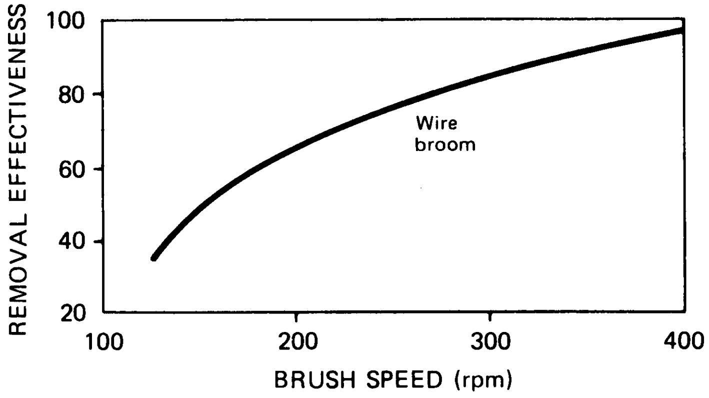
Sources: Calculated from Clark and Cobbin 1963; Sartor and Boyd 1972; and Pitt and Amy 1976.



Source: Horton, 1968

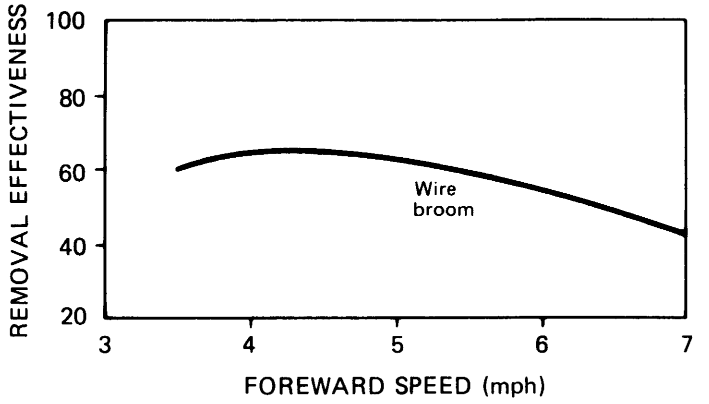
Figure 3-7. Effect of pattern* on removal effectiveness.

*The pattern is a measure of pressure applied between the main pick-up broom and the street surface. It is measured as the tangential length of main pick-up broom in contact with the street surface.



Source: Horton, 1968

Figure 3-8. Effect of brush speed on removal effectiveness.



Source: Horton, 1968

Figure 3-9. Effect of foreward speed on removal effectiveness.

SAN JOSE DEMONSTRATION STUDY RESULTS

The design of an effective street cleaning program requires not only a determination of accumulation rates but also an assessment of specific street cleaning equipment performance in the actual conditions encountered. Service goals*, another factor affecting the design of street cleaning programs, will be discussed in Section 5. The aim of this study was to determine a range of street cleaning equipment effectiveness for various types of equipment and cleaning schedules.

Tables 3-15 through 3-18 present the street cleaning equipment performance data. Twenty-six different test conditions are identified representing different test areas, equipment types, number of passes, and approximate cleaning intervals. The information presented for each of the "before" and "after" test samples includes the median particle size, the bulk density, and the street surface loading conditions. Under the "after street cleaning" heading, the residual street surface loading values (lb/curb-mile) are shown; these are generally the lowest street surface loading values that occur under each of the test conditions. Also shown is the amount removed, the percentage of the "before" loading removed, and the hopper content median particle size. The values shown are the mean ($\bar{x}$) plus or minus the standard deviation (σ).

Street cleaning performance depends on many conditions. These include the character of the street surface, the street surface initial loading characteristics (total loading value and particle size distribution), and various other environmental factors. Street cleaning program variables that most affect street cleaning performance include the number of passes the equipment makes and the street cleaning interval. The most important measure of cleaning effectiveness is <u>pounds per curb-mile removed</u> for a specific program condition. This removal value, in conjunction with the unit curb-mile costs, allows one to calculate the cost for removing a pound of pollutant for a specific street cleaning program. The <u>percentage of the before loading removed</u> has often been used as a measure of street cleaning equipment performance. It is very misleading, however, because it is not a measure of the magnitude of the amount of material removed. A street cleaning program may have a very low percentage removal value, but a high total amount removed if the initial loading is high (this occurred in the tests conducted in the oil and screens area).

Student "t" statistical tests were conducted with the data shown in Tables 3-15 to 3-18 to determine important similarities and differences in street cleaning equipment performance under the various test conditions. These statistical tests showed that initial loading values <u>in any one test area</u> varied depending on the street cleaning program (number of passes and cleaning intervals). The differences in the initial loading values <u>in various test areas</u> were controlled by differences in test area conditions (largely street surface conditions and accumulation rates), <u>irrespective of the type of equipment being used and the number of passes</u>.

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*Service goals consider effects on water quality, air quality, public safety, aesthetics, and public relations.

TABLE 3-15. STREET CLEANER PERFORMANCE DURING SAN JOSE DEMONSTRATION PROJECT - TROPICANA-GOOD ASPHALT TEST AREA

				Before Street Cleaning			After Street Cleaning			Cleaning Effectiveness		
Number of Passes	Approx. Cleaning Interval	Equipment* Type	Test** Phase	Median Particle Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Median Particle Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Removed (lb/curb-mile)	Percentage of Before Loading Removed	Hopper Contents Median Particle Size (μ)
2	Daily	C*	1**	410±95	0.82±0.13	328±93	320±29	1.06±0.09	132±56	196±131	60±32	3190±1030
1	Daily	A	1	965±1160	1.30±0.14	115±38	430±57	1.20±0.08	98±45	17±22	13±25	3170±1410
1	Daily	B	1	430±130	1.12±0.11	350±274	300±46	1.10±0.17	165±64	185±225	53±19	2090±850
1	Daily	B	2	295±21	0.95±0.06	200±10.8	275±5	1.05±0.06	116±6.1	84±16.3	42±6.2	2760±315
1	Daily	C	2	380±42	0.98±0.05	206±60	420±63	1.15±0.06	113±22.1	92±38	45±4.5	3120±455
1	Weekly	A	1	510±63	0.98±0.05	164±65	450±78	1.15±0.06	87±38	77±38	47±11	5750±4380
1	Weekly	B	2	325±8	0.98±0.08	207±20.1	300±31	1.02±0.04	128±12.6	78±15.7	38±5.1	3440±985
1	Weekly	C	2	420±22	0.86±0.11	221±32.9	435±43	1.02±0.04	117±14.3	104±21.4	47±4.3	2280±710

* A = 4-wheel mechanical
B = State of-the-art 4-wheel mechanical
C = 4-wheel vacuum assisted mechanical

** Test phase:
1 = December 1976 to May 1977
2 = May 1977 to September 1977

TABLE 3-16. STREET CLEANER PERFORMANCE DURING SAN JOSE DEMONSTRATION PROJECT - KEYES-GOOD ASPHALT TEST AREA

				Before Street Cleaning			After Street Cleaning			Cleaning Effectiveness		
Number of Passes	Approx. Cleaning Interval	Equipment Type**	Test*** Phase	Median Particle Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Median Particle Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Total Solids Removed (lb/curb-mile)	Percentage of Before Loading Removed	Hopper Contents Median Particle Size (μ)*
2	Daily	A	1	480±36	0.98±0.05	401±122	460±69	1.10±0.08	258±81	144±155	36±27	940±380
2	Daily	B	1	450±175	1.00±0.17	173±61	340±45	1.07±0.15	142±16	32±49	19±22	5520±2790
2	Daily	B	2	420±26	1.03±0.06	317±20.8	450±26	1.17±0.06	201±13.2	116±18.2	37±4.0	790±175
2	Daily	C	2	470±70	0.85±0.26	436±103	500±18	0.90±0.06	374±92.5	625±53.3	14±10.40	2260±1290
1	Weekly	B	1	520±67	0.87±0.06	381±29	390±28	0.97±0.12	294±67	87±45	23±14	4550±1100
1	Weekly	B	2	555±14	0.98±0.04	512±45.1	510±45	0.98±0.13	350±54	162±41.3	32±8.2	3280±820
1	Weekly	C	1	510±120	0.78±0.15	459±57	390±25	0.90±0.18	295±73	165±34	36±10	4460±2500
1	Weekly	C	2	560±53	0.94±0.11	548±84	490±29	1.18±0.08	291±24.6	25±81	47±8.7	4720±1980

*The hopper samples from the Keyes-good asphalt and Keys-oil and screens test areas were not separated before particle size analyses.

**A = 4-wheel mechanical
B = State-of-the-art 4 wheel mechanical
C = 4-wheel vacuum assisted mechanical

***Test phase:
1 = December 1976 to May 1977
2 = May 1977 to September 1977

TABLE 3-17. STREET CLEANER PERFORMANCE DURING SAN JOSE DEMONSTRATION PROJECT - KEYES-OIL AND SCREENS TEST AREA

				Before Street Cleaning			After Street Cleaning			Cleaning Effectiveness		
Number of Passes	Approx. Cleaning Interval	Equipment Type**	Test*** Phase	Median Particle Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Median Particle Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Total Solids Removed (lb/curb-mile)	Percentage of Before Loading Removed	Hopper Contents Median Particles Size (μ)*
2	Daily	A	1	560±19	1.35±0.06	2654±797	600±36	1.38±0.05	2208±375	445±461	17±11	940±380
2	Daily	B	1	650±250	1.3±0.14	1830±378	570±24	1.28±0.10	1930±403	-98±300	-6±17	5940±2390
2	Daily	B	2	480±19	1.15±0.06	1244±22.8	460±9	1.20±0.0	1141±91	104±76	8±6.2	835±170
2	Daily	C	2	540±21	1.18±0.05	2056±113	520±9	1.20±0.0	2078±186	-22.0±104	-1±5.2	2260±1290
1	Weekly	B	1	670±35	1.37±0.06	2370±110	600±32	1.3±0.17	1860±104	510±44	22±2	4550±1100
1	Weekly	B	2	490±25	1.08±0.08	1489±199	485±23	1.16±0.05	1318±94	164±132	11±7.6	3280±1820
1	Weekly	C	1	930±350	1.15±0.13	2200±102	660±21	1.2±0.20	2030±293	171±258	8±12	4460±2500
1	Weekly	C	2	550±20	1.06±0.11	1840±143	530±12	1.26±0.05	1730±68.4	110±85	6±4.2	4720±1980

*The hopper samples from the Keyes-good asphalt and Keyes oil and screens test areas were not separated before particle size analysis

**A = 4-wheel mechanical
B = State-of-the-art 4-wheel mechanical
C = 4-wheel vacuum assisted mechanical

***Test phase:
1 = December 1976 to May 1977
2 = May 1977 to September 1977

TABLE 3-18. STREET CLEANER PERFORMANCE DURING SAN JOSE DEMONSTRATION PROJECT - DOWNTOWN-GOOD AND POOR ASPHALT TEST AREAS

					Before Street Cleaning			After Street Cleaning			Cleaning Effectiveness		
	Number of Passes	Approx. Cleaning Interval	Equipment Type**	Test*** Phase	Median Particle (Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Median Particle Size (μ)	Bulk Density	Total Solids Loading (lb/curb-mile)	Total Solids Removed (lb/curb-mile)	Percentage of Before Loading Removed	Hopper Contents Median Particle Size (μ)*
Good Asphalt Street Surfaces	1	Daily	C	1	430±62	0.99±0.06	243±32	380±54	1.03±05	160±15	83±18	34±3	2660±1200(5)
Poor Asphalt Street Surfaces	1	Daily	C	1	570±27	0.90±0.18	1350±394	530±66	0.98±08	808±189	543±429	40±24	2660±1200(5)

*The hopper samples from both Downtown test areas were not separated before particle size analyses.

**C = 4-wheel vaccum assisted mechanical

***Test phase 1 = December 1976 to May 1977

When the residual loading values were statistically examined, the findings were similar. Differences in test area conditions were much more important than differences in equipment type. Similarly, the amount removed under each of the test conditions was more a function of the test area than the street cleaning program. In many cases, two passes with the same piece of equipment removed a larger quantity of material from the street than a single pass, as expected. An exception was found in the tests in the oil and screens test area. Here two passes per day with the state-of-the-art mechanical four-wheel machine resulted in a higher residual loading on the street surface than before the test. This result is thought to be due to the extra erosion caused by the excessive mechanical action of the broom on the "weak" oil and screens street surface. During a single pass, any extra material loosened from the street surface was removed along with some of the initial dust and dirt on the street.

The selection of the type of street cleaning equipment is less important than the characteristics of the area to be cleaned. In most cases, the street cleaning interval and number of passes were more important than the specific type of equipment used. Other considerations, such as maneuverability, life-cycle costs, hopper capacity, etc., may be more important from an equipment selection viewpoint. There are, however, expected to be situations not studied as part of this demonstration project in which one type of street cleaning equipment may perform differently from others.

The median particle size of the material collected in the equipment hopper can reflect differences in equipment performance as a function of particle size. A larger median particle size of the hopper material signifies that not as many smaller particles were removed from the street. Similarly, a smaller median particle size of the hopper material signifies a relatively greater removal of small particle sizes under the same conditions. In all cases, the hopper median particle sizes were much larger than the median particle sizes on the street surface before street cleaning. The street surface median particle size also decreased with street cleaning. There was a larger percentage of smaller particles on the street after street cleaning than before, with the street cleaning equipment being most effective in removing the larger particle sizes. Some differences in hopper content median particle sizes were found due to cleaning frequencies, but no differences were found due to equipment type.

Tables 3-19 through 3-22 summarize the loading and removal rates for the various pollutants in each test area for all street cleaning programs combined. The percentage removal values for the total solids pollutants are nearly the same as for the other pollutants; however, the removal rates, expressed on a lb/curb-mile removed basis, vary greatly. These lb/curb-mile removed values may be used to estimate the quantity of pollutants that are removed over a large area and long time period.

Table 3-23 and Figure 3-10 present removal rate information for street surface particulates by particle size for the three study areas and for all street cleaning programs combined. The larger particle sizes are shown to have had the largest removal efficiencies (as high as 55 percent), while the smallest particle sizes had the smallest removal efficiencies. However, the

TABLE 3-19. STREET CLEANER REMOVAL EFFECTIVENESS FOR VARIOUS POLLUTANTS - DOWNTOWN TEST AREAS

Pollutant	Good Asphalt Street Surface Condition				Poor Asphalt Surface Condition			
	Initial Loading (lb/curb-mile)	Residual Loading (lb/curb-mile)	Amount Removed (lb/curb-mile)	Percent Removed (%)	Initial Loading (lb/curb-mile)	Residual Loading (lb/curb-mile)	Amount Removed (lb/curb-mile)	Percent Removed (%)
Total Solids	240	160	83	34	1400	810	540	40
Chemical oxygen demand	35	24	11	32	150	93	61	40
Kjeldahl nitrogen	0.48	0.32	0.16	33	3.3	2.0	1.3	38
Orthophosphate	0.039	0.026	0.012	32	0.21	0.13	0.079	37
Lead	1.6	1.1	0.49	31	2.8	1.8	1.0	39
Zinc	0.23	0.16	0.072	31	0.69	0.43	0.27	42
Chromium	0.13	0.82	0.047	36	0.58	0.34	0.24	43
Copper	0.25	0.16	0.093	38	1.2	0.66	0.50	40
Cadmium	0.0047	0.0024	0.0023	49	0.0037	0.0022	0.0015	40

TABLE 3-20. STREET CLEANER REMOVAL EFFECTIVENESS FOR VARIOUS POLLUTANTS - KEYES-GOOD ASPHALT TEST AREA

Pollutant	Initial Loading (lb/curb-mile)			Residual Loading (lb/curb-mile)			Amount Removed (lb curb-mile)			Percentage of Initial Loading Removed (%)		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Total solids	400	170	550	280	140	370	130	35	260	33	14	47
Chemical oxygen demand	49	23	73	33	16	49	16	4.5	36	33	12	50
Kjeldahl nitrogen	0.88	0.31	1.7	0.58	0.22	1.1	0.28	0.059	0.83	32	11	50
Orthophosphate	0.059	0.031	0.073	0.042	0.027	0.054	0.018	0.0054	0.031	31	15	46
Lead	2.7	0.77	4.8	1.9	0.69	3.5	0.81	0.11	1.9	30	12	44
Zinc	0.27	0.10	0.39	0.19	0.087	0.28	0.079	0.016	0.16	29	15	44
Chromium	0.16	0.095	0.26	0.11	0.061	0.16	0.051	0.018	0.095	32	15	46
Copper	0.24	0.10	0.45	0.15	0.010	0.27	0.081	0.010	0.18	34	6	52
Cadmium	0.0010	0.00036	0.0016	0.0071	0.00029	0.0012	0.00030	0.00008	0.00053	30	18	37

TABLE 3-21. STREET CLEANER REMOVAL EFFECTIVENESS FOR VARIOUS POLLUTANTS - KEYES-OIL AND SCREENS TEST AREA

Pollutant	Initial Loading (lb/curb-mile)			Residual Loading (lb/curb-mile)			Amount Removed (lb/curb-mile)			Percentage of Initial Loading Removed (%)		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Total Solids	2000	1200	2700	1800	1100	2200	170	-100	510	9	- 1	22
Chemical oxygen demand	130	68	190	120	61	160	12	-11	38	9	- 8	20
Kjidahl nitrogen	2.2	1.6	2.6	2.0	1.5	2.4	0.14	-0.24	0.51	6	-13	19
Orthophosphate	0.12	0.080	0.22	0.11	0.075	0.17	0.0089	-0.021	0.040	7	-18	18
Lead	3.2	1.9	4.5	3.1	1.9	4.6	0.15	-0.39	0.68	5	-20	20
Zinc	0.56	0.43	0.78	0.52	0.41	0.63	0.066	-0.056	0.25	12	-12	18
Chromium	0.77	0.27	1.3	0.69	0.25	1.1	0.071	-0.055	0.27	9	- 6	22
Copper	1.0	0.21	2.2	0.92	0.12	1.9	0.13	-0.0061	0.47	13	- 2	24
Cadmium	0.0031	0.0019	0.0052	0.0029	0.0017	0.0043	0.0024	-0.00021	0.00072	8	-10	19

TABLE 3-22. STREET CLEANER REMOVAL EFFECTIVENESS FOR VARIOUS POLLUTANTS - TROPICANA-GOOD ASPHALT TEST AREA

Pollutant	Initial Loading (lb/curb-mile)			Residual Loading (lb/curb-mile)			Amount Removed (lb/curb-mile)			Percentage of Initial Loading Removed (%)		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
Total solids	230	120	350	120	87	170	100	17	200	43	13	60
Chemical oxygen demand	21	15	35	11	7.9	16	9.7	0.98	22	46	10	63
Kjeldahl nitrogen	0.45	0.24	0.81	0.25	0.19	0.33	0.21	0.057	0.48	47	24	60
Orthophosphate	0.039	0.022	0.072	0.021	0.016	0.030	0.017	0.0024	0.042	44	11	59
Lead	0.91	0.66	1.6	0.51	0.39	0.72	0.40	0.13	0.93	44	20	57
Zinc	0.11	0.051	0.17	0.059	0.041	0.082	0.049	0.034	0.095	45	12	57
Chromium	0.078	0.041	0.18	0.039	0.023	0.073	0.039	0.010	0.11	50	18	62
Copper	0.14	0.035	0.36	0.068	0.022	0.15	0.072	0.013	0.21	51	18	62
Cadmium	0.00060	0.00038	0.0010	0.00033	0.00021	0.00045	0.00027	0.000025	0.00058	45	9	56

TABLE 3-23. TOTAL SOLIDS STREET CLEANER REMOVAL EFFECTIVENESS BY PARTICLE SIZE

Study Area and Particle Size Range (μ)	Total Solids Initial Loading (lb/curb-mile)			Total Solids Removal (%)		
	Mean	Min.	Max.	Mean	Min.	Max.
Tropicana-Good Asphalt						
>6370	15	9.5	36	50	9	75
2000 → 6370	15	10	24	46	28	68
850 → 2000	21	13	42	47	22	74
600 → 850	15	8.2	42	53	41	79
250 → 600	42	19	81	46	14	63
106 → 50	50	22	80	41	6	58
45 → 106	51	24	70	40	21	54
<45	16	7.0	24	19	-54	64
all sizes	220	120	350	43	13	60
Keyes-Good Asphalt						
>6370	18	6.0	27	54	- 8	69
2000 → 6370	38	10	58	39	13	5
850 → 2000	54	16	87	35	8	5
600 → 850	28	9.2	44	35	12	5
250 → 600	85	39	120	31	14	4
106 → 250	83	45	100	26	11	4
45 → 106	76	34	100	23	-12	5
<45	21	13	34	8.3	-44	48
all sizes	400	170	550	31	14	47
Keyes-Oil and Screens						
>6370	73	13	120	36	20	58
2000 → 6370	270	77	450	24	- 5	47
850 → 2000	270	170	350	6.0	-16	23
600 → 850	160	100	200	4.0	-10	20
250 → 600	480	320	600	3.3	-16	18
106 → 250	380	280	540	4.0	-20	25
45 → 106	270	160	380	3.1	-30	25
<45	63	40	140	-12	-47	24
all sizes	2000	1200	2700	8.1	- 6	22
Downtown-Good Asphalt						
>6370	14	*	*	53	*	*
2000 → 6370	19	*	*	42	*	*
850 → 2000	25	*	*	39	*	*
600 → 850	14	*	*	38	*	*
250 → 600	48	*	*	36	*	*
106 → 250	56	*	*	33	*	*
45 → 106	57	*	*	22	*	*
<45	9.8	*	*	41	*	*
all sizes	240	*	*	34	*	*
Downtown-Poor Asphalt						
>6370	89	*	*	38	*	*
2000 → 6370	170	*	*	51	*	*
850 → 2000	180	*	*	42	*	*
600 → 850	85	*	*	41	*	*
250 → 600	270	*	*	42	*	*
106 → 250	270	*	*	39	*	*
45 → 106	230	*	*	33	*	*
<45	58	*	*	28	*	*
all sizes	1400	*	*	40	*	*

*Not enough samples were collected to obtain meaningful loading ranges.

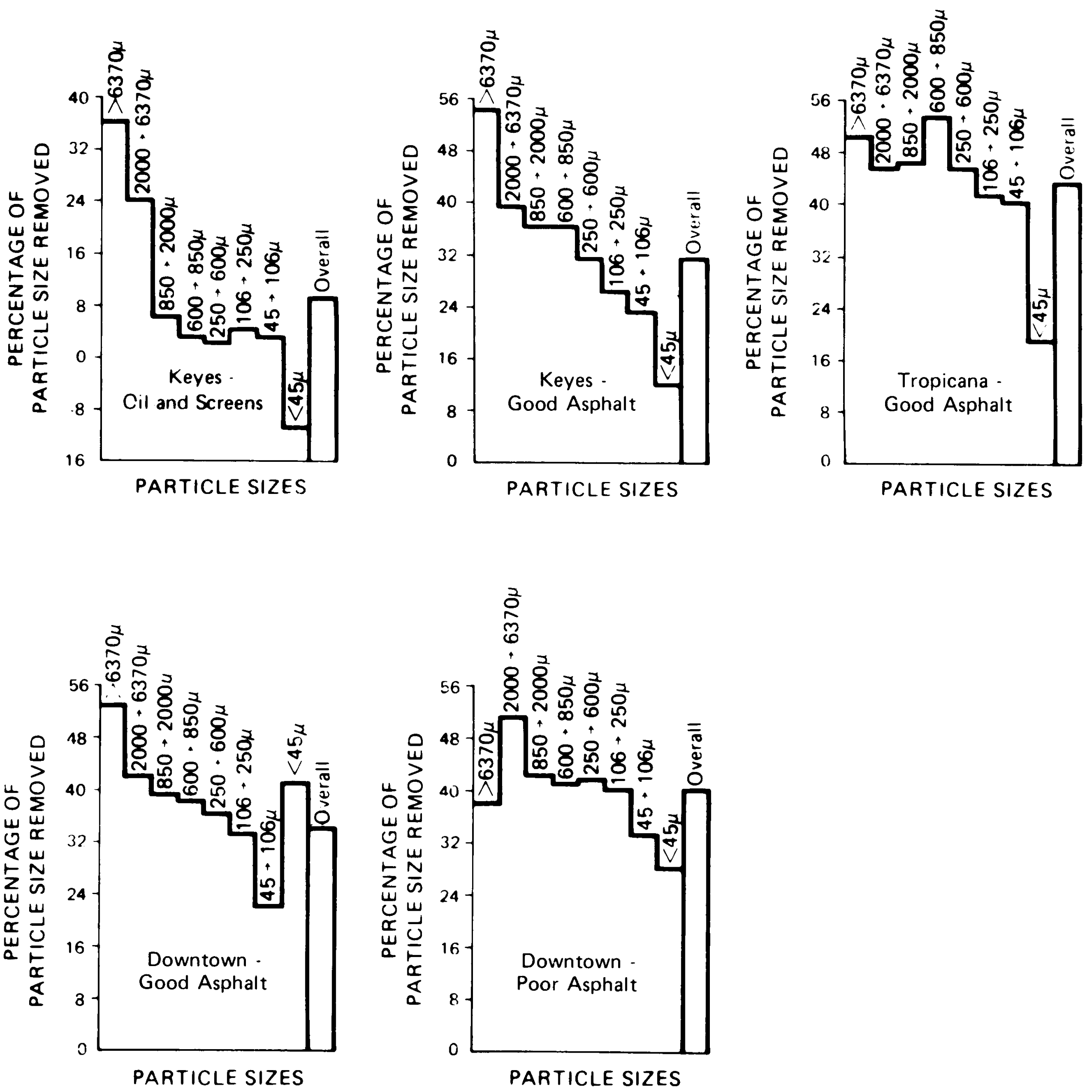


Figure 3-10. Total solids removal by particle size.

variabilities for specific values were quite large, with data ranges of about 3 to 1 not uncommon.

Figures 3-11, 3-12, and 3-13 show how the street surface material is redistributed across the street by the street cleaning equipment. Figure 3-11 for the Tropicana area (smooth streets in good repair with little parking) shows an 81 percent removal of the solids loading in the first 12 in. from the curb while the rest of the street area had increases in solids loadings. These loading increases are due to partial redistribution of the high solids loadings from the curb area out into the street due to broom action and turbulence. Figure 3-12 presents the loading redistribution of the solids during street cleaning of an oil and screens surfaced street. The high loadings next to the curb were reduced by 36 percent and some of the loadings were increased in other areas of the street. The oil and screens streets had much higher unit area loadings in the center of the street as compared with the asphalt streets. The Keyes-good asphalt test results (Figure 3-13) were similar to the Tropicana test results.

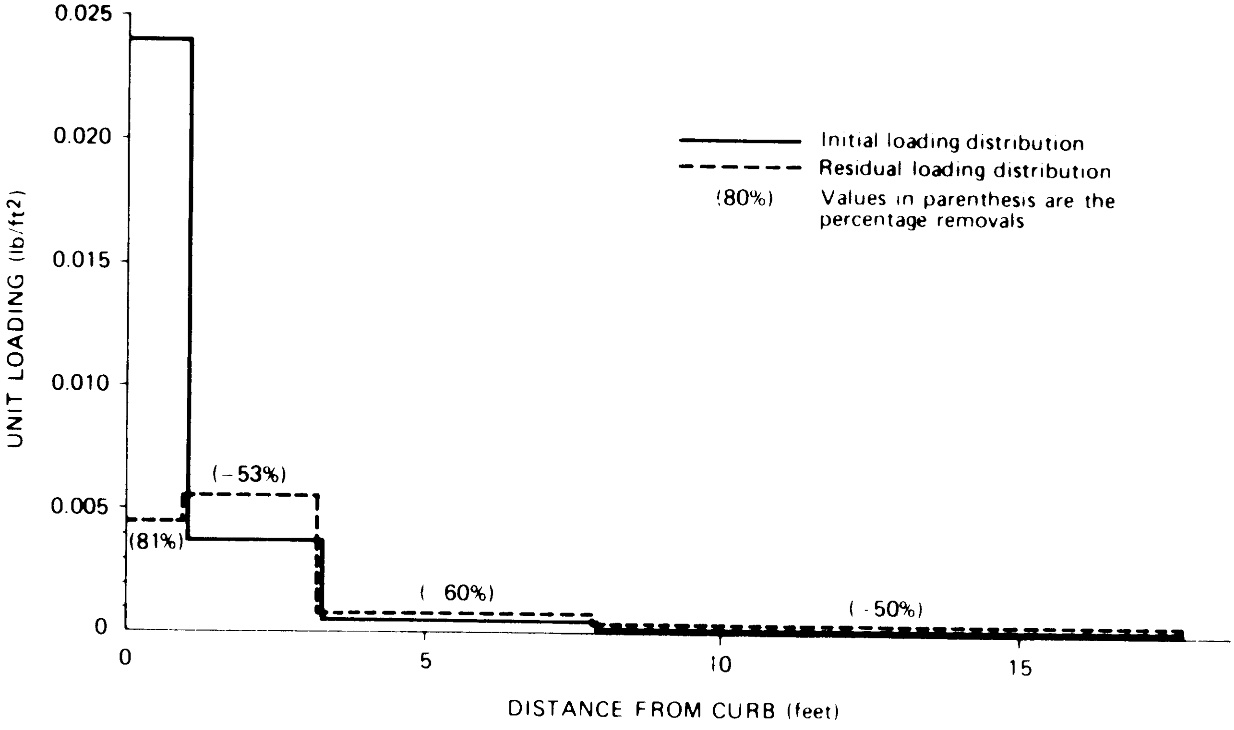


Figure 3-11. Redistribution of total solids due to street cleaning (Tropicana - Good Asphalt Test Area - averaged for all equipment types - the overall removal effectiveness was about 40%).

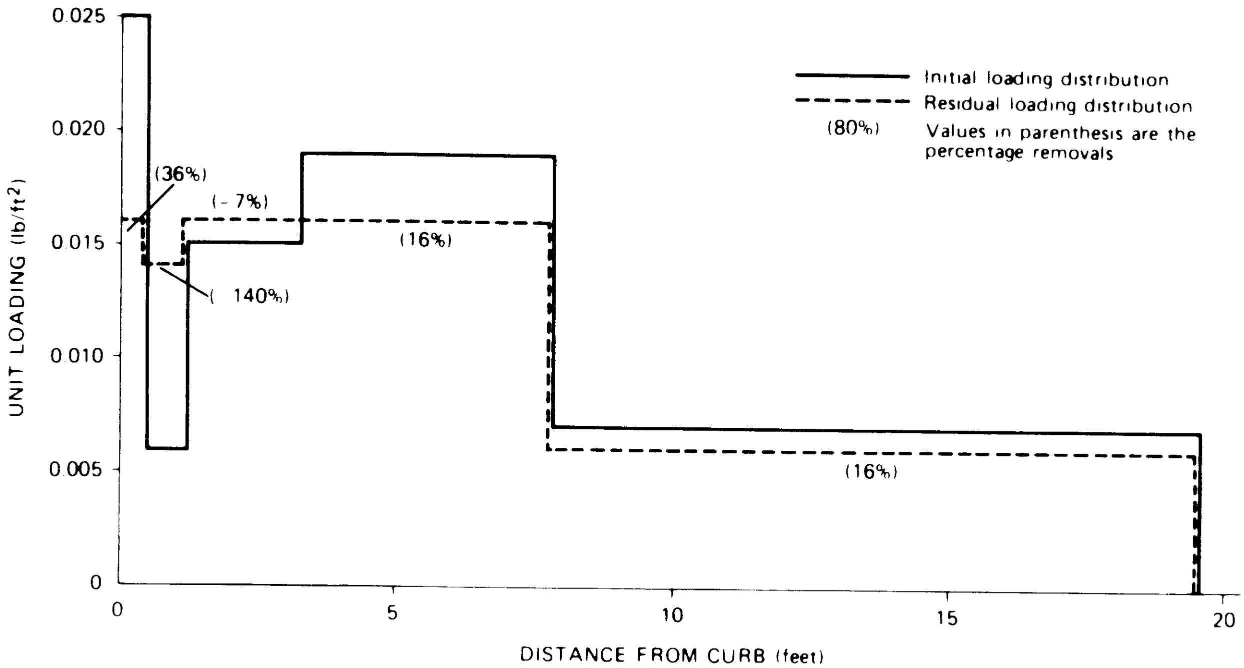


Figure 3-12. Redistribution of total solids due to street cleaning (Keyes Oil and Screens Test Area - averaged for all equipment types - the overall removal effectiveness was about 12%).

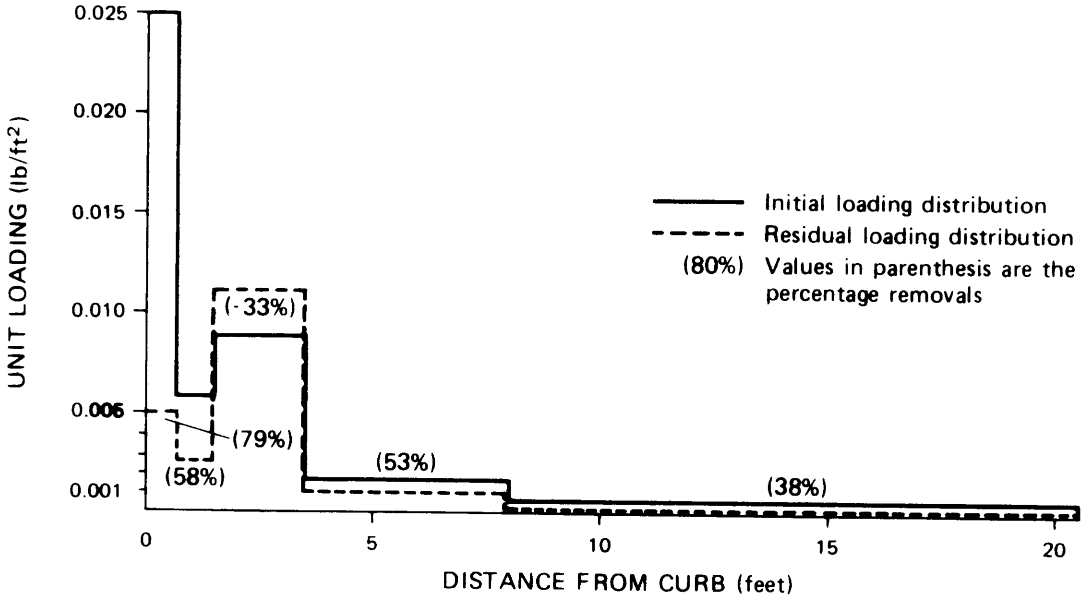
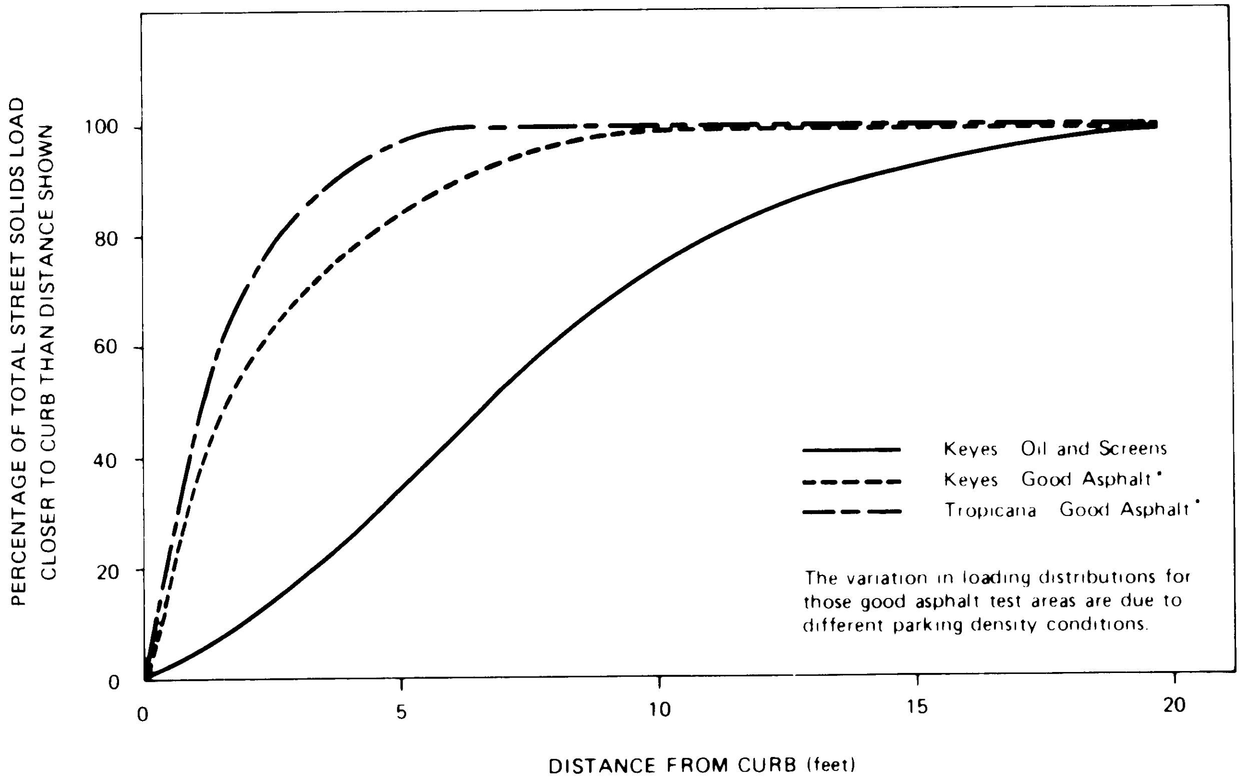


Figure 3-13. Redistribution of total solids due to street cleaning (Keyes - Good Asphalt Test Area - averaged for all equipment types - the overall effectiveness was about 26%).

Figure 3-14 and Table 3-24 present information relating to the distribution of total solids loading across the street for the different test areas The street cleaner can only remove the material from the street that lies in its path. With an 8-ft.* path, only about 60 percent of the total solids can be affected by street cleaning in the oil and screen test area, while greater than 90 percent of total solids loading can be affected in the Keyes-good asphalt and Tropicana-good asphalt test areas. This loading can be further modified by parked cars, as discussed later. Figure 3-15 shows the percentage of solids, on a size basis, that are within the normal street cleaning paths (0 to 8 ft. from the curb). A greater percentage of larger particles than finer particles were found in the oil and screens test area near the curb, possibly indicating better transport of the larger material towards the curb. The size distribution across the street in the Tropicana-good asphalt test area was about even, and no clear trends were evident from the Keyes-good asphalt data. These particulate distributions can be radically changed if debris is swept from the sidewalks onto the curb, or if leaves are piled on the street from landscaped areas.



The variation in loading distributions for those good asphalt test areas are due to different parking density conditions.

Figure 3-14. Loading distribution across the street.

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*See Metric Conversion Table 0-1.

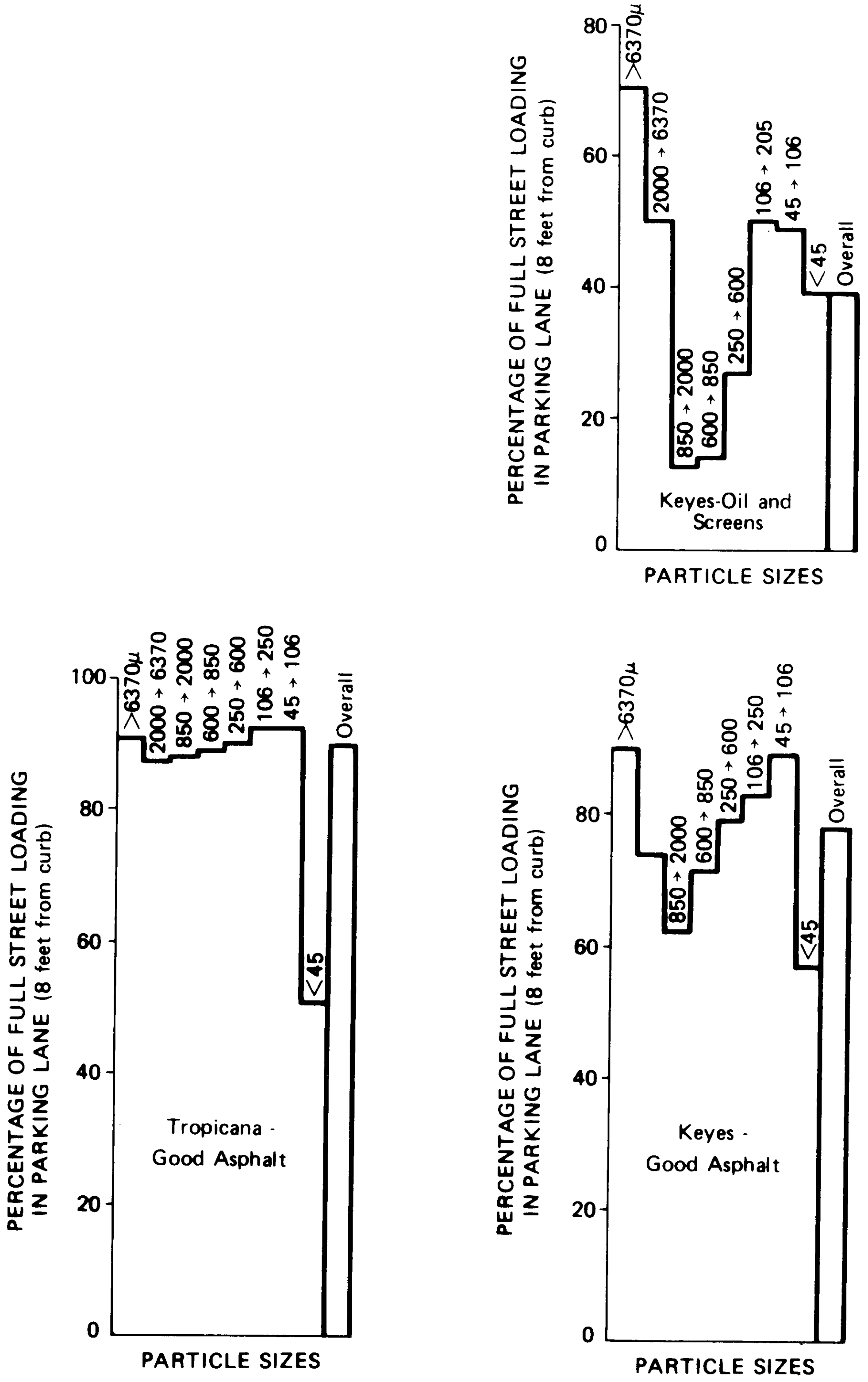


Figure 3-15. Parking lane total solids loading compared to full street loading (average of 7 to 9 tests for each study area).

TABLE 3-24. LOADING DISTRIBUTION ACROSS THE STREET

	Percentage of Total Street Loading from Curb to Given Distrance (%)		
Distance from Curb (ft.)	Keyes-Oil and Screens Test Area	Keyes-Good Asphalt Test Area*	Tropicana-Good Asphalt Test Area*
0.5	3	22	23
1	5	38	48
2	12	58	73
5	36	84	95
8	62	93	98
10	75	96	97
20	100	100	100
Distance to median (50%) loading value	6.5 ft	1.5 ft	1.0 ft
Distance to 90% of total loading	14 ft	6.7 ft	3.8 ft

---

*The variations in loading distributions for those good asphalt test areas are due to different parking density conditions.

Figure 3-16 presents an idealized distribution of the total solids on the street surface for smooth asphalt streets and oil and screens surfaced streets for different parking conditions. This figure shows a more even distribution of solids loadings on the oil and screened streets than on the smooth street surfaces. About 50 percent of the solids on oil and screened streets were within about 7 ft. of the curb for light or no parking conditions, while 50 percent of the solids on the smoother asphalt streets were within 1 ft. of the curb for similar parking conditions. Parked cars also affected the loading distribution much more radically on the smoother streets than on the rougher streets. Parked cars blocked some of the airborne street particulates that were suspended in the air by wind or by vehicle induced turbulence. The parked cars acted as barriers and caused the particulates to resettle on the street further from the curb area. With no parking, the curb itself acted as a barrier, with much of the material possibly being transported by winds across the curbs and onto adjacent areas.

Figure 3-17 is an idealized curve (based on a computer analysis of the San Jose data) reflecting the total amount of street surface materials that may be removed in a year for different street surface conditions as a function of the number of passes per year. This figure is a semi-log plot and

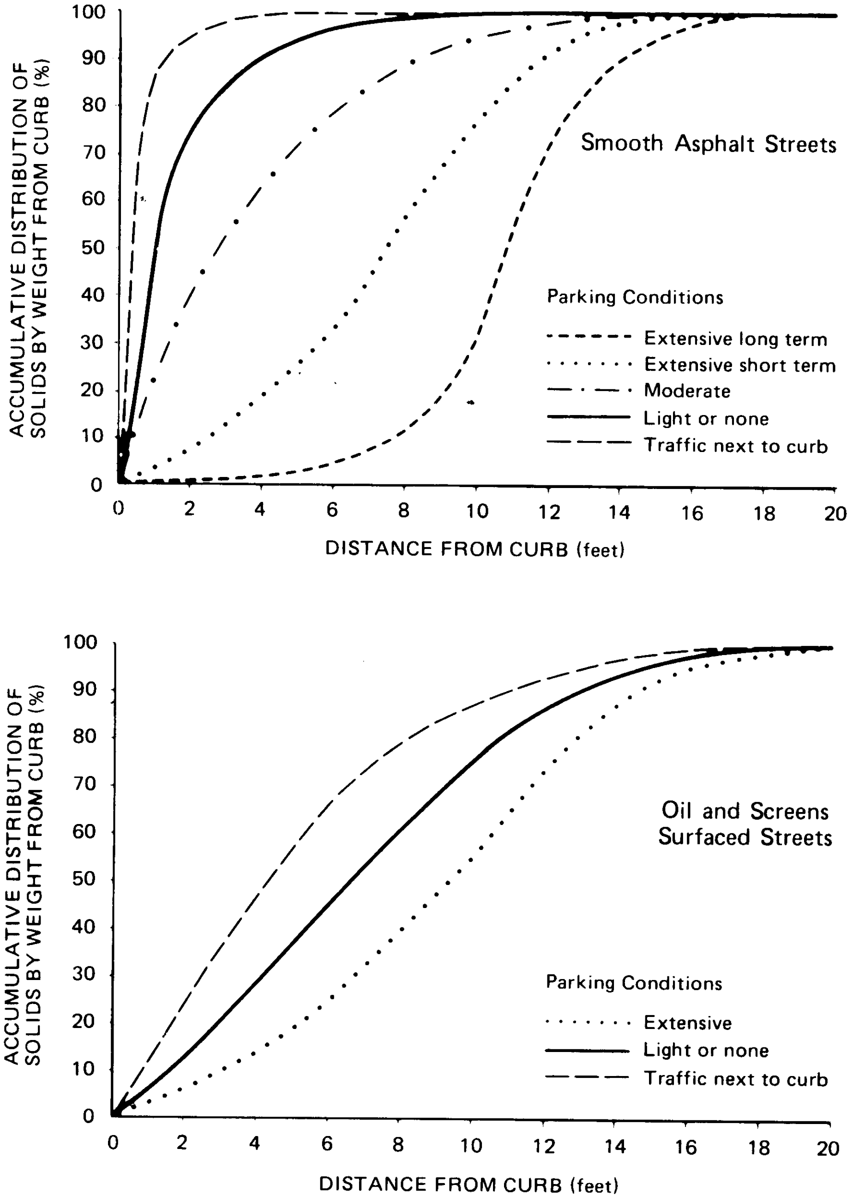


Figure 3-16. Effects of parking and street condition on solids loading distribution.

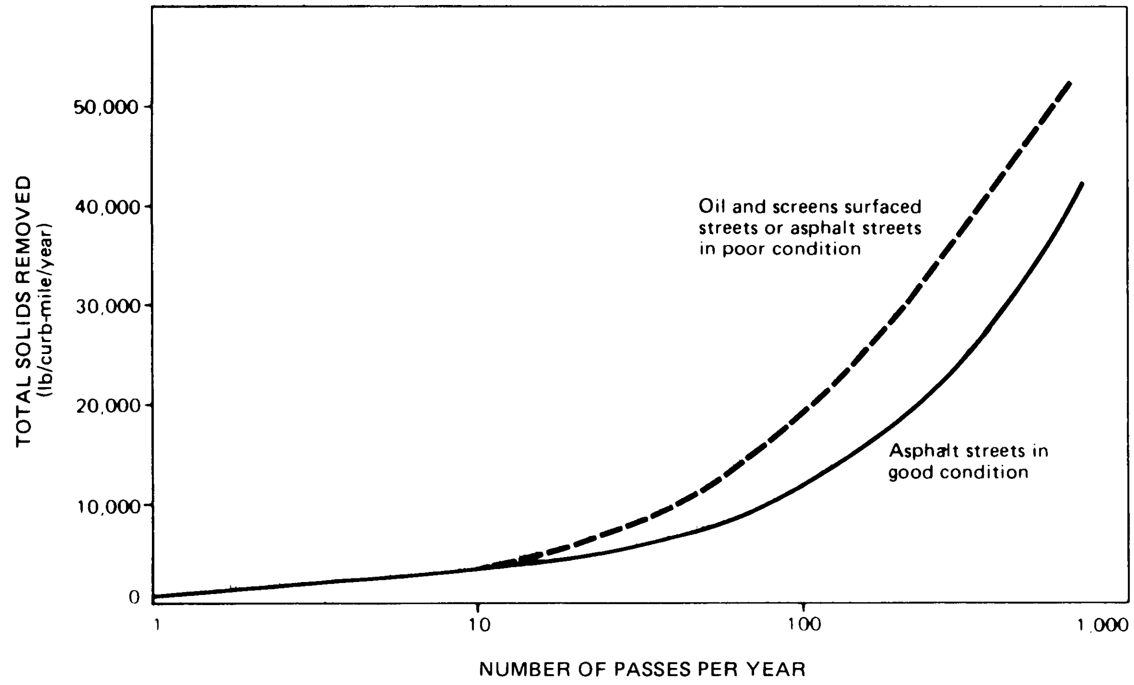


Figure 3-17. Annual amount removed as a function of the number of passes per year.

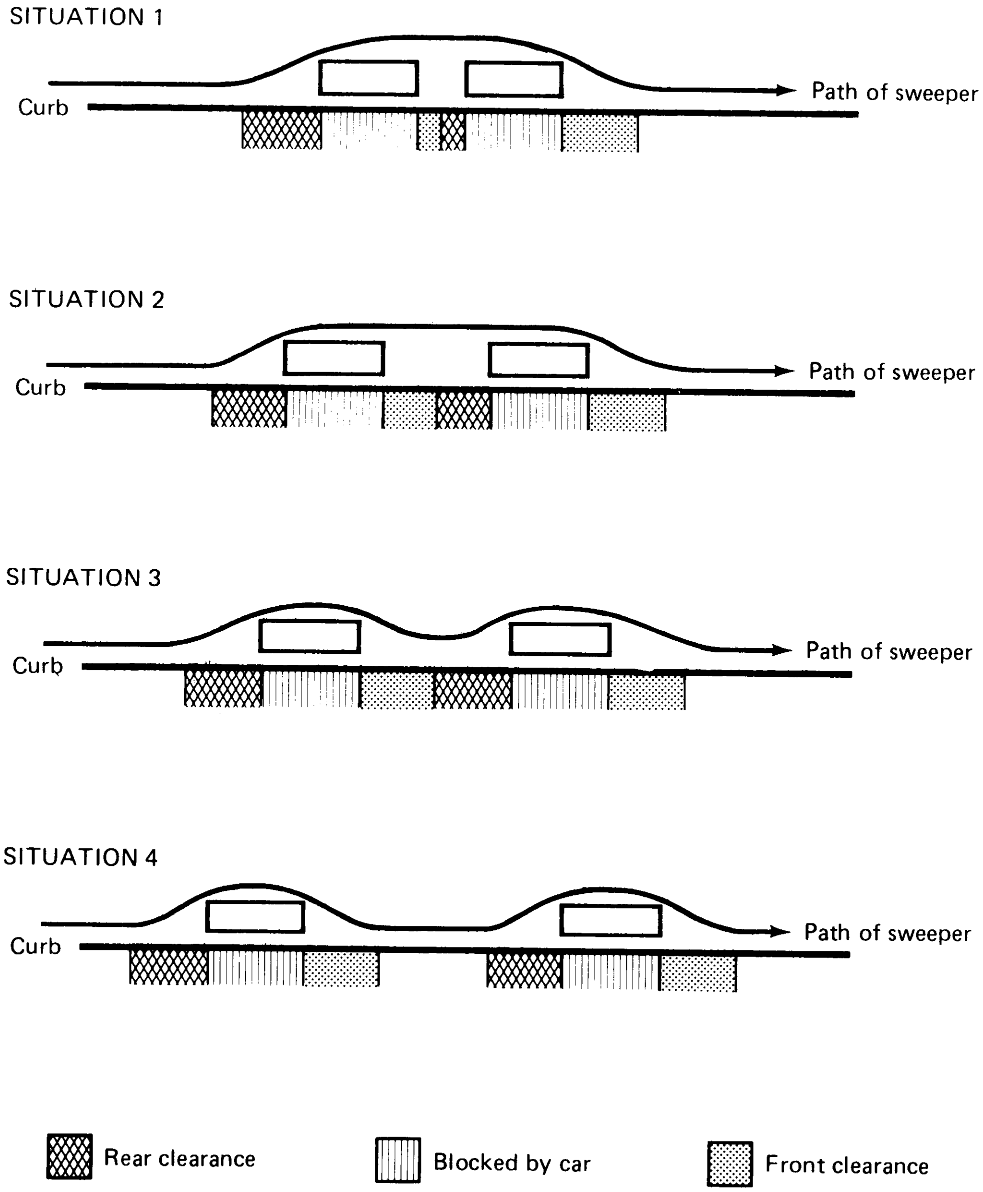
demonstrates decreased per mile removal quantities per equipment pass as the number of passes per year increases. The unit effort and costs increase by 10 times between 10 and 100 passes per year, but the actual amount removed only increases by a factor of about 4.

PARKING INTERFERENCES TO STREET CLEANING OPERATIONS

Vehicles parked along a street cleaning route reduce the length of curb that may be cleaned. Since most of the street surface pollutants are found close to the curb on smooth streets with little parking, parked vehicles can drastically reduce the cleaning effectiveness of normal cleaning programs on these streets. The following discussion attempts to quantify this relationship.

Field work associated with this demonstration project has shown that street cleaners can be partially effective when cleaning around cars. Extensively parked cars block the migration of particulates toward the curb, resulting in higher "middle-of-the-street" loading values than for streets with little or no parking.

Figure 3-18 (from Levis 1974) illustrates several possible configurations for two cars: two closely parked cars, two parked cars with little space between



Source: from Levis 1974

Figure 3-18. Effect of parked cars on street cleaner maneuverability them, two parked cars with enough space between them for the street cleaner to just get back to the curb and leave again, and two parked cars quite a distance from each other. The length of curb not cleaned because of parked cars may be determined geometrically by knowing the turning radius of a street cleaner and the parking layout along the street. As shown on Figure 3-19, the percentage of curb length occupied by parked vehicles is close to the percentage of parking spaces occupied, but is usually smaller due to parking restrictions such as driveways and fire hydrants. As the number of parked cars increases, the percentage of curb left uncleaned increases proportionally. The turning radius has a small effect (less than 5 percent) on the percentage of curb left uncleaned.

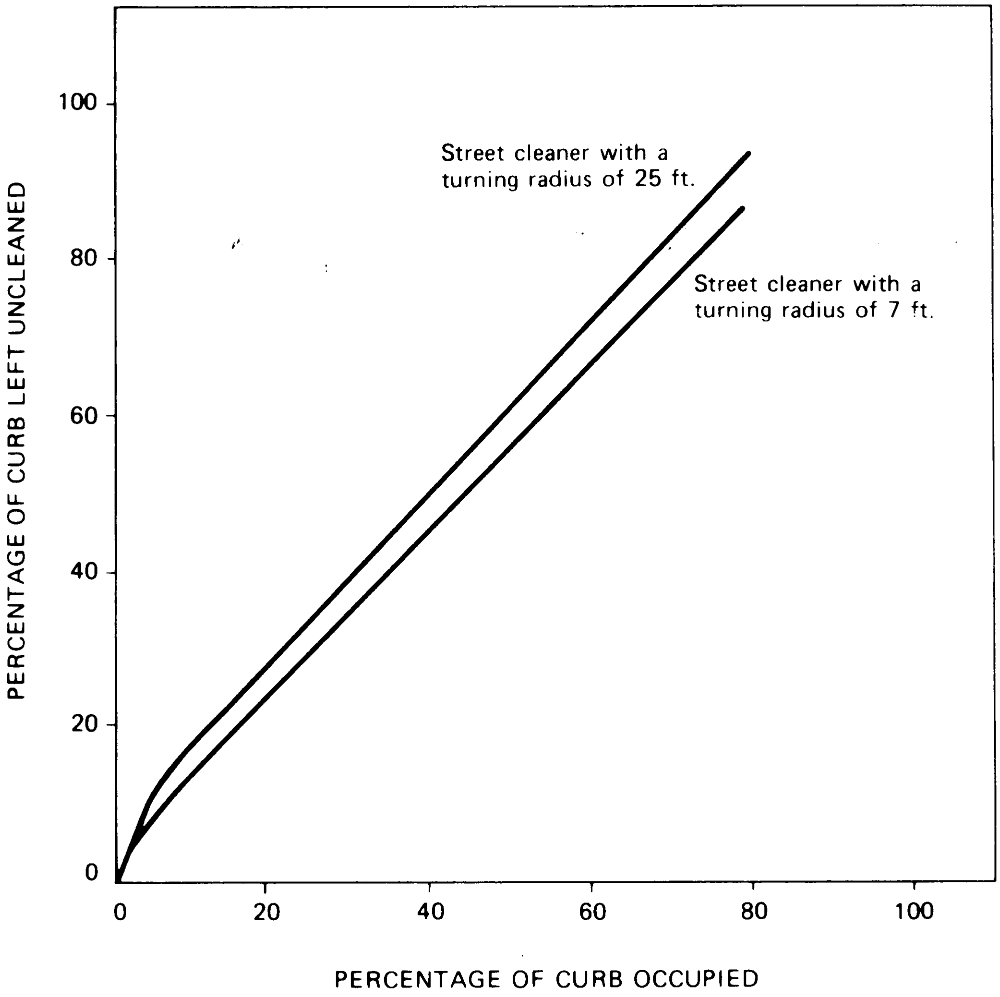


Figure 3-19. Effects of parking on urban street cleaning.

Figures 3-20 and 3-21 demonstrate the effect of parking controls on street cleaning effectiveness for two different street surface conditions and various parking conditions (based on Table 3-25). If a smooth street has extensive on-street parking 24 hours a day (such as in a high-density residential neighborhood), most of the street surface particulates would not be within the 8 ft. strip next to the curb that is usually cleaned by street cleaning equipment. Figure 3-20 shows that if the percentage of curb length occupied by parked cars exceeds about 80 percent for extensive 24-hour parking conditions, it would be best if the parked cars remained and the street cleaner swept around the cars (in the 8 to 16 ft. strip from the curb). Of course, all of the cars should be removed periodically to allow the street cleaner to operate next to the curb to remove litter caught under the cars. In an area with extensive daytime parking only (such as in downtown commercial areas), the parked cars should remain parked during cleaning (daytime cleaning) if the percentage of curb length occupied exceeds about 95 percent. The oil and screens surfaced streets are less critical to parked cars because of the naturally flatter distribution of solids across the street. Parking controls would be effective on those streets if the typical parking conditions involved less than about 95 percent curb length occupancy. Under most conditions, removal of parked cars during street cleaning operations can significantly improve the street cleaning effectiveness. Local monitoring of "across-the-street" loadings for various parking conditions should be conducted for other cities to determine their specific relationship.

Parking regulations may be necessary to improve street cleaning operations. "No Parking" signs indicating the days and hours of cleaning operations and illegal parking should be installed. The signs should be placed every 250 feet, or more frequently if objects such as trees block them from view. Compliance with parking regulations usually requires parking patrolers who will ticket illegally parked cars ahead of the street cleaner. This results in an additional labor cost, but the revenue from parking fines can be used to offset the program's expenditures. Street cleaning and parking restrictions should be scheduled on alternate sides of the street on consecutive days to lessen the problem of finding parking spaces in high density residential areas.

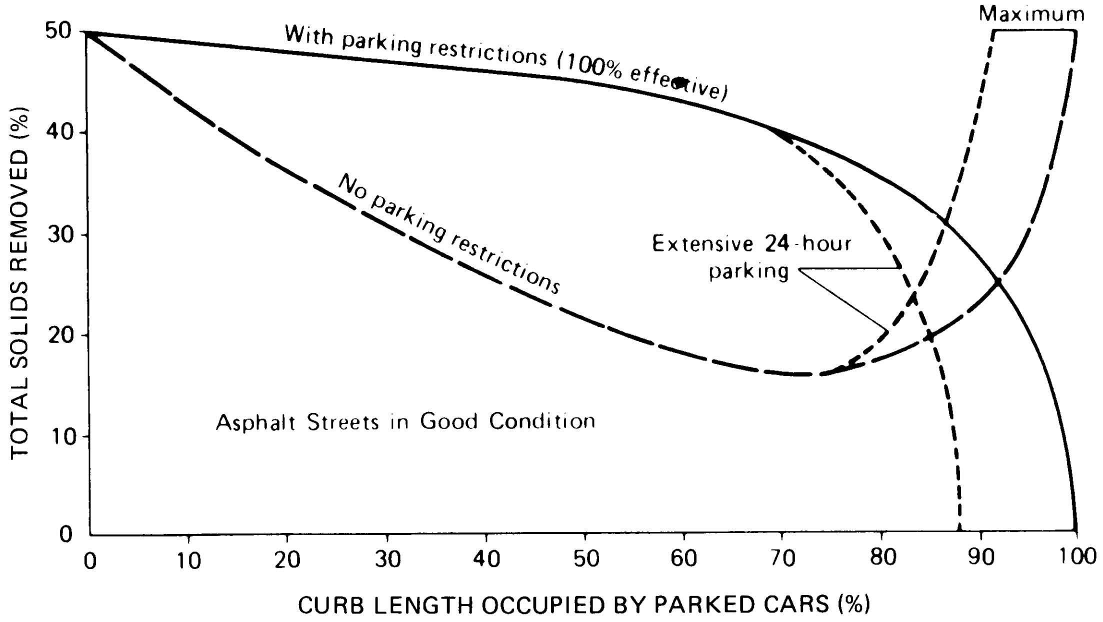


Figure 3-20. Effects of parking restrictions during street cleaning on asphalt surfaced streets in good condition.

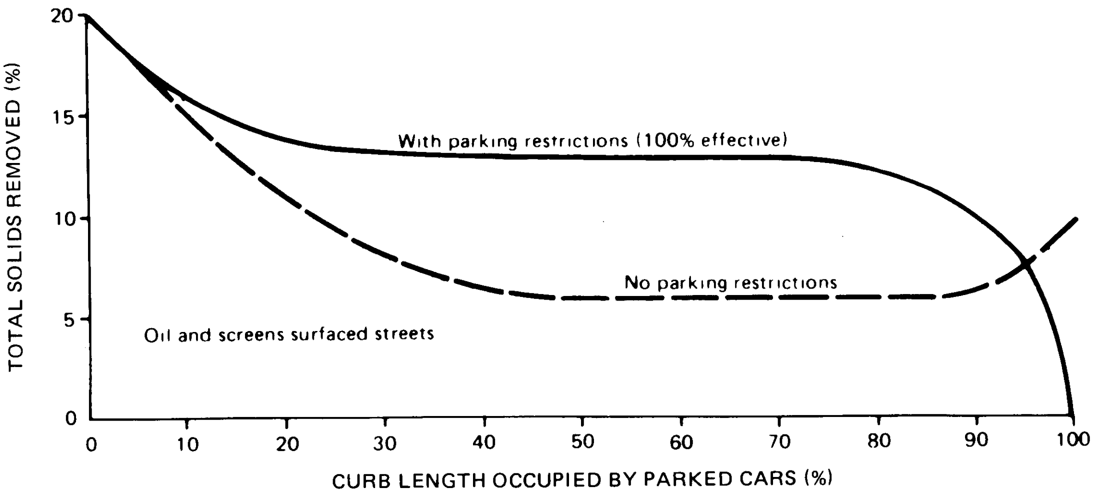


Figure 3-21. Effects of parking restrictions during street cleaning on oil and screens surfaced streets.

TABLE 3-25. PARKED CAR EFFECTS ON STREET CLEANING EFFECTIVENESS

				Smooth Asphalt Streets in Good Condition			Oil and Screens Surfaced Streets		
Percentage of Curb Length Occupied	Parking Category	Percentage of Curb Length Cleaned (0 to 8 ft. Cleaning Path)	Percentage of Distance Cleaned Around Cars (8 to 5 ft. Cleaning Path)	% of All Solids Removed with Parking Controls & Operated Next to Curb with a 0 to 8 ft. Cleaning Path	% of Total Solids Removed if the Cleaning Path is 8 ft. to 16 ft. From Curb	% Total Street Solids Removed with No Parking Controls and with Cleaner Moving Around Cars as Necessary	% of All Solids Removed with Parking Controls & Operated Next to Curb with a 0 to 8 ft. Cleaning Path	% of Total Solids Removed if the Cleaning Path is 8 ft. to 16 ft. From Curb	% Total Street Solids Removed With No Parking Controls & With Cleaner Moving Around Cars As Necessary
0	none	100	0	50	0	50	20	5	20
10	light	86	14	49	1	42	16	8	15
20	light	75	25	48	2	36	14	10	13
30	light	63	37	47	3	31	14	10	7
40	moderate	53	47	46	4	26	13	10	6
50	moderate	41	59	45	5	21	13	10	6
60	moderate	30	70	43	8	19	13	10	6
70	moderate	19	81	39	11	16	13	11	6
80	extensive	10	90	35	16	18	12	12	6
90	extensive	0	100	28	23	23	10	14	6
100	extensive	0	100	0	50	50	0	20	10
80% for 24 hrs.	extensive	0	90	30	21	19	12	12	6
90% for 24 hrs.	extensive	0	100	0	43	43	10	14	6
100% for 24 hrs.	extensive	0	100	0	50	50	0	20	10

For the tracer studies, fluorescent particles were placed in a specially constructed catchbasin. These different colored particles were used to investigate flushing of catchbasin contents from different depths to the sewerage. Resulting concentrations of fluorescent particles in the sewerage and from different depths in the catchbasin were periodically checked. Catchbasin cores were taken with a carbon dioxide freezing core sampler in order to minimize sample disturbance. The tracer study was confined to a single portion of the storm drainage system in the Keyes Street study area. Samples were periodically collected from eight internal sampling locations and at the outfall.

Automatic water samplers and flow meters were installed near the outfalls in the storm sewerage systems draining the Keyes Street and Tropicana study areas. These devices collected runoff samples during storms. The analytical programs are listed in the following subsection.

ANALYTICAL PROGRAM

The collected runoff samples were analyzed individually and in selected composites. The more important parameters were investigated at different times during a rain to see how flow and concentrations change as the rain progresses. Other parameters were analyzed only once during each monitored rain. Three storms with several separate peaks each were continuously monitored in each of the two study areas. The following list describes the general analytical scheme used for the runoff analyses:

- Periodic in situ analyses:

  dissolved oxygen
  temperature

- Individual samples (as many as one analysis per hour for each rain monitored):

  specific conductance
  pH
  oxidation-reduction potential (ORP)
  turbidity

- Up to three analyses per monitored rain:

  total solids (TS)
  suspended solids (SS)
  total dissolved solids (TDS)
  chemical oxygen demand (COD)
  5-day biochemical oxygen demand (BOD_5)
  Kjeldahl nitrogen (TKN)
  total orthophosphates (OPO)
  settleable solids
  lead (Pb)
  zinc (Zn)
  chromium (Cr)
  copper (Cu)
  cadmium (Cd)

Runoff Sampling Program

The BOD values were of particular interest in the runoff sample analysis program. A high BOD rate is thought to be one of the most important characteristics of urban runoff because of the immediate and significant oxygen demand it can make on certain receiving waters. This demand may cause an immediate and/or long-term depletion of oxygen in the receiving waters.

BOD values obtained in the incubation period from 0 to 10 days were about what was expected; the largest rate of BOD increase in this first 10 days of incubation usually occurred on the first day, with the 1-day BOD values being about 20 mg/1. This value remained relatively constant until about the fifth day, when it gradually rose to the 10-day value. The most unusual aspect of the BOD rate of change occurred in the incubation period from 10 to 20 days, when the BOD values increased by a factor of 2 or more. The initial oxygen demand is rapid and may have possible deleterious effects on certain receiving waters close to the time of discharge. As the material settles out, however, it apparently can exert a much larger, longterm oxygen demand.

These apparent BOD characteristics may be due to the standard BOD bottle test in which a standard sewage seed material was used and the runoff sample was diluted. Urban runoff has a relatively high heavy metal and low nutrient content, which can decrease the bacteria activity in the closed bottle after the wastes that are easily assimilated have been consumed. A long period of time is then necessary to reestablish an acclimatized bacteria population that will more completely stabilize the runoff. Ammonia oxygen demand can also result in long-term oxygen depletion. From this current study it is not possible to determine whether the potential long-term problem actually exists, or whether the testing procedure is faulty.

The study also compared the relative strengths* of pollutants in the runoff with the relative strengths of pollutants in the street dirt to compare the pollutant contributions from the street surface with the other watershed areas. This information helped identify those pollutants that may be most effectively controlled by street cleaning. The study showed that for lead, chromium, and copper, relative concentrations in the runoff were all much smaller than for those measured in the street dirt. The relative concentrations for COD, Kjeldahl nitrogen, and orthophosphates were much greater for the runoff samples than for the street dirt samples. These data indicate that the major sources for organics and nutrients are from areas other than the streets, while the major sources for heavy metals are associated with street activity. Organic and nutrient material wash onto the streets and into the storm drains during runoff and are diluted by the street dirt, which has lower concentrations of these materials. Conversely, these erosion materials tend to be low in heavy metals, and thus dilute the heavy metal concentrations of the street dirt. Therefore, if it is important to significantly reduce organic and nutrient discharges in the runoff, street cleaning may not be an appropriate control measure.

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*Relative strength is measured as mg of pollutant per kg of total solids.

TABLE 4-1. RAINS DURING FIELD ACTIVITIES*

Date	Total (in.)	Hours of Rain	Average Intensity (in./hr)	Peak Intensity (in./hr)
11/11/76**	0.35	8	0.04	0.10
11/12	0.09	4	0.02	0.04
11/13	0.07	3	0.02	0.04
11/14**	0.29	5	0.06	0.11
12/29**	0.34	3	0.11	0.18
12/30**	0.37	9	0.04	0.11
1/1/77	0.04	3	0.01	0.02
1/2**	0.24	6	0.04	0.09
1/3**	0.20	9	0.02	0.05
1/5	0.08	2	0.04	0.06
1/12	0.07	2	0.04	0.06
1/21	0.01	1	0.01	0.01
2/6	0.01	1	0.01	0.01
2/8	0.08	4	0.02	0.03
2/20	0.03	1	0.03	0.03
2/21	0.13	3	0.04	0.10
2/22	0.02	2	0.01	0.01
2/23	0.13	6	0.02	0.06
2/28	0.06	2	0.03	0.04
3/9	0.08	1	0.08	0.08
3/12	0.01	1	0.01	0.01
3/13	0.11	2	0.06	0.08
3/15**	0.91	15	0.06	0.13
3/16**	0.25	5	0.05	0.12
3/23	0.02	2	0.01	0.01
3/24**	0.19	5	0.04	0.08
4/8	0.03	2	0.02	0.02
4/25	0.02	1	0.02	0.02
4/30	0.06	3	0.02	0.04
5/1	0.18	6	0.03	0.08
5/6	0.01	1	0.01	0.01
5/7**	0.28	2	0.14	0.19
5/8**	0.28	4	0.07	0.09
5/9	0.01	1	0.01	0.01
5/11**	0.20	6	0.03	0.08
5/18	0.09	4	0.02	0.03
5/23	0.07	2	0.04	0.05
5/26	0.01	1	0.01	0.01
7/2	0.14	5	0.03	0.10
9/19**	0.58	5	0.12	0.33
10/27	0.18	5	0.04	0.07
10/28	0.01	1	0.01	0.01
10/29	0.01	1	0.01	0.01
11/5**	0.51	3	0.17	0.25
11/21**	0.28	6	0.05	0.20
11/22	0.10	1	0.01	0.01
12/5	0.01	1	0.01	0.01
12/14	0.06	2	0.03	0.05
12/15	0.06	2	0.03	0.05
12/16	0.11	4	0.03	0.05
12/17**	0.73	13	0.06	0.12
Total	8.20			

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* The period of study was characterized by low rainfall quantities. The number of rains were slightly fewer (about 75%) but the total rainfall quantity was substantially reduced (about 50%).

**Significant rains. See Section 3, discussion of accumulation rates, for definition and importance of these rains.

the receiving water. Monitoring the receiving water directly would give more accurate results, but runoff comparisons can give a gross indication of potential problems. Once again, identifying the problem pollutants and their source areas help in the selection of the most effective control measures.

Recommended water quality criteria are designed to protect the beneficial uses of the water with a reasonable amount of safety. If a monitored concentration exceeds these criteria, it does not mean that a problem exists, but only that a problem may occur. Additional monitoring and research should then be conducted to define the relationships between the water quality and the potential impairment of the beneficial uses for the specific receiving water.

The study showed that the heavy metals--cadmium, chromium, lead, mercury, and zinc--along with phosphates, BOD, suspended solids, and turbidity exceeded various recommended criteria during the monitored storms. Aquatic life use may be adversely affected by more pollutants than other beneficial uses.

Comparison of Urban Runoff With Sanitary Wastewater Effluent

This study compared the monitored quality of urban runoff with treated sanitary wastewater effluent. The latter is usually treated extensively, while urban runoff usually gets little or no treatment.

Water quality comparisons of urban runoff with average secondary sewage effluent showed that most of the nutrients, heavy metals, solids and oxygen-demanding materials had greater concentrations in the runoff. Thus urban runoff may have more important short-term effects on receiving waters than treated secondary effluent.

Annual yields of pollutants (lb/yr*) are a measure of potential long-term problems. Lead, chromium and suspended solids had greater annual yields in the street surface portion of the runoff than in the treated secondary effluent. Therefore, urban runoff may also cause greater long-term receiving water problems because of these heavy metal and solids yields. It follows that improvements in the sanitary sewage effluent may not be as cost-effective at removing these pollutants from the receiving water as some removal of the street surface pollutants by street cleaning.

STRUCTURE OF THE STUDY

Tracer studies and actual runoff sampling studies were conducted to investigate the solids routing and pollutant mass flow characteristics of urban runoff. These studies cannot yield data applicable to all situations because of limited sampling. A methodology that can be used to investigate and validate the anticipated processes was developed. These techniques can be reviewed and possibly adapted for larger-scale investigations and investigations of combined sewerage systems.

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*See Metric Conversion Table 0-1.

TABLE 4-2. MAJOR ION COMPOSITIONS OF RUNOFF SAMPLES (%)

	Keyes Street Study Area		Tropicana Study Area		
	3/15 and 16/77	3/23 and 24/77	3/15 and 16/77	3/23 and 24/77	4/30 and 5/1/77
Cations					
Ca^{++}	35.9%	53.7%	34.2%	29.8%	34.2%
K^{+}	10.3	4.5	3.3	3.6	4.0
Mg^{++}	30.8	18.1	21.1	20.2	17.4
Na^{+}	23.1	22.6	41.5	46.4	43.6
Zn^{++}	<2.6	0.6	<0.7	<0.4	0.4
Pb^{++}	<2.6	0.6	<0.7	<0.4	0.4
Total	100.1	100.1	100.1	100.0	100.0
Anions					
HCO_3^-	42.6	77.9	45.2	50.0	<0.8
$CO_3^=$	0.2	0.1	<0.1	0.1	<0.8
$SO_4^=$	21.3	11.2	23.7	27.0	44.8
Cl^-	18.0	10.2	24.4	21.6	40.0
$PO_4^{\equiv}$	16.4	0.3	5.2	1.0	15.2
NO_3^-	1.6	0.3	1.5	0.5	<0.8
Total	100.1	100.0	100.0	100.2	100.2
Major water type	Ca and Mg-HCO_3	Ca-HCO_3	Na and Ca-HCO_3	Na-HCO_3	Na and Ca-SO_4 and Cl

- Up to ten two-hour composite analyses per monitored rain:

  total solids
  suspended solids
  total dissolved solids

- One flow-weighted composite analysis per monitored rain:

  mercury (Hg)
  calcium (Ca^{++})
  potassium (K^{+})
  magnesium (Mg^{++})
  sodium (Na^{+})
  chlorides (Cl^{-})
  sulfates ($SO_4^{=}$)
  bicarbonates (HCO_3^{-})
  carbonates ($CO_3^{=}$)
  nitrates (NO_3^{-})
  BOD "k" rate

MONITORED RAINS

In 1977, twelve rain periods were monitored and analyzed in the two instrumented study areas. Many samples were obtained from these rains and were generally analyzed as described above. These rain periods are summarized in the following list:

- Keyes study area:

  1700 March 15 through 0900 March 16 (1.16 in.)
  1200 March 23 through 1300 March 23 (0.01 in.)
  1000 March 24 through 1700 March 24 (0.19 in.)
  1700 April 30 through 2200 April 30 (0.06 in.)
  0200 May 1 through 1500 May 1 (0.18 in.)

- Tropicana study area:

  1600 March 12 through 1100 March 13 (0.01 in.)
  0900 March 15 through 1300 March 16 (1.16 in.)
  1100 March 23 through 1700 March 23 (0.01 in.)
  1900 March 23 through 0100 March 24 (0.01 in.)
  1000 March 24 through 0000 March 25 (0.19 in.)
  1700 April 30 through 2200 April 30 (0.06 in.)
  0200 May 1 through 1500 May 1 (0.18 in.)

Table 4-1 lists the precipitation record for San Jose during the period of study. These data are from the recording rain gauge station operated by San Jose State University, 0.5 and 2 miles from the study areas. A total of 8.20 in. of rain fell from November 1976 through December 1977, as compared with a long-term average for that period of 16.53 in. It rained on 51 days, slightly fewer than normal. The runoff monitoring was started in March to enable the previous year's accumulation of sewerage solids to be flushed from the lines and to allow sufficient time for field installation and testing of the automatic sampling equipment.

Figure 4-1 presents BOD values as a function of incubation time. Selected composite samples representative of each storm were incubated and BOD values were measured at increments of approximately 1, 3, 5, 10, and 20 days. The relative BOD values shown in the time interval from 0 to 10 days are about what was expected. The 5-day BOD values are about two-thirds the 10-day BOD values. The largest rate of BOD increase in this first 10 days occurred usually on the first day, with 1-day BOD values of about 20 mg/l (for 2 of the 3 samples). This value remained relatively constant until about the fifth day when it gradually rose to the 10-day value. The most unusual character of the BOD value is shown in the period of time from 10 to 20 days when the BOD values typically increased by a factor of 2 or more. Typical sanitary wastes would have BOD_{10} to BOD_{20} increases of much less than a factor of 2. These results show that the initial oxygen demand is rapid and may have possible deleterious effects on certain receiving waters close to the time of discharge (within the first day). However, as the material settles out, it can exert a much larger, long-term oxygen demand. Therefore the oxygen depletion caused by urban runoff is important both immediately after discharge and at periods of time longer than 10 days after discharge. (These time factors are all dependent on water temperature and other physical and chemical characteristics of the receiving water.)

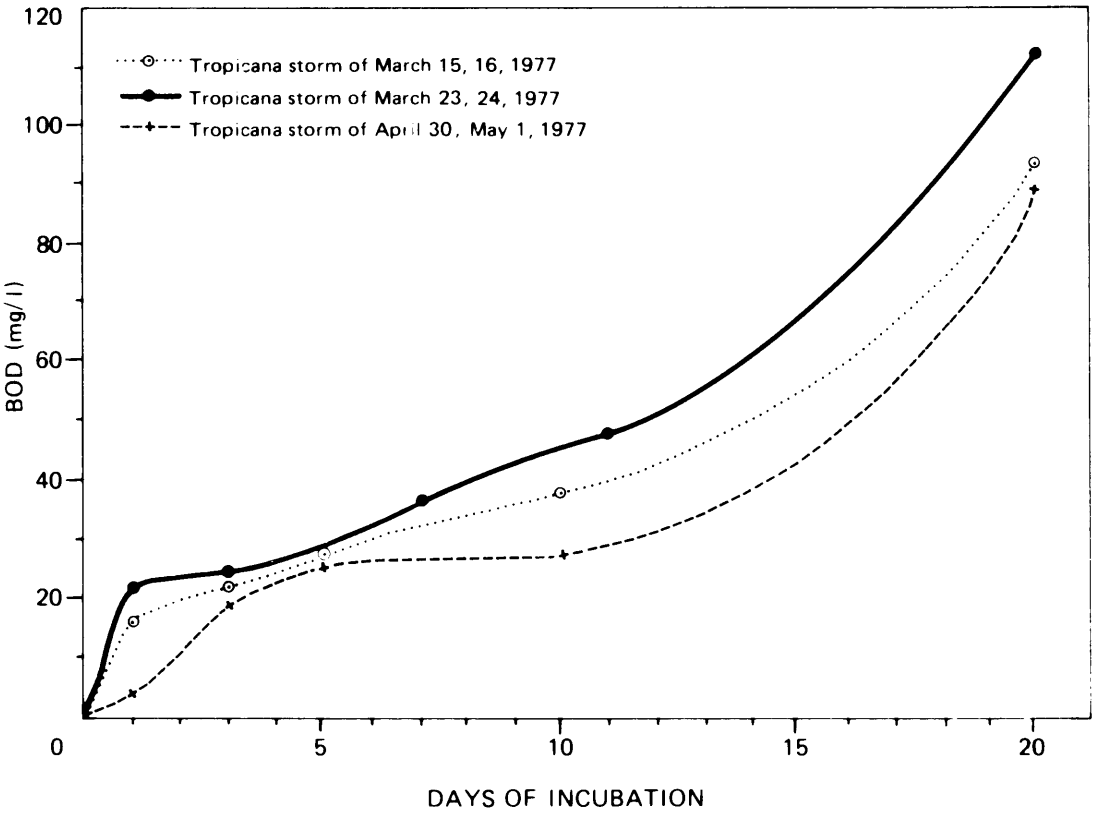

Figure 4-1. BOD values as a function of incubation time.

RUNOFF SAMPLING PROGRAM

Appendix F presents the laboratory and field data for the runoff samples that were collected. This appendix lists concentrations of major ions, major parameters, heavy metals, and solids for each of the monitored rains (see Tables F-11 through F-23). Figures F-1 through F-9 of Appendix F are hydrographs of the monitored rains showing the recorded sewerage flows, precipitation data, and the water sampling periods. Several of these rains had multiple precipitation peaks with distinct runoff peaks. A lag period of 1 to 6 hours occurred between the beginning of the precipitation and the start of measurable flow. The most common lag period was about 1 hour. The flows also continued for 3 to 8 hours after the precipitation stopped in the study areas. In almost all cases, peak recorded flows occurred 1 to 2 hours after the peak precipitation. The Tropicana study area, being about twice the size of the Keyes Street study area, had significantly greater peak flows. The largest peak flow recorded in the Tropicana study area was about 19 cubic feet per second (cfs)*. The other peak flows in the Tropicana study area ranged from 1 to about 7 cfs. Flows in the Keyes Street study area were much less, with a maximum recorded peak flow of about 4 cfs. The other peak flows were all less than 1 cfs. In most cases, a precipitation total of 0.01 in. caused a measurable flow at the outfalls. All of the rains up to March 30 were sampled hourly, while the rains since then were sampled on a flow-weighted basis.

Tables F-1 through F-10 of Appendix F present the water sample information. These tables show the water sample code numbers corresponding to the coded callouts on Figures F-1 through F-9. Also shown on these tables are the date and time that the samples were taken and the average flow for that sample period. The total flow represented by that sample, along with pH, ORP, specific conductance, and turbidity values are also shown. Appendix F also presents these data and the chemical constituents on a per unit time basis. As can be expected, the concentrations of most of the pollutants decreased with time.

Table 4-2 presents the major ion compositions for the runoff samples. It is interesting to note that the two study areas had slightly different major water types. The Keyes Street study area had a calcium and magnesium-bicarbonate or a calcium-bicarbonate major water type, and the Tropicana study area had a sodium and calcium-bicarbonate, a sodium-bicarbonate, or a sodium and calcium-sulfate and chloride water type. It is not known why sodium, sulfate, and chloride were more prevalent in the Tropicana study area.

Table 4-3 summarizes the oxygen demand and organic characteristics of the runoff samples. It presents the BOD_5, COD, TOC,** and some VSS*** data for selected samples. It is interesting to note that the COD concentrations are about 3 to 10 times greater than the BOD_5 values, and the TOC concentrations are as much as 10 times the BOD_5 concentrations. For a normal sanitary waste having low toxicity and sufficient nutrients, the COD values should only be slightly greater than the BOD_5 values.

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* See Metric Conversion Table 0-1.

** Total organic carbon.

***Volatile suspended solids.

TABLE 4-4. RUNOFF POLLUTANT RELATIVE STRENGTHS (mg pollutant/kg total solids)

Study Area	COD	BOD_5	KN	Ortho PO_4	Pb	Zn	Cr	Cu	Cd	Hg
Keyes Study Area										
3/15 & 16/77 storm	911,000	204,000	54,800	22,600	1800	750	68	140	27	<1
3/23 & 24/77 storm	520,000	32,000	5300	--	1100	470	44	59	5.9	0.15
4/30 & 5/1/77 storm	--	--	--	11,000	--	--	--	--	--	--
Tropicana Study Area										
3/15 & 16/77 storm	280,000	91,600	11,300	8000	800	360	40	70	<7	<4
3/23 & 24/77 storm	570,000	61,000	14,000	1800	711	421	33	48	<8	<0.4
4/30 & 5/1/77 storm	680,000	74,000	39,000	16,000	1700	710	50	100	5	0.5

This apparent long-term increase in oxygen demand may be caused by some of the inherent problems in the standard bottle BOD test when analyzing toxic and/or low nutrient samples. Because urban runoff has relatively high concentrations of heavy metals and low concentrations of nutrients, the seed bacteria may require a longer time for acclimatization than normal. The initial oxygen demand could be caused by the relatively easily assimilated organics being consumed by the standard seed bacteria before significant bacteria dieoffs occur from heavy metal toxicity. A lag period of several days could then be required for the surviving seed bacteria to become acclimated and reestablished so as to assimilate the remaining organics. Ammonia oxygen demand may also cause long-term oxygen depletion with about one-fourth of the observed 10 to 20 day increase possibly caused by ammonia oxidation. Colston (1974) has developed an alternative BOD procedure for urban runoff based on measurements of COD with time. His procedure uses an aerated and mixed sample, with typical receiving waters for dilution. Colston has found that typical urban runoff BOD_5 values are about one-half the corresponding COD values.

Table 4-4 presents the runoff pollutant strengths expressed as milligrams of pollutant per kilogram of total solids (or ppm) averaged over the durations of the monitored rains. There are no clear differences (because of limited data) in the pollutant concentrations between the different storms or study areas. In most cases, the range of pollutant strengths for all of the storms combined was less than a factor of 10 to 1, and in several cases even less than 3 to 1. When these runoff pollutant strengths are compared with the street surface contaminant pollutant strengths, notable differences are found. It is interesting to note that the relative concentrations in the runoff for COD, Kjeldahl nitrogen, and orthophosphates are much greater than the relative concentrations observed in the street dirt (about 3 to 180 times greater in the runoff).

Some of the zinc and cadmium relative concentrations were also greater in the runoff than in the street dirt. The relative concentrations of lead, chromium, and copper in the runoff were all much smaller than those measured on the street. These differences ranged from about 2 to 20. A difference in the particle size makeup of the runoff solids and the street dirt may explain some of these differences. It was expected that other causes would be important, such as additioinal organic and nutrient material washing onto the streets and into the storm drains from the surrounding areas because of erosion during rains. Lower concentrations of heavy metals in the soil erosion products could also cause the runoff heavy metal relative concentrations to be much smaller. If the erosion products have lower concentrations of heavy metals, the resultant runoff concentrations of heavy metals would be diluted when compared to the higher concentrations in the street dirt. Therefore, much of the organic and nutrient material in urban runoff may originate, not from the street surface or from automobile activity, but from the surrounding areas during erosion. Similarly most of the heavy metals in urban runoff are expected to be associated with street surfaces and automobile activity. A similar conclusion was also identified by Amy, et al. (1974). In that study, the authors analyzed existing runoff and street surface loading data in an attempt to determine a loading model as a function of various influencing characteristics (such as geographical area, land use, traffic conditions, etc.). They found that when the street surface loading data were compared with the runoff data the only significant differences in loading pre-

TABLE 4-5. TOTAL SOLIDS STREET SURFACE LOADING REMOVALS BY RAIN STORMS

	Keyes - Oil and Screens Test Area			Keyes - Good Asphalt Test Area			Tropicana - Good Asphalt Test Area		
Particle Size and Storm Date (µ)	Before Storm Loading (lb/curb-mile)	Loading Decrease During Storm (lb/curb-mile)	% Difference	Before Storm Loading (lb/curb-mile)	Loading Decrease During Storm (lb/curb-mile)	% Difference	Before Storm Loading (lb/curb-mile)	Loading Decrease During Storm (lb/curb-mile)	% Difference
3/15 and 16/77 storm									
>6370 µ	100	45	44	16	2.4	17	18	10.5	60
2000 → 6370	200	2	1	18	-4.8	-26	5.9	5.9	30
850 → 2000	210	-90	-42	25	-4.9	-20	26	10.6	41
600 → 850	140	-21	-15	16	0.8	5	15	9.8	65
250 → 600	470	-14	- 3	64	10.8	17	42	27.8	66
106 → 250	350	52	15	72	15.8	22	45	29.7	66
45 → 106	210	88	42	62	16.7	27	41	23.2	57
<45	71	54	76	12	-7.7	-66	10	- 2.2	-23
Total	1900	116	6	290	29.0	10	220	115	53
Avg; peak intensity		0.06: 0.13 in./hr			0.06; 0.13 in/hr			0.06; 0.13 in/hr	
Duration; total rain		20 hrs; 1.16 in.			20 hrs; 1.16 in.			20 hrs; 1.16 in.	
Days since last swept; number of passes		2 days; 1 pass			2 days; 1 pass			11 days; 1 pass	
3/23 and 24/77 storm									
>6370 µ	92	-33	-36	18	15.7	85	26	18.6	7
2000 → 6370	350	-99	-28	50	27.0	54	31	15.6	50
850 → 2000	290	-216	-74	75	32.1	43	52	29.9	57
600 → 850	190	- 51	-27	44	26.1	60	39	30.1	77
250 → 600	700	- 14	- 2	150	92.9	63	100	79.6	79
106 → 250	520	109	21	160	125	77	100	78.2	74
45 → 106	310	95	31	140	115	85	81	56.2	69
<45	110	81	74	30	0.6	2	20	- 6.5	-32
Total	2600	-128	- 5	660	434	66	460	302	66
Avg; peak intensity		0.03; 0.08 in./hr			0.03; 0.08 in./hr			0.03; 0.08 in./hr	
Duration; total rain		7 hrs; 0.21 in.			7 hrs; 0.21 in.			7.hrs; 0.21 in.	
Days since last swept; number of passes		5 days; 1 pass			5 days; 1 pass			21 days; 1 pass	
4/30 and 5/1/77 storm									
>6370 µ	130	15	12	41	51.7	127	25	28.0	112
200 → 6370	470	-145	-31	66	55.2	84	20	18.4	93
850 → 2000	100	-343	-340	73	53.0	73	27	23.8	88
600 → 850	100	-65	-62	48	45.2	94	19	18.4	96
250 → 600	320	-124	-39	140	153	107	57	56.0	98
106 → 600	280	54	19	130	155	119	65	65.3	100
45 → 106	170	46	27	110	136	121	54	49.9	92
<45	66	21	32	13	- 3.8	-30	9	-3.1	-34
Total	1600	-541	-33	630	645	103	280	257	93
Avg; peak intensity		0.03; 0.08 in./hr			0.03; 0.08 in./hr			0.03; 0.08 in./hr	
Duration; total rain		9 hrs; 0.25 in.			9 hrs; 0.25 in.			9 hrs; 0.25 in.	
Days since last swept; number of passes		22 days; 2 passes			22 days; 2 passes			4 days; 1 pass	

dictions were for nutrients. In that case, the nutrient values predicted for runoff data were greater than for street loading data, reflecting the fact that most of the nutrients originate in off-street areas.

POLLUTANT REMOVAL CAPABILITIES OF MONITORED STORMS

Tables 4-5 and 4-6 present the total solids and various street surface pollutant loading changes that occurred for each of the rain storms. Table 4-5 values were calculated from street surface loadings before and after the rain storms. Table 4-6 compares these values with actual stormwater runoff yields. A negative value in Table 4-5 signifies an increase in loading on the street surface during the storm. It is interesting to note that the rains had a much smaller effect on removing materials from the oil and screens streets as compared with the asphalt streets. It is thought that the increased roughness of the street surface in the oil and screens area trapped much of the erosion material from the surrounding areas on the street and prevented it from reaching the storm sewerage system. The Keyes-good asphalt and Tropicana-good asphalt test areas, both with relatively smooth asphalt streets, showed larger removals of material. The first storm showed a smaller absolute removal as compared to the latter two storms, possibly because of its increased intensity and larger erosion yields from surrounding areas that found their way onto the street during the rain.

The runoff removals in both the Keyes-asphalt and Tropicana study areas for the March 23-24 storm and for the April 30-May 1 storm were very similar. These last two relatively small storms were capable of removing significant quantities of material from the street surface, yet did not cause large amounts of erosion products in the runoff.

Table 4-6 summarizes the pollutant street surface loading changes for the different rain storms on a curb-mile basis and also on a total pounds basis for the two study areas. These runoff yields, as measured on the street surface, are compared to the total pollutant yields of the storms. The observed ratios between street surface loading differences of the pollutants as measured on the street and the runoff yield as measured by analyzing runoff vary. Values smaller than 1 possibly signify that more of that pollutant originated in the surrounding areas and storm sewerage than on the street surface. Values greater than 1 possibly indicate that most of the material that originated from street surfaces accumulated in the storm sewerage.

These ratios appear to vary as a function of the rainstorm characteristics, the study area, and the specific pollutants. The March 15 and 16 storm generally had ratios less than 1 for all of the pollutants in both study areas, while the last two storms shown in Table 4-6 had many values greater than 1. Again, the initial storm was of much greater intensity and volume, possibly causing greater erosion in the surrounding areas and increased sewerage velocities that would keep the particulate material from settling in the storm drainage. The last two storms, however, were of relatively small intensity and showed almost complete removal of street surface contaminants from the street surface. That is probably due to the extra energy imparted on the street surface materials from automobile traffic and the sufficient rain available to wash the loosened materials from the street surface to the storm drain inlet. However the smaller streets would wash off during a rain and contribute to the pollution of urban runoff. Table 4-7 shows the estimated effectivenesses of various street cleaning programs (cleaning intervals) in controlling total urban runoff pollutant yields.

The estimates shown in Table 4-7 are based on too few runoff measurements (as discussed previously in this section) to be more quantitative. A runoff monitoring program designed to yield this specific information would require sampling many storms over a relatively long period of time. Nevertheless, several interesting observations were noted during this data analysis. It was found that very little difference in runoff water quality would be evident between cleaning programs operating twice every workday (520 passes a year) and once every workday (260 passes a year). A similar conclusion was found for cleaning programs of little intensity: cleaning once a month and once every three months would yield similar runoff quality conditions. As expected, the heavy metals may be controlled much more effectively (up to about 50 percent of this runoff yield could be removed for very intensive cleaning efforts) than the other pollutants. Total solids may also be controlled to a reasonably high value (up to about 40 percent). Organics and nutrients, which originate mostly from non-street areas within the watershed, would only be reduced by less than 10 percent. Removal effectiveness decreases by about a factor of three when reducing the cleaning effort from one or two passes every weekday to one pass every week. The removal effectivenesses are reduced by more than a factor of ten when reducing the effort from weekday cleaning to monthly (or less) cleaning.

Table 4-7. ESTIMATED EFFECTIVENESS OF VARIOUS STREET CLEANING PROGRAMS IN CONTROLLING URBAN RUNOFF*

	Cleaning Interval		
Parameter	One to Two Passes Per Weekday	One Pass Per Week	One to Three Passes Every Three Months
Total Solids	A	C	C
COD	C	C	D
KN	C	C	D
Ortho PO_4	C	D	D
Pb	A	C	C
Zn	A	C	C
Cr	A	C	C
Cu	A	C	C
Cd	B	C	C

---

*A = greater than 40% effective
B = 20 to 40% effectiveness
C = 1 to 20% effectiveness
D = less than 1% effective

TABLE 4-6. STREET SURFACE POLLUTANT REMOVALS COMPARED WITH RUNOFF YIELDS

	Keyes Street Study Area							Tropicana Study Area			
	Oil and Screens		Asphalt								
Parameter	lb/curb-mile difference	total lb difference in 2.2 curb-mile	lb/curb-mile difference	total lb difference in 2.7 curb-mile	Total Keyes Area lb difference	Runoff yield (lb)	Street Surface Difference to Runoff Yield Ratio	lb/curb-mile diference	total lb difference in 11.1 curb-mile	Runoff Yield (lb)	Street Surface Difference to Runoff Yield Ratio
MARCH 15-16, 1977, STORM											
Total solids	120	260	29	78	340	942	0.36	120	1300	8099	0.16
COD	24	53	3.0	8.1	61	859	0.071	11	120	2267	0.05
KN	0.33	0.73	5.2	14	15	51.8	0.28	0.22	2.4	90.2	0.03
$OrthoPO_4$	0.23	0.051	0.0049	0.013	0.064	21.1	0.003	0.020	0.22	65.8	0.003
Pb	0.40	0.88	0.19	0.51	1.4	1.75	0.79	0.47	5.2	6.5	0.80
Zn	0.067	0.15	0.022	0.059	0.21	0.71	0.29	0.054	0.60	2.9	0.21
Cr	-0.0084	-0.018	0.014	0.038	0.020	0.065	0.31	0.059	0.66	0.4	1.6
Cu	-0.014	-0.031	0.024	0.065	0.034	0.13	0.26	0.13	1.4	0.45	3.2
Cd	0.00031	0.001	0.0001	0.0001	0.001	0.026	0.038	0.0003	0.003	0.055	0.06
MARCH 23-24, 1977, STORM											
Total solids	-130	-290	430	1200	910	134	6.8	300	3300	1260	2.6
COD	8.8	19	58	160	180	68	2.6	.27	300	740	0.41
KN	0.21	0.46	0.97	2.6	3.1	0.7	4.4	0.57	6.3	17	0.37
$OrthoPO_4$	0.016	0.035	0.076	0.21	0.25	--	--	0.053	0.59	2.1	0.28
Pb	0.47	1.0	2.0	5.4	6.4	0.15	43	1.3	14	0.90	16
Zn	0.037	0.081	0.26	0.70	0.78	0.063	12	0.14	1.6	0.53	2.9
Cr	-0.14	-0.31	0.22	0.59	0.28	0.0059	47	0.16	1.8	0.042	42
Cu	-0.32	0.7	0.37	1	1.7	0.0079	210	0.34	3.8	0.060	63
Cd	0.0001	0.0001	0.0012	0.003	0.003	0.0008	3.8	0.0007	0.008	0.009	0.86
APRIL 30 - MAY 1, 1977, STORM											
Total solids	-540	-1200	650	1800	600	11.6	52	260	2900	1850	1.6
COD	- 20	- 44	88	240	200	--	--	24	270	1250	0.21
KN	-0.24	-0.53	1.4	3.8	3.3	--	--	0.49	5.4	72	0.076
$OrthoPO_4$	0.018	0.040	0.11	0.30	0.26	0.13	2.0	0.045	0.50	29	0.017
Pb	-0.075	-0.17	2.6	7	6.8	--	--	1.1	12	3.2	3.8
Zn	-0.089	-0.2	0.36	0.97	0.77	--	--	0.12	1.3	1.3	1.0
Cr	-0.35	-0.77	0.34	0.92	9.15	--	--	0.13	1.4	0.1	14
Cu	-0.62	-1.4	0.59	1.6	0.2	--	--	0.28	3.1	0.23	14
Cd	-0.0007	-0.002	0.0017	0.005	0.003	--	--	0.0006	0.007	0.009	0.74

flows in the sewerage were not capable of preventing the material from depositing in the sewerage. The small number of data points available prevents a specific model from being developed. The data demonstrate several relationships between rainfall characteristics, street surface conditions, relative pollutant yields from street surfaces and surrounding land-use areas, and pollutant deposition in the sewerage system.

EFFECTIVENESS OF STREET CLEANING IN IMPROVING URBAN RUNOFF WATER QUALITY

Street cleaning can be effective in reducing the quantity of some pollutants in urban runoff. Most of the material removed by a street cleaner on smooth

TABLE 4-8. RUNOFF CONCENTRATIONS OF VARIOUS POLLUTANTS

	Keyes Street Study Area				Tropicana Study Area					
	3/15 and 16/77 Storm		3/23 and 24/77 Storm		3/15 and 16/77 Storm		3/23 and 24/77 Storm		4/30 and 5/1/77 Storm	
Parameter*	Range	Avg	Range	Avg	Range	Avg	Range	Avg	Range	Avg
pH(pH units)	6.6 → 7.4	6.8	6.3 → 7.1	6.7	6.7 → 7.3	6.9	6.6 → 7.6	7.0	6.0 → 6.6	6.3
Temp. (°C)	15 → 16	15	15 → 16	16	14 → 16.5	15	15 → 16.5	16	--	--
DO	6.5 → 9.4	8.0	7.4 → 9.9	8.7	5.4 → 12.8	7.9	7.5 → 8.6	7.5	--	--
Turbidity (NTU)	10 → 81	43	43 → 120	86	12 → 90	37	4.8 → 130	38	12 → 68	41
TDS	22 → 40	34	All 107	107	35 → 376	275	26 → 371	160	80 → 330	160
SS	51 → 142	110	238 → 845	571	15 → 266	164	15 → 265	120	68 → 540	220
NO_3	--	0.5	--	0.9	--	1.5	--	0.5	--	0.3
PO_4	0.6 → 4.6	3.3	--	0.2	1.4 → 3	2.2	0.4 → 0.8	0.5	0.8 → 17.6	6.0
Cl	--	3.9	--	11.7	--	11.7	--	15.7	--	17.6
SO_4	--	6.3	--	17.5	--	15.2	--	26.4	--	27
Na	--	2.1	--	9.2	--	14.4	--	26.8	--	22.6
Cd	--	0.04	--	0.004	All <0.002	<0.002	All <0.002	<0.002	<0.002 → 0.006	0.002
Cr	--	0.01	--	0.03	0.01 → 0.02	0.01	0.005 → 0.01	0.009	0.01 → 0.04	0.02
Cu	--	0.02	--	0.04	0.01 → 0.02	0.02	0.01 → 0.03	0.013	0.02 → 0.09	0.05
Pb	--	0.27	--	0.76	0.10 → 0.32	0.22	0.15 → 0.19	0.20	0.26 → 1.5	0.66
Hg	--	<0.0001	--	0.0001	All <0.0001	<0.0001	All <0.0001	<0.0001	<0.0001 → 0.0006	0.0002
Zn	--	0.11	--	0.32	0.06 → 0.13	0.10	0.08 → 0.12	0.12	0.11 → 0.55	0.27
BOD_5	--	29.8	--	22	--	25.2	--	17	--	28

*Parameters are measured in mg/l unless otherwise noted.

TABLE 4-9. RUNOFF WATER QUALITY COMPARED TO BENEFICIAL USE CRITERIA

			Beneficial Use Criteria[b]						
Parameter[a]	Overall Observed Range	Overall Observed Average	Irrigation	Livestock	Wildlife	Aquatic Life	Marine Life	Recreational Uses	Freshwater Public Supply
pH (pH units)	6.0 → 7.6	6.7	4.5 → 9.0 desired	--	6.0 → 9.0 desired	6.0 → 9.0 desired	6.5 → 8.5 desired	5.0 → 9.0 desired	5.0 → 9.0 desired
Temp. (°C)	14 → 16.5	16	Narrative	--	Maintain natural pattern	Narrative	Narrative	86°F	Narrative
DO	5.4 → 12.8	8.0	--	--	--	Usually 5.0 mg/l min.	6.0 mg/l min.	--	Narrative
Turbidity (NTU)	4.8 → 130	49	--	--	--	Small change	--	4 ft (secchi)	Narrative
TDS	22 → 376	150	500 → 5000 mg/l max.	--	--	Narrative	--	--	Narrative
SS	15 → 845	240	Narrative	--	--	80 mg/l	--	--	--
NO_3	0.3 → 1.5	0.7	Narrative	450 mg/l (including NO_2)	--	--	--	--	45 mg/l
PO_4	0.2 → 17.6	2.4	--	--	--	--	0.0003 mg/l	0.3 mg/l for streams; 0.08 for lakes	Narrative
Cl	3.9 → 17.6	12	--	--	--	--	--	--	250 mg/l
SO_4	6.3 → 27	18	--	--	--	--	--	--	250 mg/l
Na	2.1 → 26.8	15	Narrative	--	--	--	--	--	Narrative
Cd	<0.002 → 0.04	0.01	0.01 → 0.05 mg/l max.	50 mg/l	--	0.004 → 0.03 mg/l max. for soft → hard water	0.01 mg/l	--	0.01 mg/l
Cr	0.005 → 0.04	0.02	0.1 → 1.0 mg/l max.	1.0 mg/l	--	0.03 mg/l	0.1 mg/l	--	0.05 mg/l
Cu	0.01 → 0.09	0.03	0.02 → 5.0 mg/l max.	0.5 mg/l	--	Narrative	0.05 mg/l	--	1 mg/l
Pb	0.10 → 1.5	0.4	5.0 → 10.0 mg/l max.	0.1 mg/l	--	0.03 mg/l	Narrative	--	0.05 mg/l
Hg	<0.0001 → 0.0006	<0.0001	--	0.001 mg/l	Narrative	0.00005 mg/l	0.1 mg/l	--	0.002 mg/l
Zn	0.06 → 0.55	0.18	--	25 mg/l	--	Narrative	0.1 mg/l	--	5 mg/l
BOD_5	17 → 31	24	--	--	--	10 mg/l	Narrative	--	Narrative

Sources: McKee and Wolf 1963; USEPA 1973; USEPA 1975.

[a] Parameters are measured in mg/l unless otherwise noted.
[b] Maximum limits unless stated as desired range or minimum values.

pollutants from the street surface before rains can wash them into the receiving waters. Section 5 discusses the relative unit costs for removing these pollutants by street cleaning as compared with alternative runoff treatment and combined wastewater treatment systems.

COMPARISONS OF RUNOFF WATER QUALITY WITH SANITARY WASTEWATER EFFLUENT WATER QUALITY

Table 4-10 presents a comparison between secondary sanitary wastewater effluent and urban runoff for the study areas. The average and peak one-hour runoff concentrations observed and average secondary sanitary wastewater effluent concentrations are shown along with the ratios between them. The sanitary wastewater treatment facility is a modern, advanced secondary treatment plant serving the study areas. The short-term effects of urban runoff on a receiving water occur (by definition) during and immediately following a runoff event: short-term effects are associated with instantaneous concentrations. A comparison between the urban runoff average concentrations and the sanitary wastewater treatment plant effluent average concentrations shows that the concentrations of lead, suspended solids, COD, cadmium, TOC, turbidity, zinc, chromium, and BOD_5 are all higher in the runoff than in the sanitary wastewater effluent. Copper and Kjeldahl nitrogen, in addition to the previously listed parameters, have greater runoff peak concentrations than the wastewater average concentrations. Therefore, urban runoff may have more important short-term effects on receiving waters than average treated sanitary wastewater effluent.

The annual yield for the different sources gives a measure that indicates the long-term problems. Table 4-10 shows the annual sanitary wastewater treatment plant effluent yield expressed as tons per year (derived from monthly average concentrations and effluent quantities), and the calculated annual street surface portion of the urban runoff yield expressed in tons per year for a similar service area. On an annual basis, the total orthophosphates and Kjeldahl nitrogen associated with the street dirt are less than 2 percent of the total sanitary wastewater treatment plant effluent plus urban street surface runoff yield. Total solids, cadmium and mercury contribute from 1 to 10 percent of this total, while chemical oxygen demand, biochemical oxygen demand, copper, and zinc contribute from 10 to 50 percent of this total. Suspended solids, chromium and lead street surface runoff contributes more than 50 percent of the total.

These data show that for a receiving water getting both secondary treated sanitary wastewater and untreated urban runoff, additional improvements in the sanitary wastewater effluent may not be as cost-effective as some street cleaning (except for nutrients). That is especially true for lead where more than 95 percent of this total wasteload is due to street surface runoff. If all of the lead were removed from the sanitary wastewater effluent, this total annual lead discharge would only decrease by less than 4 percent.

TRACER ANALYSIS OF SEWERAGE PARTICULATE ROUTING

A special catchbasin was constructed and partially filled with street surface particulate simulant and fluorescent particle tracer material to monitor

TABLE 4-10. COMPARISON OF URBAN RUNOFF AND WASTEWATER TREATMENT PLANT EFFLUENT

	Runoff Concentration (mg/l unless otherwise stated)		STP[a] Effluent Concentration (mg/l unless otherwise stated)	Ratio of Avg. Runoff to STP conc.	Ratio of Peak Runoff to Avg. STP conc.	Street Surface Annual Runoff[b] (tons/yr)	Annual STP Effluent[c] (tons/yr)	Ratio of Street Surface Runoff to STP Annual Yields
Parameter	Avg	Peak (1-hr)	Avg.					
Ca^{++}	13	19	65	0.20	0.29	350	8000	0.040
K^{+}	2.7	3.5	24	0.11	0.15	73	3200	0.023
Mg^{++}	4.0	6.2	35	0.11	0.18	110	4700	0.023
Na^{+}	15	27	220	0.07	0.12	410	30,000	0.014
Cl^{-}	12	18	330	0.04	0.05	330	45,000	0.007
$SO_4^{=}$	18	27	150	0.12	0.18	490	20,000	0.025
HCO_3^{-}	54	150	230	0.23	0.66	1500	32,000	0.047
NO_3	0.7	1.5	4.9	0.14	0.31	19	660	0.029
BOD_5	24	30	21	1.1	1.4	480	2800	0.17
COD	200	350	35[d]	5.6	10	950	4700[d]	0.20
KN	6.7	25	24	0.28	1.1	17	3200	0.005
OrthoPO_4	2.4	18	19	0.13	0.92	1.2	2600	0.0005
Total solids	350	950	1000	0.34	0.92	9500	140,000	0.07
TDS[e]	150	380	1000	0.15	0.37	4100	140,000	0.029
Suspended solids	240	850	26	9.2	32	4700	3500	1.3
Cd	0.01	0.04	0.002	5	20	0.018	0.27	0.07
Cr	0.02	0.04	0.016	1.3	2.5	3.5	2.2	1.6
Cu	0.03	0.09	0.081	0.37	1.1	5.5	11	0.5
Pb	0.4	1.5	0.0098	41	150	36	1.3	28
Zn	0.18	0.55	0.087	2.1	6.3	3.9	12	0.33
Hg	<0.0001	0.0006	0.0019	<0.05	0.32	0.0032	0.26	0.01
Specific conductance (μmhos/cm)	120	660	1900	0.06	0.36	--	--	--
Turbidity (NTU)	49	130	20	2.5	6.5	--	--	--
pH (pH units)	6.7	7.6	7.6	--	--	--	--	--
TOC[f]	110	290	30	3.5	9.7	3000	4100	0.73

[a] Secondary sanitary wastewater treatment plant.

[b] About 200 people correspond to 1 curb-mile (2880 curb-miles in San Jose/575,000 population). Therefore a population of 850,000 corresponds to about 4250 curb-miles, with about 1100 curb-miles of streets surfaced with oil and screens. These annual runoff values were calculated based on a year of the appropriate accumulation rates and these mileage estimates.

[c] An estimated population of 850,000 is served by the sanitary wastewater treatment facility.

[d] Estimated. [e] Total dissolved solids. [f] Total organic carbon.

the routing of particulates in a stormwater sewerage system. Figure 4-2 shows the storm drainage system in the Keyes Street study area that was selected for this portion of the study. The catchbasin was constructed at the south corner of south 12th and Bestor Streets. Figure 4-3 presents the storm drainage system details from this catchbasin to the outfall. The sewerage is all concrete pipe ranging in size from 10 to 27 in. in diameter. The sewerage slopes range from 0.16 to 0.79 percent. A total of about 2700 feet of sewerage is between the catchbasin and the last manhole before the outfall. The outfall is located several hundred feet northeast of the last manhole and is directly on Coyote Creek.

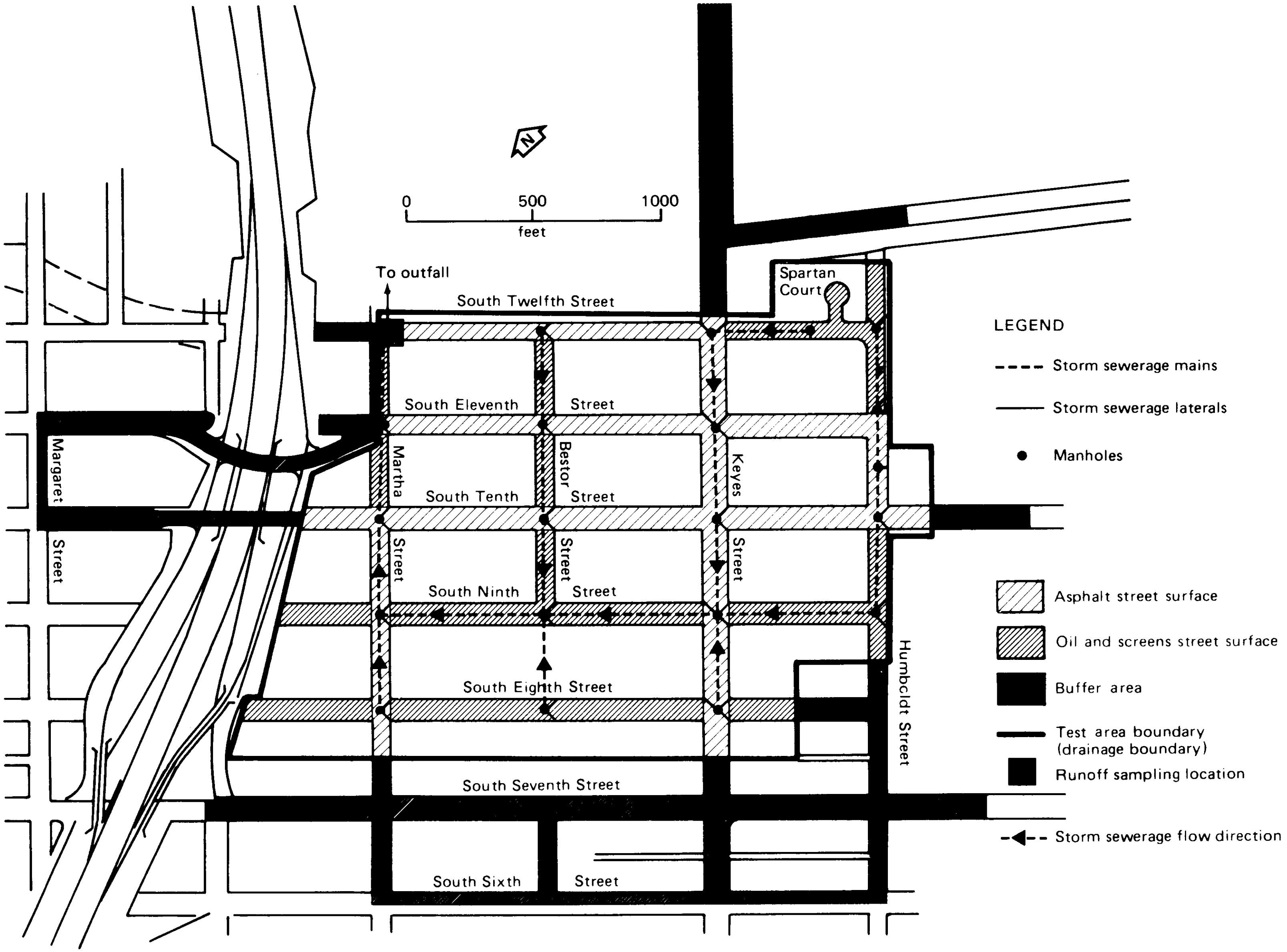

Figure 4-2. Storm drainage in Keyes study area.

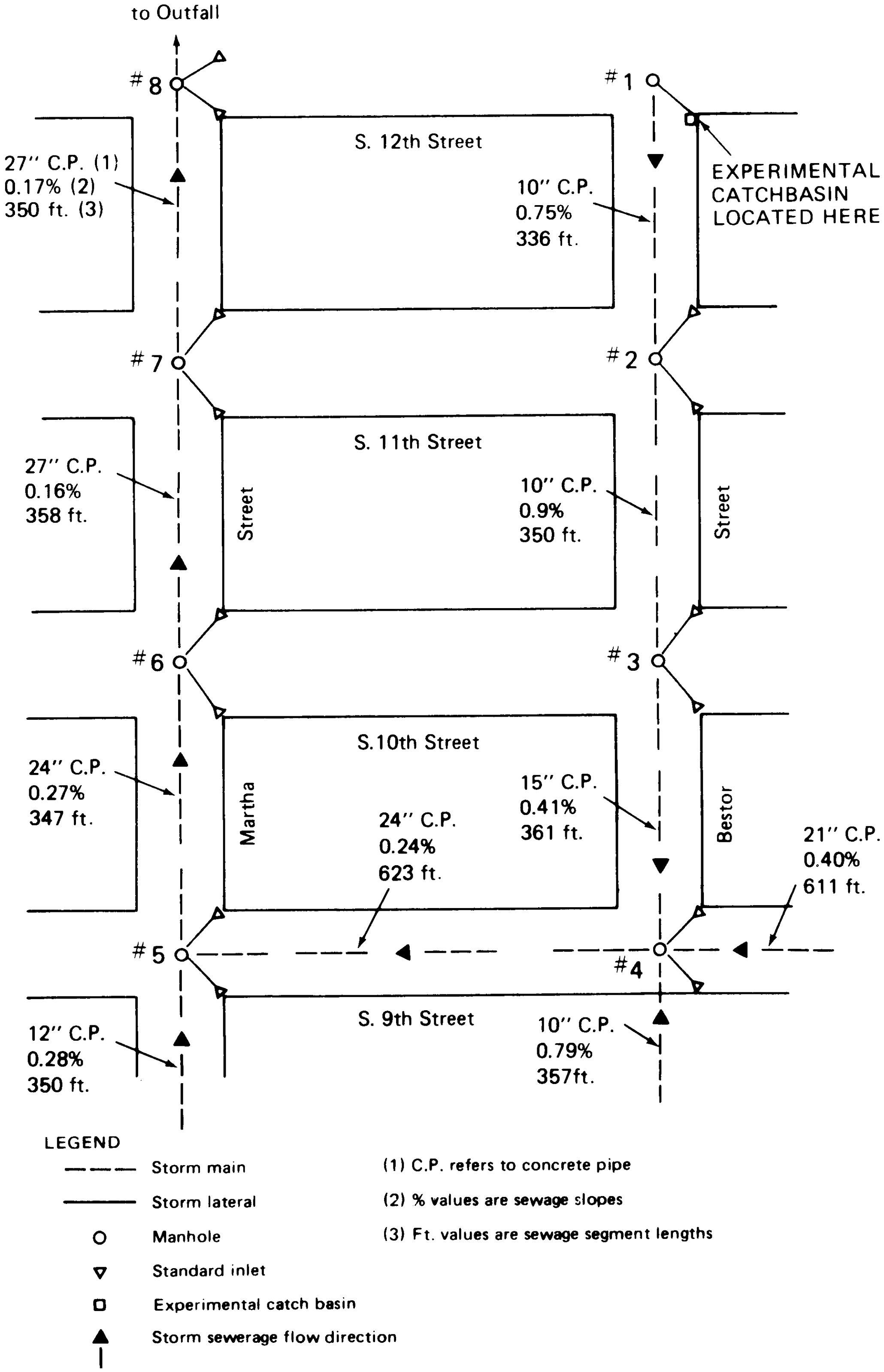

Figure 4-3. Storm drainage from special catchbasin to outfall.

A special catchbasin was constructed following the recommendations presented by Lager and Smith (1976); this design is supposed to maximize solids retention. The catchbasin is circular in shape and was formed from a section of 39 in. inside diameter (48 in. OD) reinforced concrete pipe. The outlet is a 10 in. inside diameter concrete pipe located 25 in. below the top of the catchbasin and 40 in. above the bottom. These dimensions follow the idealized proportions as presented by Lager and Smith. If the outlet diameter is noted as dimension D, it should be located 2.5D below the top of the catchbasin and 4D from the bottom of the catchbasin. The overall height of the catchbasin from the street surface to the bottom is therefore 6.5D while the inside diameter is 4D.

A total of 500 lb of street surface simulant was placed in the catchbasin. The simulant was designed to have the same solids size distribution as the street surface particulates measured in this test area (See Figure 3-4). Types and amounts of simulants used included: 105 lb of No. 2 clay, 260 lb of No. 20 fine sand, 30 lb of No. 1 sand, 60 lb of No. 3 sand and 45 lb of pea gravel (slightly less than 0.25 in. in diameter). The clay, sand and gravel were well washed and sieved before mixing. 2.5 lb of yellow fluorescent particles were mixed with the bottom half of the simulant, and 2.5 lb of green fluorescent particles were mixed with the top half of this simulant.

Samples were collected five times from the catchbasin, downstream manhole locations, and directly off of the outfall in the creek between September 1977 and January 1978. During this time, more than 10 days of rain occurred with each day having rain volumes ranging from 0.01 in. to more than 0.75 in. Rains on at least four of these days were capable of washing off significant quantities of street surface particulates, irrespective of traffic conditions.

Core samples were taken from the catchbasin using a carbon dioxide (CO_2) freezing core sampling apparatus. This unit consisted of a 0.5 in. rigid copper pipe with a braised brass point that was driven into the catch-basin sediment. A 0.375 in. flexible copper tube was connected to a liquid CO_2 supply (a CO_2 gas bottle with a syphon tube). Liquid CO_2 was then supplied to the larger copper tube which froze the adjoining sample to the outer tube. The CO_2 flowed for about 1 minute, allowing a sample thickness of about 0.25 to 0.5 in. to form. This frozen core was then withdrawn from the catchbasin and the frozen sample was separated from the tube and analyzed as a function of depth.

The samples were collected from the manhole access points by manually scraping sediment into sample collection bottles. Sewerage inspections were also routinely conducted during this time period. These inspections documented the amount (depth) of sediment in the main sewerage and in the adjacent laterals. All of the laterals and mains were flushed out before the beginning of the tests.

Table 4-11 presents the results of this tracer study averaged for all sampling periods. This table shows the relative tracer concentrations for the green and yellow particles in various locations of the storm sewerage system compared to the catchbasin tracer concentrations. As an example, the average green fluorescent particle concentration in the catchbasin simulant was about 18,000 green fluorescent particles/gm of simulant. The average concentration of

TABLE 4-11. TRACER CONCENTRATIONS IN SEWERAGE COMPARED TO CATCHBASIN TRACER CONCENTRATIONS (ppm)

Manhole Location	Green Particles*			Yellow Particles**		
	Average	Min.	Max.	Average	Min.	Max.
1	350	52	520	390	150	680
2	290	0	680	270	0	830
3	57	29	81	150	0	270
4	300	52	900	900	0	3500
5	95	52	160	240	0	680
6	120	0	320	660	0	1500
7	57	29	110	98	0	150
8	67	29	130	220	0	410
Outfall	120	110	130	73	0	150

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* The green fluorescent particles were mixed with the top half of the simulant in the catchbasin.

**The yellow fluorescent particles were mixed with the bottom half of the simulant in the catchbasin.

the green fluorescent particulates at manhole location number one averaged about 7.4 particles of fluorescent material/gm of sediment. Therefore, the relative concentration of green fluorescent particles at this station was about 350 parts per million when compared to the concentration in the catchbasin. The range of relative concentrations varied widely for the different periods of sample collection. No trends were evident in particle concentrations, except that none were found on the first day when the material was installed. Three days later, green and yellow fluorescent particles were found at practically all of the manhole stations, even though no rain occurred. The sewerage system had a continuous dry weather flow due to many small leaks from the domestic water supply system, from sidewalk and automobile washing, possible groundwater infiltration, and irrigation. The relative concentrations for the different dates of sampling did not significantly change with time. A general decrease in relative concentrations was noted, but the variations were quite large. No significant pattern was noted in relative concentrations at any of the sampled manhole locations. Yellow particulates were not found at most of the manhole sampling locations during some of the sampling periods. This was expected because the yellow material was located at the very bottom of the catchbasin and would not be discharged into the sewerage system except with runoff-induced turbulence. The overall depth of simulant in the catchbasin slightly decreased (by about 20 percent) during the four-month period of study. The only notable increase in catchbasin sediment material was floating organic material.

Some of the simulant and tracer material was removed from the catchbasin during periods having dry weather flows. Increases in fluorescent tracer relative concentrations at the various sampling locations were not significant, even with several significant rains. Little stratification of flourescent particles was noted relative to the simulant material in the catchbasin. The concentrations of flourescent particles in the catchbasin did not significantly change with time. This technique may be a useful procedure for monitoring catchbasin performance and sediment releases in other studies.

SECTION 5

TREATABILITY OF NONPOINT POLLUTANTS BY STREET CLEANING

SUMMARY

The objective of this portion of the study was to assess the cost and labor effectiveness of various methods of street cleaning, runoff treatment, and combined wastewater treatment systems in controlling nonpoint pollution. The results of the street surface contaminant and runoff monitoring tests (see Sections 3 and 4) were used to estimate the treatability of urban runoff and to estimate costs of treatment. The basic information for street cleaning labor and costs were derived from San Jose's street cleaning program (September 1976 through August 1977). San Jose street cleaning costs were about $14 per curb-mile cleaned, and about one man-hour was required for each curb-mile cleaned (1976-1977 dollars).

About 75 percent of the street cleaning costs were for labor, which makes street cleaning a labor-intensive operation. This trait is desirable, because if different control measures have equal cost effectiveness, it is socially beneficial to choose the measure that employs the most people. Maintenance costs were about 30 percent of the overall program costs. Other important costs include disposal costs, equipment depreciation, and operating expenses. Equipment replacement to reduce costs could achieve a maximum cost savings of much less than 30 percent (the total maintenance costs). The other costs are constant and would not vary significantly for different types of currently available street cleaning equipment.

A cost increase of about a factor of 10 over typical monthly or bimonthly cleaning program costs may be necessary to obtain significant runoff control for heavy metals and total solids. This cost increase may increase the runoff control possible from street cleaning from less than 10 percent to more than 25 percent (for these parameters). Increased street cleaning would also decrease fugitive dust emissions to the air, improve litter loadings, etc., which is not possible with other control practices.

To obtain a comparison of street cleaning costs with costs of other treatment systems, the unit costs for these other systems were calculated. If flow equalization costs were included, the unit pollutant removal costs for street cleaning were found to be significantly less than runoff treatment costs. Unit costs for the combined sewage and runoff treatment considered in this study were generally less than for special runoff treatment facilities. There are no data to show the effectiveness or cost of treating heavy metals in the runoff by a combined system. Such costs are expected to be much greater than street cleaning costs. Runoff treatment--whether in special systems or combined runoff and sanitary wastewater systems--requires much less labor than street cleaning.

The downstream alternative control-treatment practices affect only water quality, while street cleaning can also benefit air quality, aesthetics, and public safety.

STRUCTURE OF THE STUDY

Typical runoff water quality (see Section 4) was compared with information from the literature to determine approximate costs and removal effectiveness of various runoff treatment systems (based on Lager and Smith 1974). This information is presented in Appendix G. Street cleaning cost estimates are based on the City of San Jose's experience. The cost effectiveness of the various street cleaning practices are shown in dollars per pound removed and reflect the various real-world conditions encountered. These conditions include such factors as parked cars, traffic, and street cleaning schedules. An estimate of the final cost for disposal of the street surface debris is also shown.

The unit costs and unit labor requirements were compared with similar rates calculated for alternative treatment systems and are presented in Appendix G. These include a range of systems that have been specially designed and tested for treating urban runoff, combined sanitary wastewater and urban runoff and the San Jose-Santa Clara Waste Water Treatment Facility, which treats only sanitary wastewater. Erosion control costs and benefits are also presented in Appendix G. Finally, because there are multiple objectives* in the choice of pollution control methods, a decision analysis framework is discussed in Appendix G that considers trade-offs among these objectives.

STREET CLEANING COSTS

Average 1973 street cleaning program costs for about 400 cities surveyed nationwide are shown in Table 5-1. These costs, as a function of material removed, population, and percentage of the city's budget are shown in Table 5-2. The typical removal costs are between $15 and $20 per ton or cubic yard removed or a little more than one dollar per person per year. This is 1 percent of the typical city budget (APWA 1975). These program costs generally do not include all of the costs associated with normal street cleaning operations, and are therefore low. Inflation also has significantly increased these costs during the past five years.

A large portion of the typical street cleaning budget goes for equipment maintenance. Table 5-3 shows the average maintenance costs ($/curb-mile cleaned) from 14 nationwide cities (Mainstem 1973). The total maintenance cost in 1973 was about $1.65 per curb-mile cleaned. The greatest portion was spent for brooms and brushes and major repairs. These costs have also increased substantially since the survey was conducted.

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*Improved air quality, aesthetics, public safety, recreation, water supply, and public relations are other important objectives.

TABLE 5-1. STREET CLEANING PROGRAM COSTS (1973)

Costs	Median	10th Percentile	90th Percentile
\$/ton of material	18	3.0	80
\$/yd^3 of material	16	6.1	47
\$/person/year	1.2	0.60	3.0
% of city budget	1	0.015	9.4

Source: APWA 1975.

TABLE 5-2. STREET CLEANING PROGRAM COSTS FOR CITIES OF VARIOUS POPULATIONS

City Population	1973 Street Cleaning Program Costs (thousands of dollars)	
	Average	Range
<10,000	39	9 → 90
10,000 → 25,000	88	7 → 530
25,000 → 50,000	73	3 → 490
50,000 → 100,000	160	15 → 680
100,000 → 250,000	350	82 → 1500
250,000 → 500,000	840	40 → 2500
500,000 → 1,000,000	2000	360 → 6200
>1,000,000	4900	3000 → 6800
Overall	360	3 → 6800

Source: APWA 1973.

TABLE 5-3. MAINTENANCE COSTS ($/curb-mile cleaned for 1973)

	Average	Percentage of Total	Range
Major repairs	$ 0.40	24%	$0.18 → 0.84
Minor repairs	0.28	17	0.07 → 0.46
Preventive maintenance and lubrication	0.13	8	0.02 → 0.45
Brooms and brushes	0.41	25	0.08 → 0.71
Chains and sprockets	0.15	9	0.02 → 0.30
Other mounted systems	0.28	17	0.15 → 0.46
Total Maintenance Cost	$1.65	100%	$0.69 → 3.10

Source: Mainstem 1973.

The following list shows which equipment components the surveyed cities thought were most subject to wear (APWA 1975):

- Brushes (49 percent)
- Conveyor and elevator drives (26 percent)
- Tires (8 percent)
- Elevator (8 percent)
- Flights (5 percent)
- Hydraulic system (3 percent)
- Transmission (1 percent)

Table 5-4 shows the average main broom life (in miles) for three broom materials (Laird and Scott 1971). Synthetics offered the best service, followed by steel and natural fibers. However, Horton (1968) explains broom life is not the most important factor: removal effectiveness is the goal and removal effectiveness has been shown to be a function of broom fiber, brush speed, pattern, and forward speed (as shown in Section 3).

TABLE 5-4. AVERAGE MAIN BROOM LIFE (curb-miles cleaned)

	Synthetic	Natural	Steel
Average	1100	270	560
Minimum	120	150	100
Maximum	2500	750	2000

Source: Laird and Scott, 1971.

Fifty percent of the cleaning equipment was operated with a main broom rotational speed of 1500 to 2000 rpm and a strike of 4 to 6 inches (Scott 1970). Optimum broom adjustments and selection of fiber must be determined for each city. These determinations will depend on the type and quantity of litter and particulates to be removed, street type and condition, weather, etc.

Table 5-5 presents San Jose street cleaning costs by specific item and the total costs for the year ending September 30, 1977. Labor accounts for about 75 percent of the total costs which makes street cleaning a relatively labor intensive urban runoff control measure. Those categories that may be affected by a significant change in street cleaning equipment (maintenance supplies and labor) make up 35 percent of the total costs. A major change in equipment type may slightly reduce those maintenance costs. The other street cleaning costs would not vary appreciably for different types of street cleaning equipment. Actual maintenance savings would have to be determined by a specific city's experience using different equipment types. Replacement of street cleaning equipment before it would normally be replaced could significantly increase depreciation costs.

During this test year (1976-1977), the Public Works Department of San Jose spent about $800,000 to clean 55,761 curb-miles. The unit cost was therefore about $14 per curb-mile cleaned and the labor requirement was about 0.9 man-hours per curb-mile. These costs appear high, but it must be realized that most other evaluations of street cleaning costs (such as summarized in the previous discussion) do not include all of the actual costs of the street cleaning program. Most other street cleaning cost evaluations include only maintenance and operations supplies and operator labor expenses. Few other jurisdictions have all the other cost information available. The usual practice is to use the odometer mileage on the street cleaner as an indication of curb-miles cleaned. The odometer mileage is about twice the curb-mileage cleaned because of travel from the service yard to the cleaning route, travel to the landfill, etc. This mileage factor could double the unit cost alone.

Tables 5-6 through 5-10 present the average unit costs and labor requirements to remove a pound of the various pollutants from the five test areas. The unit costs for total solids range from about $0.025 to $0.17/lb removed for

TABLE 5-5. SAN JOSE ANNUAL STREET CLEANING EFFORT (1976-1977)

	COST			LABOR		
	Total Cost ($)	Cost ($/curb-mile cleaned)	Percentage of Total Cost	Total Labor (person-days)	Unit Labor (hr/curb-mile cleaned)	Percentage of Total Labor
Maintenance Supplies[a]	93,000	1.60	12	--	--	--
Operation Supplies[b]	29,000	0.48	3	--	--	--
Disposal	65,000	1.17	8	780	0.12	13
Equipment Depreciation	31,000	0.48	3	--	--	--
Cleaner Operators[d]	326,000	5.76	41	3400	0.50	56
Maintenance Personnel[d]	176,000	3.20	23	1200	0.18	20
Supervisors[d]	80,000	1.44	10	650	0.10	11
Total Annual Costs	$800,000	$14.00	100%	6030 Days	0.90 Hrs	100%
Total Annual Curb-Miles Cleaned	55,761 Miles					

[a] Includes gutter and pick-up broom replacement.

[b] Tires, fuel, and oil.

[c] The street cleaners dumped their hopper contents on the streets in interim piles, where they were later removed by front-end-loader and dump truck crews. The landfill was located centrally, with maximum distances of about 15 miles from the cleaner routes to the landfill.

[d] These labor costs include administration, warehouse, secretary, and overhead costs.

TABLE 5-6. COST EFFECTIVENESS FOR SAN JOSE STREET CLEANING OPERATIONS, TROPICANA-GOOD ASPHALT TEST AREA

	*Average Removal (lb/curb-mile cleaned)	Average Unit Cost ($/lb removed)	Average Unit Labor (hr/lb removed)
Total Solids	100	0.14	0.009
Suspended Solids**	50	0.28	0.018
COD	9.7	1.4	0.093
BOD_5**	4.9	2.9	0.18
Ortho PO_4	0.017	820	52
Kjeldahl Nitrogen	0.21	67	4.3
Lead	0.40	35	2.3
Zinc	0.049	290	18
Chromium	0.039	360	23
Copper	0.072	190	13
Cadmium	0.00027	50,000	3300

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*Average removal values from Table 3-19.
**Estimate.

TABLE 5-7. COST EFFECTIVENESS FOR SAN JOSE STREET CLEANING OPERATIONS, KEYES-GOOD ASPHALT TEST AREA

	*Average Removal (lb/curb-mile cleaned)	Average Unit Cost ($/lb removed)	Average Unit Labor (hr/lb removed)
Total Solids	130	0.11	0.0069
Suspended Solids**	65	0.22	0.014
COD	16	0.88	0.056
BOD_5**	8.0	1.8	0.11
Ortho PO_4	0.018	780	50
Kjeldahl Nitrogen	0.28	50	3.2
Lead	0.81	17	1.1
Zinc	0.079	180	11
Chromium	0.051	270	18
Copper	0.081	170	11
Cadmium	0.0003	47,000	3000

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* Average removal values from Table 3-17.
**Estimate

TABLE 5-8. COST EFFECTIVENESS FOR SAN JOSE STREET CLEANING OPERATIONS, KEYES-OIL AND SCREENS TEST AREA

	*Average Removal (lb/curb-mile cleaned)	Average Unit Cost ($/lb removed)	Average Unit Labor (hr/lb removed)
Total Solids	170	0.082	0.0053
Suspended Solids**	85	0.16	0.011
COD	12	1.2	0.075
BOD_5**	6	2.3	0.15
Ortho PO_4	0.0089	1600	100
Kjeldahl Nitrogen	0.14	100	0.38
Lead	0.15	93	6
Zinc	0.066	210	14
Chronium	0.071	200	13
Copper	0.13	110	6.9
Cadmium	0.00024	58,000	3800

*Average removal values from Table 3-18.
**Estimate.

TABLE 5-9. COST EFFECTIVENESS FOR SAN JOSE STREET CLEANING OPERATIONS, DOWNTOWN-GOOD ASPHALT TEST AREA

	*Average Removal (lb/curb-mile cleaned)	Average Unit Cost ($/lb removal)	Average Unit Labor (hr/lb removed)
Total Solids	83	0.17	0.010
Suspended Solids**	43	0.33	0.021
COD	11	1.3	0.082
BOD_5**	5.5	2.5	0.16
Ortho PO_4	0.012	1200	75
Kjeldahl Nitrogen	0.6	88	5.6
Lead	0.49	29	1.8
Zinc	0.072	190	13
Chromium	0.047	300	19
Copper	0.093	150	9.7
Cadmium	0.0023	6100	390

*Average removal values from Table 3-16.
**Estimate.

TABLE 5-10. COST EFFECTIVENESS FOR SAN JOSE STREET CLEANING OPERATIONS, DOWNTOWN-POOR ASPHALT TEST AREA

	*Average Removal (lb/curb-mile cleaned)	Average Unit Cost ($/lb removal)	Average Unit Labor (hr/lb removed)
Total Solids	540	0.026	0.0017
Suspended Solids**	270	0.052	0.0033
COD	61	0.23	0.015
BOD_5**	31	0.46	0.030
Ortho PO_4	0.079	180	11
Kjeldahl Nitrogen	1.3	11	0.69
Lead	1.0	14	0.90
Zinc	0.27	52	3.3
Chromium	0.24	58	3.8
Copper	0.50	28	1.8
Cadmium	0.0015	9300	600

*Average removal values from Table 3-16.
**Estimate.

average conditions encountered in the five areas. As expected, it costs much more ($0.11 to $0.17) to remove a pound of solids from the asphalt streets in good condition as compared to the poorer quality asphalt streets ($0.025/lb) and the oil and screens surfaced streets ($0.08/lb). The same is generally true for the other pollutants, except for the oil and screens test area. Street surface particulates were abundant in the oil and screens test area, but the pollutant concentrations were relatively low. This was because the major source of the particulates in this test area was street surface wear material, which was relatively "clean". The same was true for the unit labor requirements, where more labor was generally needed to remove the same quantity of material from the smooth asphalt streets as compared to the streets in poorer condition.

Figure 5-1 (based on computer analyses of the San Jose data) demonstrates the increase in unit costs to remove a pound of total solids as the number of cleaning passes increases in a year. A cost of $0.08/lb corresponds to about 20 or 30 passes per year, but it could be as low as $0.02 or $0.03/lb for two passes per year, or as high as $0.25/lb for 200 to 300 passes per year, depending on street surface condition. These increasing costs reflect the decrease in rate of return as the streets are cleaned more often. Frequent street cleaning results in lower solids loadings on the street surfaces and pollutant removals per pass, while the cost of operating the street cleaning equipment remains practically the same (within about ± 10 percent) per pass. Figure 5-2 is a similar figure for unit labor requirements. Again, the unit requirements increased dramatically with increasing passes per year.

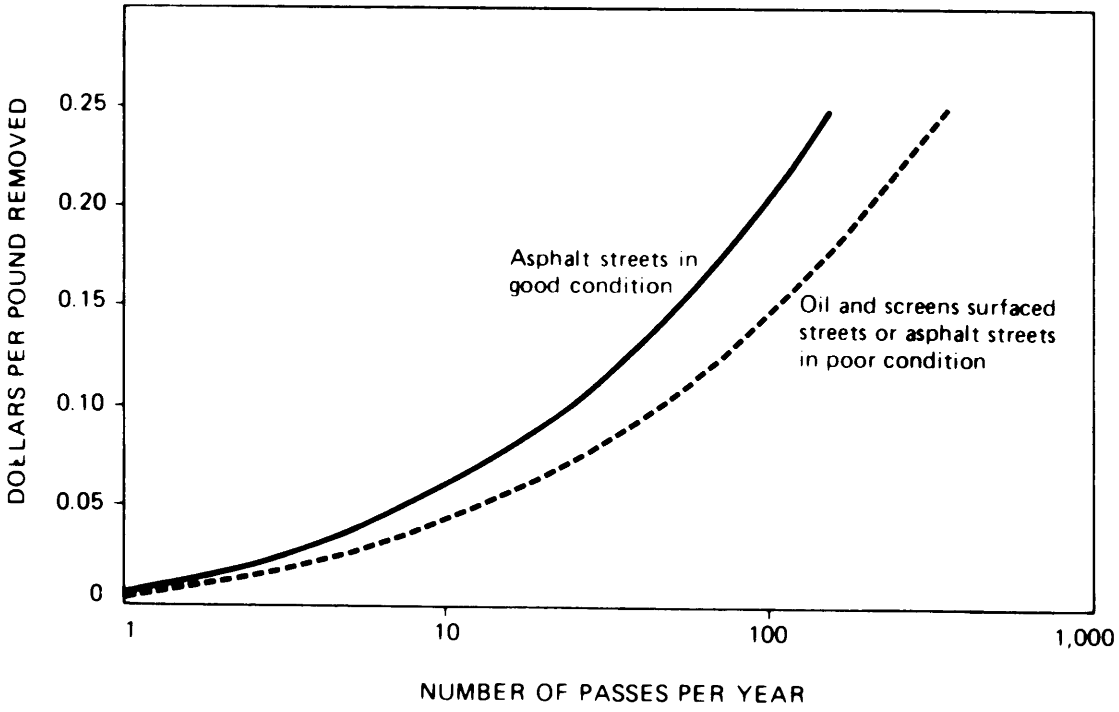


Figure 5-1. Costs to remove a pound of street dirt as a function of the number of passes per year.

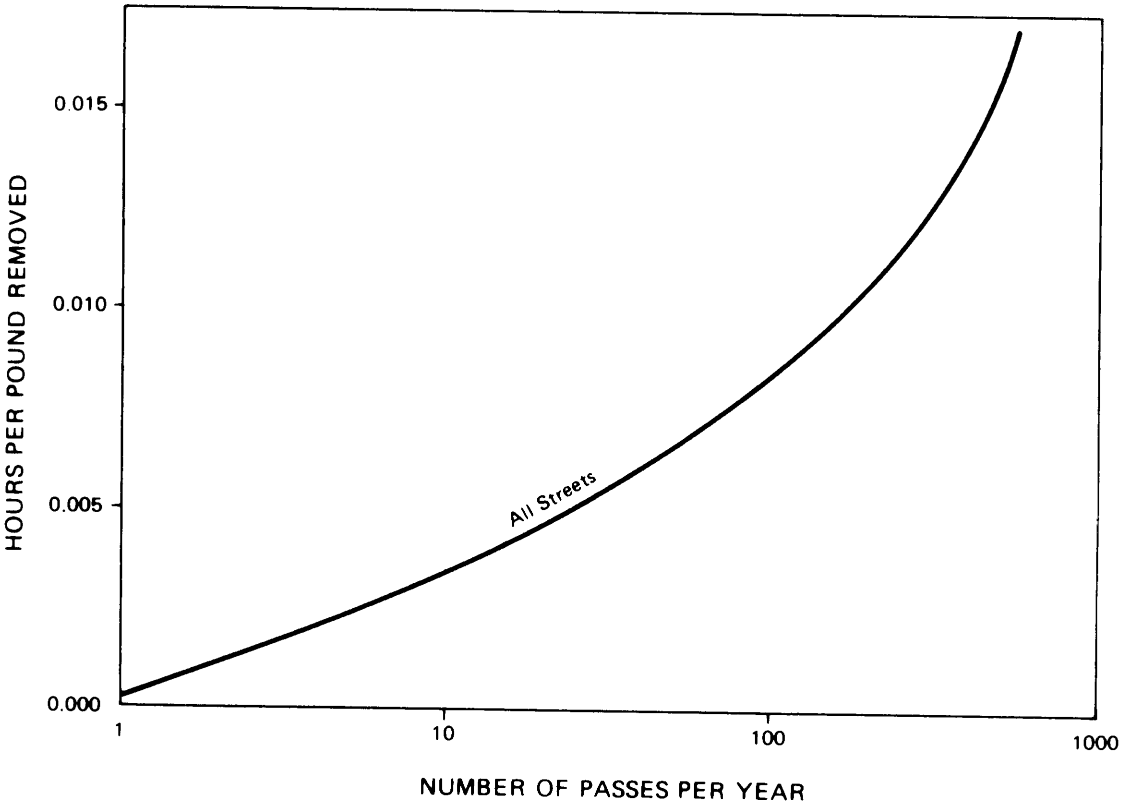


Figure 5-2. Labor needs to remove a pound of street dirt.

A street cleaning program effective in reducing substantial quantities of pollutants (more than 25 percent removal of total solids and heavy metals from the runoff) would require cleaning frequencies of about three passes per week or more (preferably on separate days). A typical street cleaning program conducted to control litter in residential neighborhoods uses about one to two passes per month. This less frequent cleaning may remove only about 10 percent, or less, of the total solids and heavy metals in the runoff. Therefore, an expenditure increase of about ten times is necessary to obtain about four times the pollutant removals from the runoff.

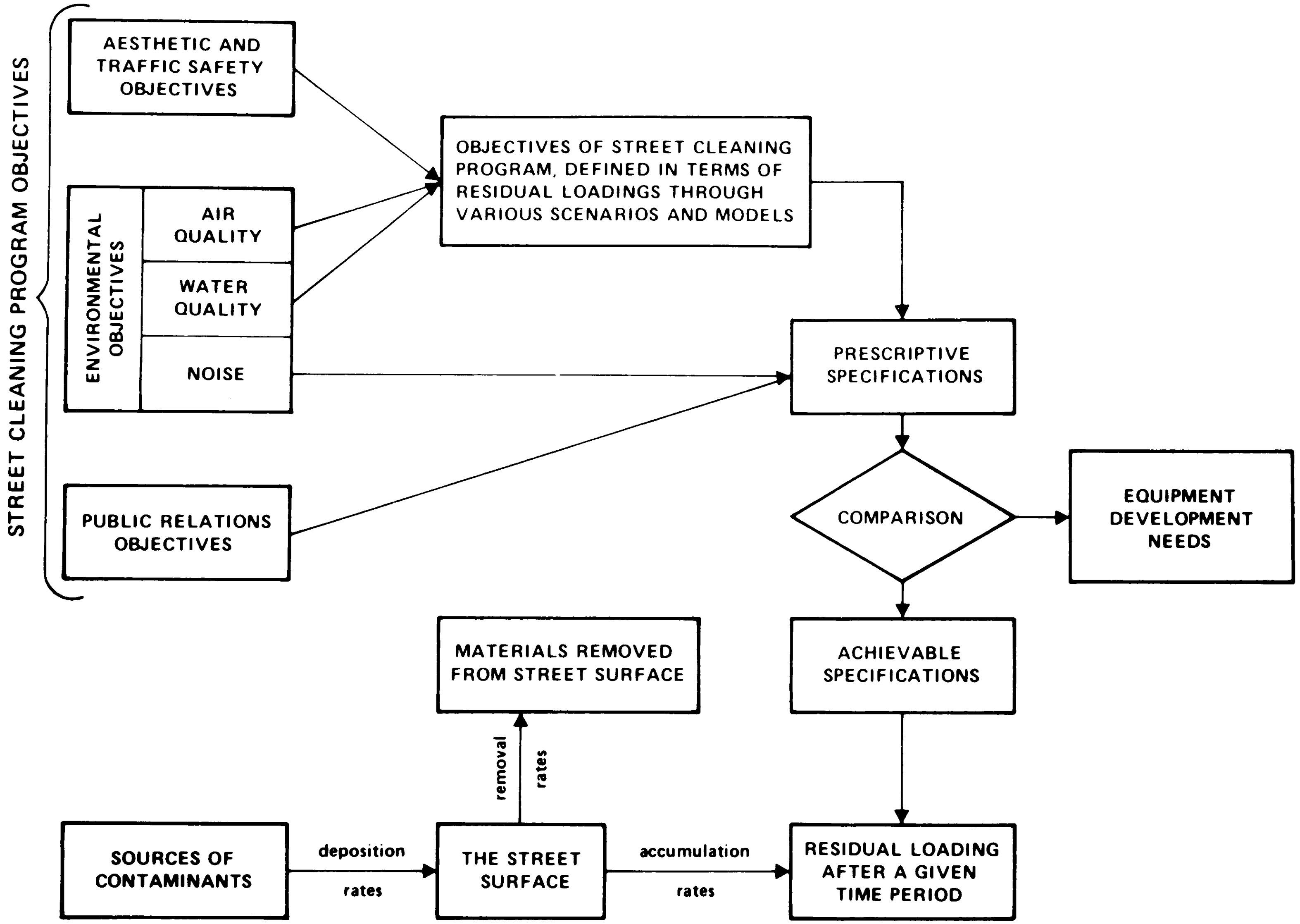
Any existing litter control street cleaning program removes the least costly portion of the pollutants and additional cleaning becomes more costly. This should be considered in evaluating the street cleaning program over a large area. The extensive street cleaning effort usually expended in downtown areas may best be reduced in order to increase the effort in "dirtier" areas receiving little street cleaning. A much greater quantity of pollutants can then be removed from the watershed for the same total program expenditures. Re-education of the residents in the service area receiving reduced street cleaning would of course be necessary. Adequate litter control may be effective in downtown areas by using some manual litter pick-up effort to supplement reduced mechanical street cleaner use.

Additional street cleaning effort also improves the other benefits of street cleaning. These include reducing fugitive particulate (dust) emissions to the air (see Section 6), improving public safety by controlling excessive dirt on the roadway, reducing litter, reducing service area complaints, and decreasing flooding caused by clogged sewerage and inlets. Alternative urban runoff control procedures (see Appendix G) usually only benefit water quality.

As stated above, if the objective of a street cleaning program is to remove the most pollutants from the runoff, then an appropriate street cleaning program could be simply designed by stressing those service areas with road types that result in the largest unit removal rates (pounds removed per pass) and keeping the number of passes a year for a specific area to a minimum. No service objectives are this simple, and more complex program design techniques are usually necessary. The following discussion describes a procedure to select the level of effort necessary, considering local rainfall patterns. Appendix G describes alternative control measures that can be used to meet water quality objectives and a decision analysis procedure that may be used in selecting the most appropriate combination of control measures. If one wants to optimize the existing street cleaning program for current budget conditions or for future budget reductions, the Appendix G discussions are not necessary. Appendix G can be appropriately used when a regional stormwater management control plan (208 study) is to be designed and to estimate the costs of several control objective levels ("needs" survey).

DETERMINATION OF STREET CLEANING PROGRAM

Figure 5-3 (Pitt, Ugelow and Sartor, 1976) is a flow diagram that shows the relationships between a city's street cleaning objectives, operating conditions, and the resulting equipment performance requirements. This figure shows that an accumulation rate and an accumulation interval must be determined



Source: Pitt, Ugelow and Sartor, 1976.

Figure 5-3. Relationship of objectives, operating conditions, and street cleaning equipment specifications.

before the residual loading can be estimated. This information can be obtained utilizing the procedures used during this study. The objectives of the street cleaning program must be defined in terms of allowable residual loadings; the required cleaning effectiveness and cleaning frequency are then determined based on these prescriptive specifications. The prescriptive specifications are compared with the achievable specifications and possible equipment performance improvements can then be identified.

Street Cleaning Program Objectives

The determination of a city's prescriptive specifications for street cleaning equipment is based on that city's objectives and operating conditions. These objectives are determined by environmental, safety, aesthetic, and public relations requirements. They are defined in the following paragraphs.

- Environmental Objectives. These objectives should ensure compliance with applicable water, air, and noise regulations, criteria, and standards. These may include urban runoff load allocations (as determined in Areawide Wastewater Management -208- Plans), ambient air quality standards, vehicle emission standards, roadway fugitive dust emission allocations (from an area's air quality compliance plans), and state and local noise regulations.

- Aesthetic and Traffic Safety. The objectives relate directly to the quantity and type of street surface materials. Traffic safety problems may be caused by excessive accumulations of loose debris or oils in the traffic lanes. Aesthetic problems are subjective and depend on an individual's personal values.

- Public Relations Objectives. These objectives include other objectives but are measured by service-area complaints. Reduction of these complaints to an acceptable level requires meeting the program objectives and convincing the public that the objectives are correct and that they are being met.

All of these objectives can be measured in various units. Water quality measures can be expressed as concentrations (milligrams per liter) or runoff yields (tons per acre per year*); air quality measures can be expressed as concentrations (parts per million or micrograms per cubic meter) or emission factors (grams per second or tons per year); noise can be expressed as noise levels (dB_A); safety and aesthetic measures can be expressed as street surface particulate loading (pounds per curb-mile); and public relations objectives can be expressed as the number of complaints received per unit time. It is necessary that all these objectives be expressed as a common unit that can be directly affected by the street cleaning program. With the exception of noise level objectives and possibly public relations objectives, allowable street surface loadings (pounds per curb-mile) can be used as a common unit.

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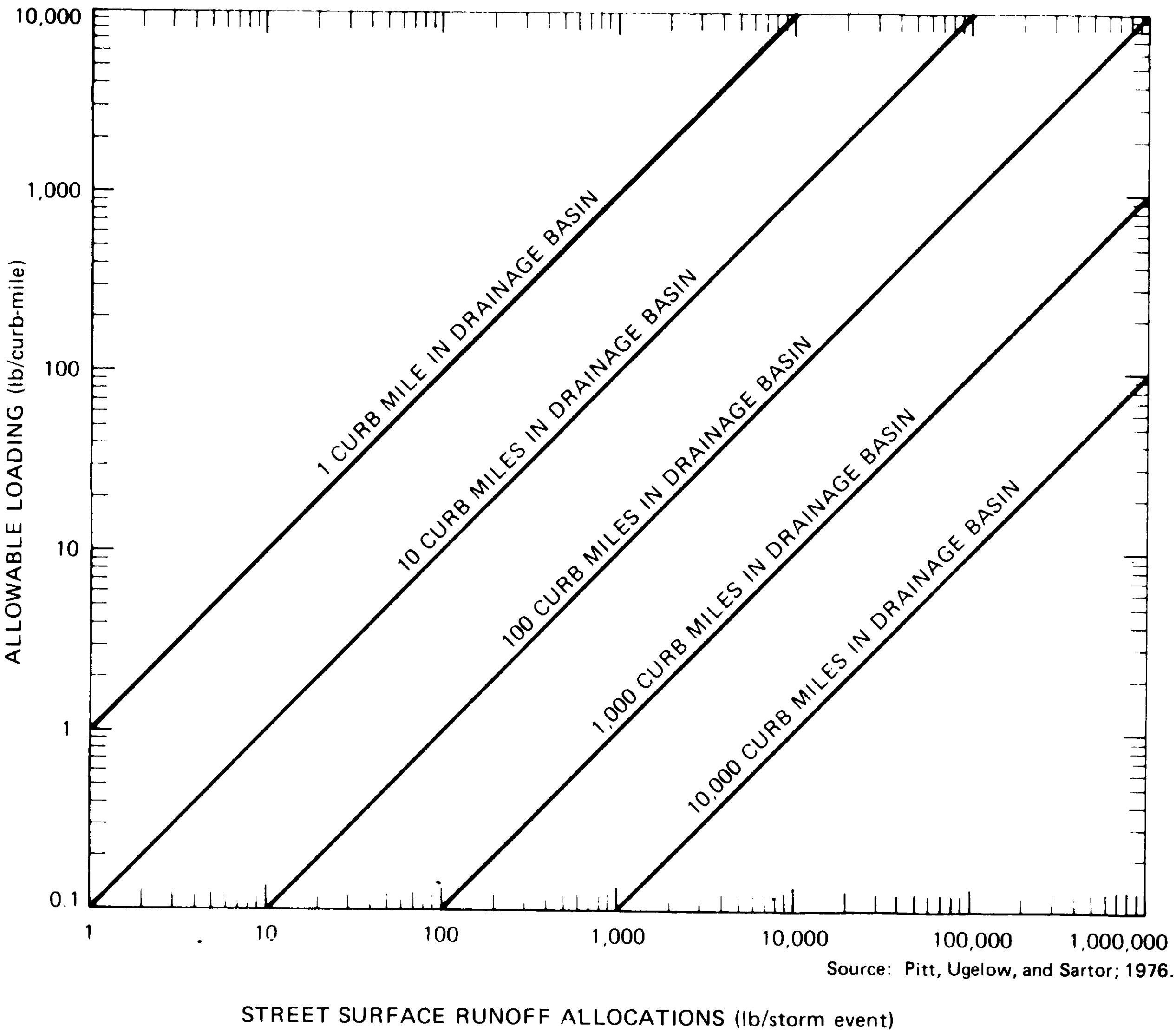
*See Metric Conversion Table 0-1.

Determining Allowable Street Surface Loading

If an urban street surface runoff discharge allocation value is available, the maximum allowable street surface loading can be estimated knowing the number of curb-miles in the watershed. A street cleaning program capable of meeting the allowable loading can be designed if the pollutant accumulation rate for the study area and the performance characteristics of the street cleaning equipment are known. Figure 5-4 graphically relates street surface runoff allocations to allowable loadings. The allowable loading increases as the runoff allocation increases and as the curb-miles in the drainage area decrease. It is possible to obtain a desirable residual particulate loading by using equipment with low removal efficiencies, but the cleaning interval would have to be short.



Source: Pitt, Ugelow, and Sartor; 1976.

Figure 5-4. Determination of allowable loading.

Other important variables that affect street cleaning programs include site-specific conditions (uncontrollable external operating conditions). These include the assimilative capacity of the receiving environments (water and air), the street surface pollutant accumulation rates, and the frequency of rainfall that washes off the street surface pollutants.

Street surface particulates tend to accumulate as described earlier (see Section 3). A significant rain is capable of washing off most of the street surface particulates, and the loading after a storm of this type would be very low, in the absence of erosion products. The particulates would then increase until removed by street cleaning, wind or automobile induced turbulance and/or rain runoff. The following methodology was developed to help estimate the type of street cleaning program that may be necessary to meet street surface loading objectives. Several simplifications were made to keep this procedure uncomplicated; namely, constant accumulation rates and street cleaning effectiveness values are assumed. It is known that accumulation rates decrease with time (due to wind or traffic induced turbulance causing fugitive dust losses) and that the percentage removals of street surface particulates decrease with lower loading values. Therefore, this simple model assumes that particulate loadings would increase linearly with time, in the absence of rain or street cleaning, but would reach a maximum, constant value, after repeated street cleanings.

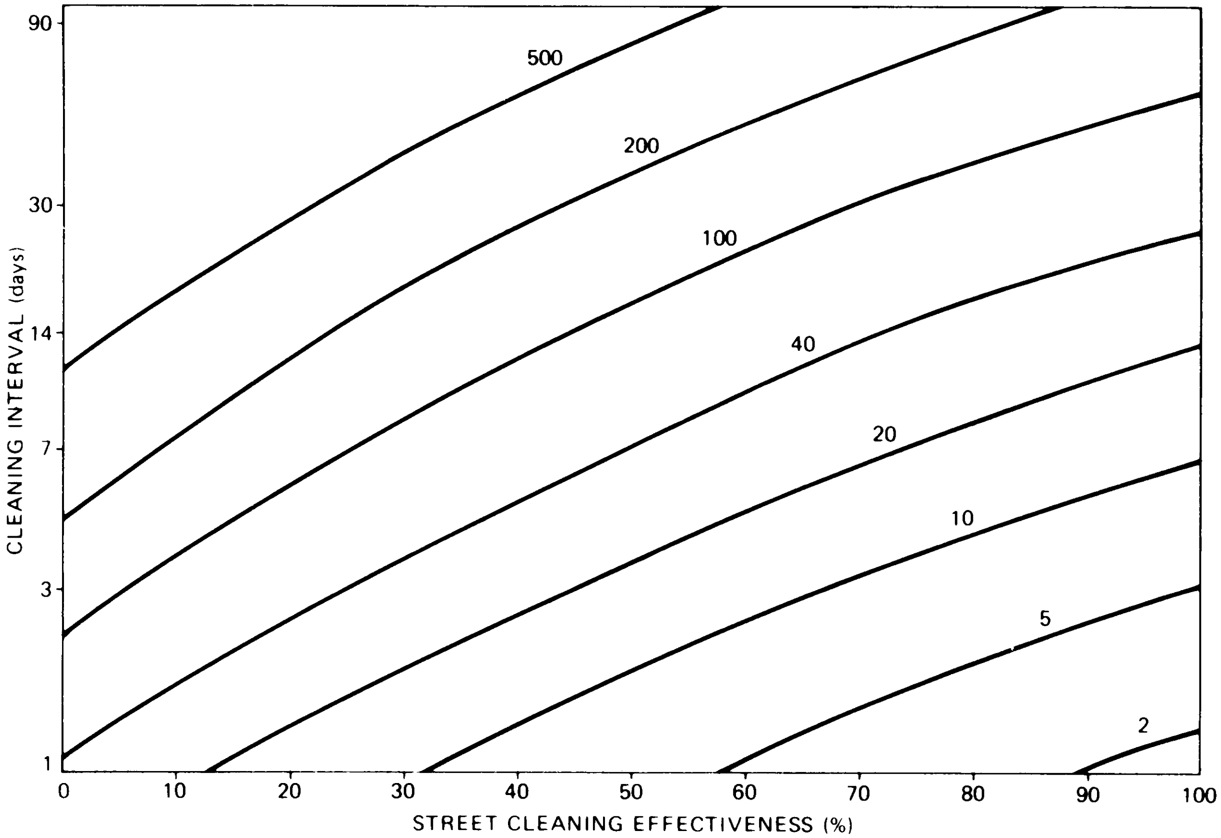


Figure 5-5. Days after significant rain to maximum street surface loading.

Figure 5-5 shows when maximum particulate loading values would occur on streets as a function of street cleaning effectiveness and cleaning interval (in the absence of rains). If a significant rain occurs before these time limits are reached, then the maximum values would not be obtained. An increase in street cleaning effort (more frequent street cleaning) or an increase in cleaning effectiveness, substantially reduces the time required before the maximum loading value occurs. Figure 5-6 shows the value of the maximum loadings for different street cleaning programs as measured by effective days of accumulation (EDA). As an example, if the EDA was shown to be 10 for a particular condition and the average accumulation rate for the area was 15 lb/curb-mile/day, the maximum loading condition would be 150 lb/curb-mile. Therefore, these two figures can be used to estimate the street cleaning program necessary to meet a specific maximum allowable street surface loading condition. If an allowable loading goal of 300 lb curb-mile existed along with an average accumulation rate of 15 lb/curb-mile/day, then an EDA of 20 (300 lb/curb-mile divided by 15 lb/curb-mile/day) is necessary. Examining Figure 5-6 shows that this goal can be met using several alternative street cleaning programs, including one with a cleaning interval of three days and a removal efficiency of about 20 percent, or one with a cleaning interval of about once every two weeks and a removal efficiency of about 80 percent. Both of these cleaning programs would result in a maximum

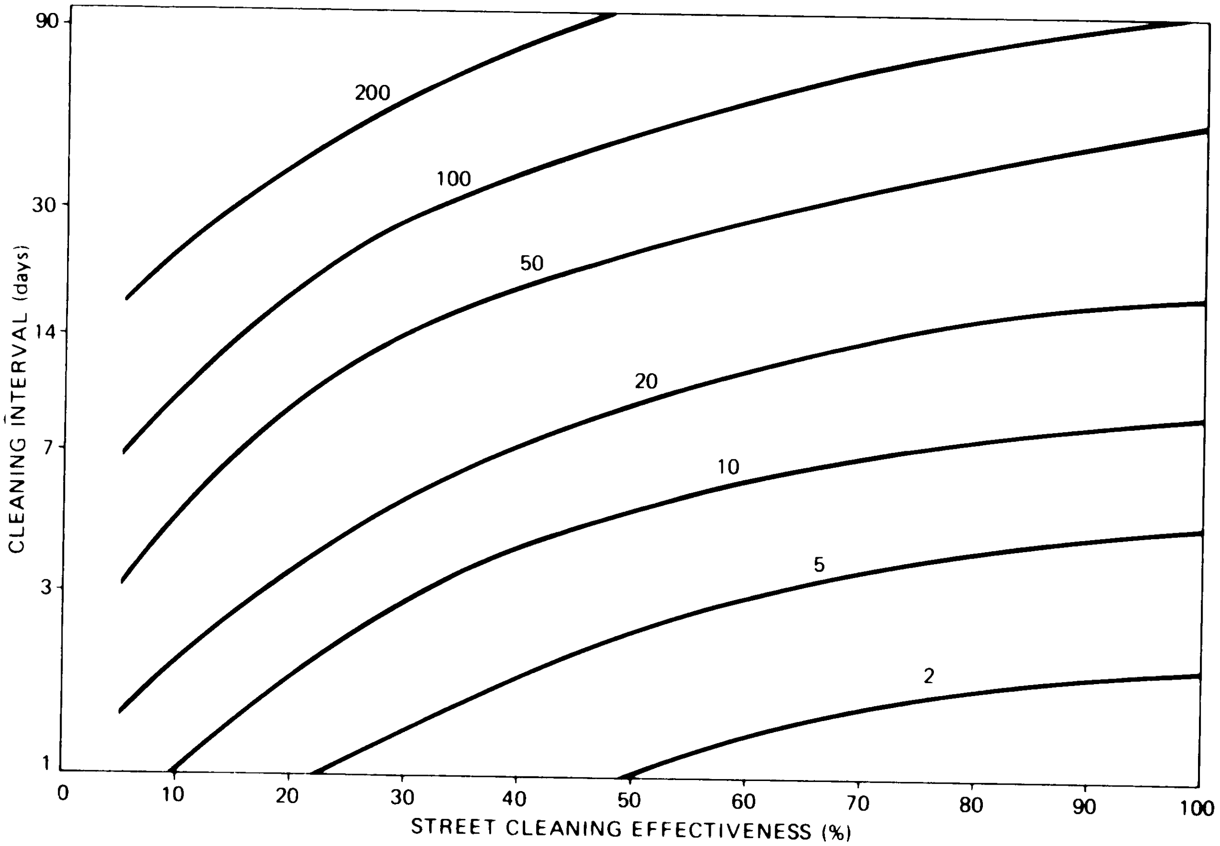


Figure 5-6. Maximum street surface loadings (effective days of accumulation).

street surface particulate loading value of about 300 lb/curb-mile, which would occur after about 40 dry days (from Figure 5-5). If it rained before 40 days, the street surface runoff yield could be much less.

Figure 5-7 relates the percentage of maximum street surface loading that would occur for cleaning programs of different cleaning effectivenesses and for various periods of time since the last significant rain. In the example described above, assume a rainfall interval of 20 days. This would correspond to about 7 cleaning cycles for a 3-day cleaning interval (of 20 percent effectiveness) and about 1.5 cleaning cycles for a 14-day cleaning interval (of 80 percent effectiveness). The resultant maximum street surface particulate loadings would therefore be about 230 lb/curb-mile (75 percent of 300 lb/curb-mile) and about 270 lb/curb-mile (90 percent of 300 lb/curb-mile) respectively, both obviously below the 300 lb/curb-mile goal. Therefore, a sufficient street cleaning program could be less effective than determined by directly using Figures 5-5 and 5-6 if the rainfall interval is less than the indicated time to maximum loading. A more cost effective street cleaning program may be estimated using a reiterative technique. Again, it must be stressed that this procedure only results in estimates and that it is very difficult to have high percentage removal values when the street surface particulate loadings are low.

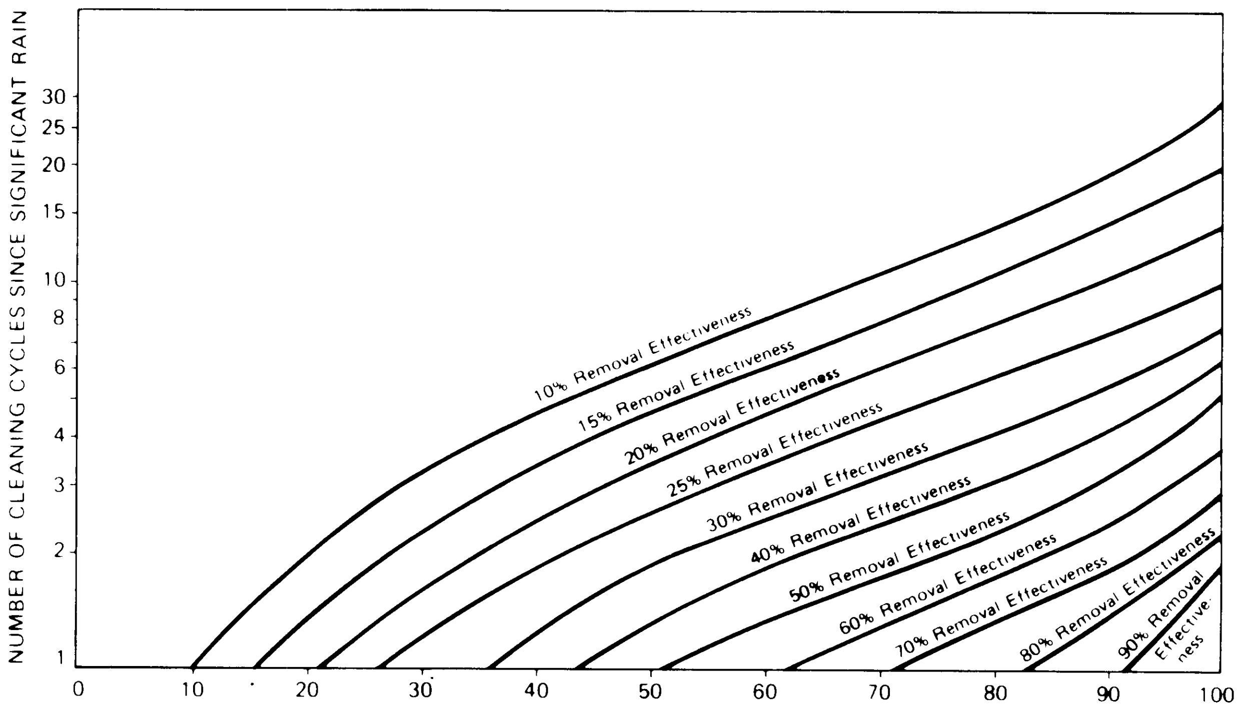


Figure 5-7. Portion of maximum loading values occurring versus the number of cleaning cycles since last significant rain and removal effectiveness.

SECTION 6

AIRBORNE FUGITIVE PARTICULATE LOSSES FROM STREET SURFACES

SUMMARY

The objectives of this portion of the study were: (1) to determine roadside dust (fugitive particulate) concentration increases and emissions from paved street surfaces caused by automobile induced turbulance and wind; and (2) to measure particulate concentrations in the street cleaning equipment cabs during street cleaning operations. Downwind roadside particulate concentrations were about 10 percent greater than upwind concentrations (on a number basis). About 80 percent of the concentration increases, by number, were associated with particles in the 0.5 to 1.0 μ size range, but about 90 percent of the particle concentration increases, by weight, were associated with particles >10 μ. Fugitive emission factors were estimated for the five test areas based on differences between initial street surface particulate accumulation rates and the lower rates observed at later periods. The accumulation rates decreased with time after street cleaning or a significant rain, and this decrease is assumed to be caused by particulate losses to the air. Calculations showed that the loss rate was about 4 to 6 lb/curb-mile/day. This rate corresponds to an automobile use emission rate of approximately 0.66 to 18 g/veh-mi. The rate increases for larger cleaning intervals and varies widely for different street and traffic conditions. Particulate concentrations in and around the state-of-the-art four-wheel mechanical street cleaner were measured with and without use of the water spray to assess the effectiveness of the water spray in dust control. It was found that the water spray was very effective in controlling dust inside the cab and the ambient concentrations* in the vicinity of the equipment. An exception was the area immediately behind the main pickup broom, where the water spray did not significantly change the high total dust levels. The changes in particulate concentrations (by number) were mostly for the smaller particles (<10 μ); the larger particle concentrations did not change significantly. The study did not assess the effect of the water spray on street dirt removal effectiveness.

LITERATURE REVIEW

Street cleaning can reduce airborne particulate emissions and particulate concentrations in areas near roadways. Studies have shown the potential relationships between clean streets and reduced emissions of resuspended particulates (notably Sehmel 1973; Stewart 1964; Mishima 1964; Roberts 1973;

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*Background dust levels in the immediate vicinity.

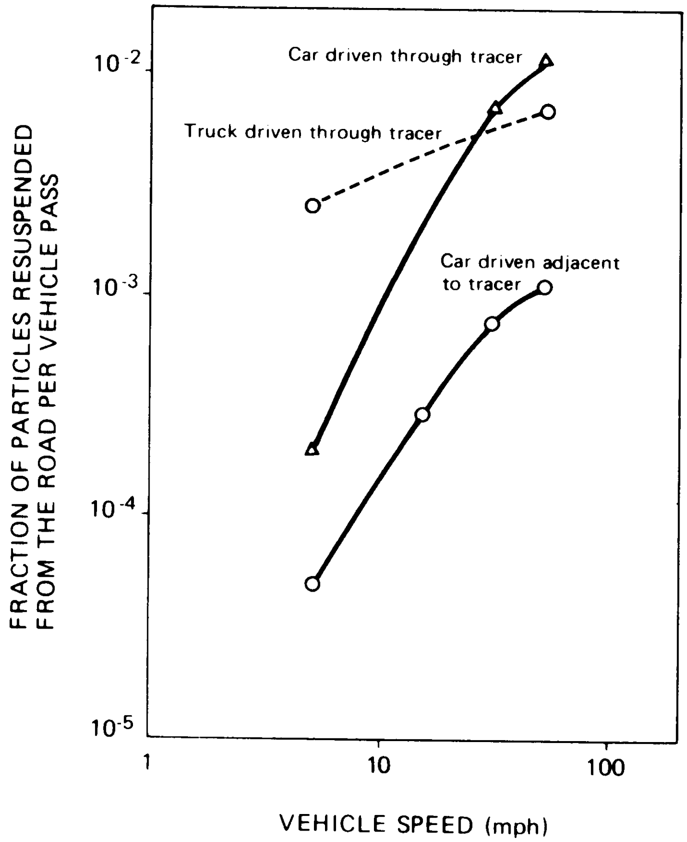
Cowherd, et al., 1977; and PEDCo, 1977). Each of these studies demonstrated this benefit of street cleaning, but none were able to quantify the specific relationships. The following discussion attempts to describe this relationship and its potential impact on the design of street cleaning programs.

As early as 1915 (Goss), there was concern about roadways being significant particulate emission sources. But until recently, there have not been significant attempts to improve air quality related to that source. Roberts (1973) has shown that paving a dirt road could reduce roadway particulate emissions by 75 percent and cleaning a "dirty" paved road could reduce particulate emissions by more than 80 percent.

Reductions in auto traffic have caused noticeable reductions in roadside particulate concentrations. During a three-day driving moratorium in Sweden in 1969 (to change signs and roadways from left-hand-side-of-the-road to right-hand-side-of-the-road driving), particulate concentrations dropped substantially, even though point source emissions and meteorological conditions remained about the same (Murphy 1975). Diurnal fluctuations in suspended particulate concentrations in Chicago were found to correlate well with carbon monoxide concentrations (a good indicator of traffic activity), even though most of the recognized particulate emissions were not associated with automobile exhaust (Murphy 1975). As part of this Chicago study, the collected airborne particulate material and the street surface particulates were microscopically examined and found to be similar in nature (mostly limestone and quartz by weight), indicating that the airborne particulates could have been resuspended street surface particulates.

Emission factors for the resuspension of particulates from roadways can be estimated from several sources. Roberts (1973) measured particulate losses for paved and unpaved roads in the Duwamish Valley, Washington. He estimated a particulate emission factor of 3.5 lb/veh-mi at 10 mph for unpaved roads; 0.8 lb/veh-mi at 20 mph for "dusty" paved roads with no curbs; and 0.15 lb/veh-mi at 20 mph for "clean" paved roads with curbs that are flushed weekly and swept every two weeks. These results demonstrate the degree of emission reductions possible by paving and cleaning a road. Unfortunately, no information was given to quantify the particulate loadings on the streets.

Sehmel (1973) conducted experiments to quantify the relationships between street surface particulate loading, vehicle speed, and particulate resuspensions by using zinc sulfide (ZnS), a particulate tracer. He also measured the effective area of the resulting downwind plume. The values obtained by Sehmel are only approximate order-of-magnitude estimates because of the differences between the tracer material and actual street dirt (including particle size, density, weathering, and distribution of material on the street). The tracer compound, which has a specific gravity of about 6.5 and a particle size <20 μ, was evenly spread over the test area at about 100 lb/curb-mile. Figure 6-1 shows the observed relationship of vehicle speed and resuspension fraction for a car driven adjacent to the tracer, a car driven through the tracer, and a light three-quarter-ton truck driven through the tracer. Because most of the street surface particulates on smooth roads that have moderate to heavy traffic with little parking have been shown to lie close to the curb, the drive-through test results may only



Source: Sehmel 1973

Figure 6-1. Particle resuspension rates caused by vehicle passage for an asphalt road.

apply to curb lanes on streets with no parking permitted. The drive-by test results may indicate conditions where no driving is permitted adjacent to the curb. Without exception, it is seen that the higher vehicle speeds caused a greater resuspension of particulates. In the drive-through tests for a car, the resuspended fraction ranged from 2 x 10^{-4} to 10^{-2} for 5 to 50 mph vehicle speeds. The truck drive-through tests resulted in resuspended fractions ranging from 2.5 x 10^{-3} to 6 x 10^{-3} of the loading. These truck values at the lower speeds are larger because of increased turbulence. Table 6-1 relates these resuspension fractions to various expected emissions for 25 to 50 mph vehicle speeds. The values for an adjacent lane, next to a parking lane, are seen generally to agree with Robert's values.

Sehmel (1973) also reported that about 80 percent of the emitted tracer remained suspended for more than 30 ft. downwind. As the distance increased, the amount that was redeposited increased. It is expected that actual resuspended street surface particulates would behave differently because of differences in particle size, specific gravities and weathering.

Using the resuspension values in Table 6-1, it is possible to estimate the order of magnitude of the total U.S. airborne emissions from this source. In 1972, it was estimated that 680 billion vehicle-miles were driven in the United States (EPA 1973). Assuming a low street surface particulate loading of about 100 lb/curb-mile and a vehicle speed ranging from 25 to 50 mph, 0.1 lb of particulates/veh-mi may be lost. This results in an estimated total particulate (<20 μ) nationwide emission loss for 1972 of 35 million tons for this fugitive particulate source. This value is compared to an estimated total of 29 million tons of particulate emmissions from all point sources combined (transportation: 1 million tons; stationary fuel combustion: 8 million tons; industrial processes: 12 million tons; solid waste disposal: 6 million tons; miscellaneous: 2 million tons) (EPA 1973, 1974).

TABLE 6-1. PARTICULATE RESUSPENSION FROM AUTO TRAFFIC

Street surface particulate loading		Particulates Lost per Car Pass (lb/vehicle-mile)	
lb/curb-mile	grams/ft^2	Curb lane (driven through)	Parking lane (driven by)
100 ("clean" street)	0.5	1.0	0.1
1000 ("dirty" street)	5.0	10.0	1.0

Resulting roadside particulate concentrations may be estimated from resuspension factors for vehicular traffic as presented by Stewart (1964) and summarized by Mishima (1964). The resuspension factor is defined as the ratio of airborne concentration (weight/volume) to the surface concentrations (weight/area). It is not an accurate value because of irregularities in plume geometry and meteorological conditions, but it may be indicative of roadside particulate concentrations. Values of the resuspension factor for vehicular traffic usually range from 10^{-7} to 10^{-5} per meter. With a "clean" street surface (particulate loading of 100 lb/curb-mile), the resulting roadside airborne particulate concentration from auto traffic may vary from 0.5 to 50 μg/m^3. These added concentrations may cause significant local problems.

A recent study conducted by PEDCo-Environmental, Inc. of Kansas City, Missouri for the EPA (August 1977) examined the control of reentrained dust from paved streets. They conducted some limited tests to measure directly the effects of several different street cleaning control measures on roadside particulate concentrations. They also reviewed several previous studies that examined the resuspension of road surface fugitive particulates and the effectiveness of control measures including street paving, flushing and sweeping. They found the reentrained portion of the traffic-related particulate emissions (by weight) is an order of magnitude greater than the direct emissions accounted for by vehicle exhaust and tire wear. They also found that particulate emissions from a street are directly proportional to the traffic volume and that the suspended particulate concentrations near the streets are associated with relatively large particle sizes. The median particle size found (by weight) was about 15 μ with about 22 percent occurring at particle sizes greater than 30 μ. These relatively large particle sizes resulted in substantial particulate fallout near the roads. They found that about 15 percent of the resuspended particulates fall out at 10 meters, 25 percent at 20 meters and 35 percent at 30 meters from the street (all percentages are expressed by weight).

PEDCo's measurements of the effects of control measures and their literature review results were inconclusive in relating street cleaning effects on adjacent road-side particulate concentrations. Exceptions were noted in those areas that had large street surface loadings (especially at construction sites). Their inconclusive results were most likely caused by large variations in measured concentrations and the lack of experimental controls (the studies were conducted over long periods of time without quantifying other particulate sources). The number of actual samples was also small. However, PEDCo reviewed a study conducted by the New Jersey State Bureau of Air Pollution that examined roadside particulate concentrations near streets on days with flushing compared with days of no flushing. This New Jersey study found significant reductions in roadside concentrations on days with flushing. Although many studies were inconclusive, some of them reported reductions of up to 20 micrograms/m^3 in near-road particulate concentrations with extensive use of various kinds of street cleaning operations. Again, these reductions were most noticeable in those study areas with higher street surface particulate loadings. Paving roads reduced roadside concentrations up to 35 micrograms/m^3.

The vehicle-related reentrainment emission factors measured by PEDCo averaged about 4 g/veh-mi. The standard deviation was about 3 g/veh-mi with 35 sampling periods, while the range of measured emission rates ranged from about 0.2 to 20 g/veh-mi. When the data was separated by land-use type (and therefore street surface loading, traffic characteristics and traffic volume), differences in emission factors were found. Roads with no curbs had emission factors of about 5 g/veh-mi, while the emission factor was about 3 g/veh-mi in park areas. Residential streets having some commercial developments had emission rates of about 2 g/veh-mi, while a commercial and campus area had an emission rate of about 4 g/veh-mi. PEDCo also calculated emission rates for lead and found them to average about 0.07 g/veh-mi, with no apparent fallout of particulate lead near the roadway.

The measured street surface loadings for the different study areas examined by PEDCo were relatively small, ranging from 46 to 335 lb/curb-mile with an average of about 170. These low loadings are common on street surfaces that are well maintained and in good condition, but can be 10 times these amounts for rough streets or streets in poor condition.

Midwest Research Institute (MWRI) of Kansas City, Missouri also conducted a study for the EPA on quantification of dust entrainment from paved roads

(Cowherd, et al., 1977). MWRI's study differed from the PEDCo study in that they applied an artificial material to road surfaces in large quantities (1500 to 5700 lb/curb-mile) and measured the resulting downwind concentrations using standard high volume samplers. MWRI's study resulted in an emission factor of about 0.03 lb (14 g) per veh-mi, and found direct relationships of emission factors with particle loading. The emission factors reported by MWRI are about four times those reported by PEDCo, while the MWRI street surface loading values were about 10 times the PEDCo values. MWRI also reported a wind erosion threshold value of about 13 mph. At this wind speed or greater, significant dust losses from the road surface can result, even in the absence of traffic.

As described in the following sections, roadside particulate concentrations and particulate emission rates were calculated from field measurements using two different procedures in this San Jose demonstration project. The procedures used in this study attempt to overcome some of the shortcomings of the procedures and calculation techniques reported so far. Most of these previous studies developed emission factors using line source dispersion and diffusion models applied very close to the emission sources. These models were developed for source distances substantially greater than used in these studies. Some of the earlier work utilizing tracer materials, where actual decreases in in tracer material loadings on the streets were compared to airborne tracer concentrations, may be more reliable.

This San Jose study utilized particle counters to directly measure roadside particle concentrations as a function of particle size. This allowed many more reliable data sets to be obtained and analyzed for a given period of time than the use of high-volume samplers alone. These measured concentrations were then analyzed by computer to determine resultant concentrations downwind from the road. Expected important variables, as described, did not vary significantly during the course of our studies. The emission rates to be presented are all based on evaluations of long term (up to one year) studies of actual accumulation rates on the road surfaces in three different study areas. In all cases, the accumulation rates decreased with time, reflecting an increase in airborne losses from the road surface after the streets were cleaned or a significant rainfall. It was assumed that the deposition rates were constant and the decreases in accumulation rates with time were mostly associated with airborne losses. The following portions of this section describe the results of these San Jose studies.

MEASURED ROADSIDE DUST LEVELS

Several factors influencing fugitive particulate emissions were measured for each test monitoring roadside dust levels. These factors included traffic speed and density, meteorological conditions (wind speed, wind direction, humidity, and atmospheric stability), and street surface conditions (pavement material and condition and particulate loading). Statistical tests were conducted to determine the importance of these variables.

Specific information collected in this study included the variables noted above and airborne particulate concentrations related to these variables. The following list describes these variables and the estimated importance of their effect on the fugitive particulate emission rates:

- Traffic density: high importance; changed slowly throughout the day as a function of time.

- Wind speed: high importance; changed during the day as a function of time, season, and general synoptic conditions.

- Pavement material: high importance; was constant for each monitoring site (asphalt or oil and screens surfaced).

- Pavement condition: high importance; was constant for each monitoring site.

- Particulate loading: high importance; gradually changed for each test day.

- Traffic speed: medium importance; changed slightly with traffic density.

- Particulate size distribution: medium importance; was generally constant for each test site.

- Wind direction: low importance (can be accounted for); changed during the day as a function of time, season, and general synoptic conditions.

- Relative humidity: low importance; changed slowly during the day as a function of time, season, and general synoptic conditions.

An experimental design phase was also conducted to maximize the sampling program efficiency. The design of the sampling program and number of required samples depended upon the variability of the above listed field conditions and the desired accuracy of the results. As the field program progressed, modifications were made to account for new conditions.

Particle size and concentrations were measured at three stations, one upwind and two downwind from the source street. A particle counter and a high-volume (hi-vol) sampler were located at each of the stations. Sampling was performed simultaneously at each location. Data from the particle counters were displayed in five particle size ranges (>0.5, >1, >2, >5 and >10 μ) and recorded about every four minutes.

Data from the upwind station was used to indicate background particle concentrations. The downwind stations were located so that the results were not affected by other sources. As reported by PEDCo (1977), the automobile particulate emissions (exhuast and tire wear) are expected to be much less, by weight, than the fugitive particulate emissions (<10%).

A mechanical weather station was also used to measure and record air temperature, wind speed and direction continuously during each sampling period. It was located so that wind data was not influenced by traffic or other nearby obstacles. Relative humidity was also periodically monitored. Particulate loadings on the street surface and particle size distributions during the test periods were also measured. Automatic car counters were also used to record total traffic every 15 minutes during the tests.

An appropriate monitoring location was difficult to find because of the need to eliminate particle count interferences and topographic effects on particulate dispersion. The monitoring locations required flat topography with no trees or buildings, and with open spaces on both sides of the road several hundred feet deep. The open spaces could not be susceptible to wind erosion and had to be either grass (in good condition) or paved. Care was also taken to eliminate small areas of denuded loose soil near the sampling points. Nearby construction activities or other sources of particulate emissions eliminated potential test locations. Several days of testing were initially conducted along a busy asphalt surfaced street in a mixed commercial/residential area. This location was eliminated because of building interferences and small patches of denuded soil along a cross street. Another area considered was an oil and screens surfaced street in a well maintained residential area, but the traffic volume on the monitored street was too low to allow sufficient and complete data utilization. The sampling site finally selected was located on a street that had been oil and screens surfaced about one year before and had moderate to heavy traffic. One side of the street was a regional shopping center that had a fairly clean asphalt surfaced parking lot with minimal traffic activity, while the other side of the street was an abandoned gas station surrounded by asphalt.

The prevailing winds were usually perpendicular to the street. Time periods with low winds or winds less than 45 degrees to the street were eliminated. A total of about nine hours of continuous monitoring was utilized out of more than 40 hours of actual field monitoring. In all cases, the sampling probe inlets of the particle counters were kept facing into the wind. The particle counters and other equipment were operated from a 5000 watt generator which was located so that its exhaust would not interfere with the data.

Most of the data selected for reduction was collected between 1 p.m. and 5 p.m. on three days, when the prevailing winds were consistently perpendicular to the road and of moderate speed. Table 6-2 summarizes the conditions during these periods of monitoring. The wind speeds during the selected period of monitoring ranged from about 0.5 to 6 mph, with most of the wind speeds ranging from 2 to 5 mph. Relative humidity values ranged from about 30 to 60 percent and the cloud cover ranged from 0 to 100 percent. The total street surface particulate loadings during these periods of monitoring ranged from about 900 to 2200 lb/curb-mile. The monitored traffic density ranged from about 400 to 900 vehicles per hour. The range of total particle counts per cubic foot monitored during the selected period of data reduction were as follows:

Size Range (μ)	Particle Counts
0.5 - 1	15,000 - 130,000
1 - 2	10,000 - 30,000
2 - 5	600 - 7,500
5 - 10	0 - 2,000

TABLE 6-2. CONDITIONS DURING FUGITIVE PARTICULATE MONITORING

	Wind Speed (mph)	Traffic (Vehicle/ hour)	Relative Humidity (%)	Cloud Cover (%)	Atmos- pheric Stability	Street Surface Loading (lb/curb-mi)
Mean ($\bar{x}$)	3.8	675	42	30	Unstable	1420
Standard dev. (σ)	1.2	71	--	--	--	660
Ratio of σ to $\bar{x}$ ($\sigma/\bar{x}$)	0.32	0.11	--	--	--	0.5
Min.	0.50	444	29	0	Unstable	860
Max.	6.5	864	60	100	Unstable	2150

Most of the particles were found, by count, in the smallest size ranges. These smallest ranges were also more statistically significant from a particle counting technique viewpoint. The precision of the counts in the smallest size ranges typically had percent errors of less than ±10 percent for a 50 percent probability value. This means that the data most likely occurred within the values reported ± 10 percent with a 50 percent certainty. With a 95 percent certainty, the true values lie within the reported values ± 20 percent. The larger particle sizes, because of the smaller counts, had precisions which were much less. In these cases, the percentage errors ranged up to 100 percent for the short sampling periods. When the data was combined, the percent of errors substantially decreased (to much less than 1 percent for the small sizes and less than 10 percent for the larger sizes).

Table 6-3 summarizes the total airborne particulate populations measured over 135 selected time periods on these three days. The mean particulate populations measured (expressed as number per 0.01 ft^3), the standard deviation, relative standard deviation (standard deviation divided by mean), and number of data points are shown for each particle size range for the upwind control station and the near road downwind station. The probability that the downwind (about 4 meters from the curb) populations were not equal to the up-upwind control populations is also shown. The probability values are based on a 95 percent confidence limit (the probability value shown can be wrong 1 out of 20 times). A probability value of 0.75 signifies that the means (or variations) are not equal 75 percent of the time. About three-quarters of all the measured particles by count (in the size range from 0.5 μ to about 100 μ), were in the range of 0.5 to 1 micron. Most of the remaining particles were in the range from 1 to 2 microns. Less than 5 percent of the total particles were in the range from 2 to 100 microns. The larger particles, however, made up most of the particle mass. Particulate concentrations for the downwind station were generally greater than for the upwind control station. These increases were due to automobile and roadway related emissions. Auto-

TABLE 6-3. TOTAL AIRBORNE PARTICULATE POPULATIONS (number/0.01 ft^3)

	February 28, 1978			March 15, 1978			March 16, 1978		
	Upwind*	Near Downwind**	Prob. Near ≠ Upwind***	Upwind*	Near Downwind**	Prob. Near ≠ Upwind***	Upwind*	Near Downwind**	Prob. Near ≠ Upwind***
>0.5 μ									
mean ($\bar{x}$)	1302	1574	1.00	398	409	0.55	510	534	061
st.dev. (σ)	140	259	1.00	57	77	0.96	128	150	072
$\sigma/\bar{x}$	0.11	0.16	--	0.14	0.19	--	0.25	0.28	--
N	37	37	--	48	48	--	50	50	--
>1.0 μ									
mean ($\bar{x}$)	266	311	1.00	175	173	0.24	172	189	0.96
st. dev. (σ)	37	53	0.97	39	28	0.96	34	48	0.98
$\sigma/\bar{x}$	0.14	0.17	--	0.22	0.16	--	0.20	0.25	--
N	37	37	--	48	48	--	50	50	--
>2.0 μ									
mean ($\bar{x}$)	19	21	0.65	19	21	0.75	30	29	0.25
st. dev. (σ)	5.4	9.6	1.00	6.3	7.1	0.57	7.9	10	0.92
$\sigma/\bar{x}$	0.28	0.46	--	0.33	0.34	--	0.26	0.34	--
N	37	37	--	48	48	--	50	50	--
>5.0 μ									
mean ($\bar{x}$)	1.2	0.9	0.47	1.2	1.3	0.11	1.2	3.3	1.00
st. dev. (σ)	1.4	1.6	0.51	2.9	1.5	1.00	1.3	4.5	1.00
$\sigma/\bar{x}$	1.2	1.8	--	2.4	1.2	--	1.1	1.4	--
N	37	37	--	48	48	--	50	50	--
>10 μ									
mean ($\bar{x}$)	0.7	0.2	0.98	0.1	0.3	0.96	0.3	0.5	0.77
st. dev. (σ)	1.2	0.4	1.00	0.1	0.4	1.00	0.6	1.2	1.00
$\sigma/\bar{x}$	1.7	2.0	—	1.0	1.3	--	2.0	2.4	--
N	37	37	--	48	48	--	50	50	--

*Upwind (background) particulate concentration conditions.

**Near-downwind particulate concentrations were monitored about 10 ft. from the traffic lane, on the sidewalk at nose height.

***The probability value shown relates to the significance of the difference between the near-downwind particulate concentrations and variances. A value of 1 signifies that the upwind and near-downwind values are significantly different at 95 percent confidence value (may be wrong 1 time out of 20).

mobile exhaust and tire wear particulate emissions (by weight) have been previously reported to be less than about 10 percent of the fugitive roadway particulate emissions (PEDCo 1977). Almost all of these particulate concentration increases can be assumed to be caused by the fugitive roadway particulate emissions. The concentration increases were larger for the smaller size ranges. The relative standard deviation values (a measure of variability) increased for the larger particle sizes signifying less precise results for those particle sizes. The measured variabilities of the downwind and upwind sampling stations were also significantly different in almost all cases.

Table 6-4 summarizes the fugitive particulate concentration increases at the near road downwind station over background conditions for specific particle size ranges. Again, the important concentration increases by number occurred in the two smallest size ranges, while most of the increases by weight occurred in the largest size range. About 80 percent of the concentration increases (by count) occurred in the 0.5 to 1 μ size range and about 19 percent of the total increases occurred in the 1 to 2 μ size range. Less than 1 percent of the concentration increases occurred in size ranges greater than 2 μ. However, about 90 percent of the concentration increases by weight were in the largest size range. These concentration increases were 10 percent or more of the total populations measured. Concentration increases from asphalt surfaced roads can be expected to be about 50 percent greater than these values because of expected increased fugitive particulate losses from asphalt surfaced streets (see the next subsection).

Statistically significant concentration increases also occurred further downwind from the street (about 30 to 50 meters), but the absolute differences were quite small; typically less than 1 percent of the total population counts.

The following discussion presents measured fugitive particulate emission rates based on monitored street surface accumulation values over a long period of time. It is not possible to reasonably predict emission rates directly from these concentration values because of the proximity of the monitoring stations to the emission sources, and the undefined effects of automobile induced turbulence on dispersion and diffusion of particulates. Suitable tracer material could be used to relate these close-by concentrations with probable fugitive losses.

FUGITIVE PARTICULATE EMISSION RATES

As previously stated, the street surface particulate accumulation rates were greatest when the streets were relatively clean, shortly after street cleaning. Particulate loading values then tended to level off with the passage of time. It is assumed that the deposition rate was constant and that the increasing difference between the deposition rate and the accumulation rate was caused by fugitive particulate losses to the air. Therefore, if the effects of rain and street cleaning operations are eliminated, it is possible to estimate these dust losses from the accumulation rates, if one assumes that the initial highest accumulation rate value approximates the constant deposition rate.

TABLE 6-4. NEAR-ROAD FUGITIVE PARTICULATE CONCENTRATION INCREASES (number per 0.01 ft^3)

	February 28, 1978*	March 15, 1978**	March 16, 1978***
0.5 → 1.0 μ			
mean ($\bar{x}$)	227	13	7.2
st. dev. (σ)	197	85	124
$\sigma/\bar{x}$	0.87	6.5	17
1.0 → 2.0 μ			
mean	44	-3.7	18
st. dev. (σ)	44	41	39
$\sigma/\bar{x}$	1.0	--	2.2
2.0 → 5.0 μ			
mean ($\bar{x}$)	1.9	1.5	-2.8
st. dev. (σ)	11	8.9	9.9
$\sigma/\bar{x}$	5.8	5.9	--
5.0 → 10 μ			
mean ($\bar{x}$)	0.29	-0.15	2.0
st. dev. (σ)	2.1	3.5	4.9
$\sigma/\bar{x}$	7.2	--	2.5
>10 μ			
mean ($\bar{x}$)	-0.51	0.22	0.22
st. dev. (σ)	1.4	0.75	1.3
$\sigma/\bar{x}$	--	3.4	5.9
Total			
mean ($\bar{x}$)	272	10	24
st. dev. (σ)	221	85	121
$\sigma/\bar{x}$	0.81	8.5	5.0

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*37 value data sets were obtained on February 28, 1978.

**48 value data sets were obtained on March 15, 1978.

***50 value data sets were obtained on March 16, 1978.

Monitored accumulation rates, as presented in Section 3, were compared for various periods of accumulation after street cleaning. These accumulation rates were highest closest to the day of street cleaning. It is assumed that this highest accumulation rate value approximates the constant deposition rate. The difference between this assumed deposition rate and subsequent accumulation rates is due to fugitive particulate losses to the air. Other phenomena, such as tracking of dirt by vehicles, is assumed to be constant, with equal amounts of dirt being brought into the test areas as carried out. These accumulation rate calculations did not include any periods of data affected by rain events. Fugitive particulate losses from the street can be caused by a combination of wind and traffic induced turbulence. As stated previously (Cowherd, et al., 1977), a wind speed threshold value of about 13 mph is required before wind erosion of particulates from the street surface becomes important. Most of the winds during the study period had wind speeds much less than this threshold value. Therefore, most of the particulate losses from the streets in the study areas were from automobile induced turbulence.

Tables 6-5 through 6-7 present the calculated fugitive particulate emission factors for the three test areas and for several different pollutants. These emission factors are expressed as lb/curb-mile/day and as g/veh-mi. In almost all cases, the emission rates are seen to increase with time since street cleaning. The emission rates are typically 3 to 4 times as great in the period from 60-75 days as compared with 2-4 days after street cleaning for the Keyes-good asphalt and Tropicana-good asphalt test areas. Losses in the Keyes-oil and screens test area at 30-45 days were over 10 times the values found in the period of time of 2-4 days after street cleaning. Therefore, street cleaning frequencies can be very important in affecting fugitive particulate emission rates from road surfaces.

The Keyes-good asphalt test area and Tropicana-good asphalt test area emission rates, on a curb-mile basis, are the same because their accumulation rates were similar. However, there were major differences in traffic volume in these two test areas resulting in the Tropicana area having substantially greater emission rates expressed on a vehicle-mile basis. The Keyes-oil and screens test area had little traffic and high particulate losses expressed by vehicle-mile. The average particulate emission losses from these three test areas ranged from 0.66 to 18 g/veh-mi. Information presented from Sehmel (1973) leads to an estimate of about 45 g/veh mi. PEDCo (1977) reported values ranging from 0.2 to 20 with an average of about 4 g/veh-mi, while MWRI (Cowherd, 1977) values averaged about 13 g/veh-mi. The overall reported range is about 0.2 to 45 g/veh-mi, with typical values in the range of 2 to 5 g/veh-mi, Tables 6-5 through 6-7 also present values for some other pollutants. The emission losses for lead ranged from about 0.003 to 0.02 g/veh-mi, where PEDCo (1977) reported an average fugitive particulate lead emission rate of about 0.07 g/veh-mi.

These particulate losses can contribute a large portion of an area's total particulate emissions. Street cleaning frequency can have a large effect on fugitive particulate emission rates. This is expected to be due to both an overall reduction in street surface particulate loadings and a modification in the particle size distribution. The particulate emission rates from a typical asphalt surfaced street can be reduced to about one-thirdif it is cleaned every week instead of every 2 or 3 months. Therefore, street cleaning can have a

TABLE 6-5 FUGITIVE PARTICULATE EMISSION FACTORS FOR STREET SURFACE LOSSES - KEYES-GOOD ASPHALT TEST AREA

Parameter	Time After Street Cleaning or Significant Rain (Days)	lb/Curb-Mile/day	Grams/ Vehicle-Mile	Increase Over Initial Rate
Total Solids	2 → 4	4	0.44	-
	4 → 10	4	0.44	1.0
	10 → 20	5	0.55	1.3
	20 → 30	7	0.77	1.8
	30 → 45	8	0.88	2.0
	45 → 60	9	0.98	2.3
	60 → 75	12	1.3	3.0
	Average	6	0.66	-
Chemical Oxygen Demand	2 → 4	0.4	0.044	-
	4 → 10	0.4	0.044	1.0
	10 → 20	0.6	0.066	1.5
	20 → 30	0.8	0.088	2.0
	30 → 45	0.9	0.098	2.3
	45 → 60	1.1	0.12	2.8
	60 → 75	1.4	0.15	3.5
	Average	0.7	0.077	-
Kjeldahl Nitrogen	2 → 4	0.006	0.00066	-
	4 → 10	0.006	0.00066	1.0
	10 → 20	0.010	0.0011	1.7
	20 → 30	0.012	0.0013	2.0
	30 → 45	0.015	0.0016	2.5
	45 → 60	0.017	0.0019	2.8
	60 → 75	0.023	0.0025	3.8
	Average	0.011	0.0012	-
Orthophosphate	2 → 4	0.0006	0.000066	-
	4 → 10	0.0006	0.000066	1.0
	10 → 20	0.0008	0.000088	1.3
	20 → 30	0.0010	0.00011	1.7
	30 → 45	0.0008	0.000088	1.3
	45 → 60	0.0013	0.00014	2.2
	60 → 75	0.0018	0.00020	3.0
	Average	0.0009	0.000098	-
Lead	2 → 4	0.015	0.0016	-
	4 → 10	0.015	0.0016	1.0
	10 → 20	0.026	0.0028	1.7

(Continued)

TABLE 6-5 (Concluded)

Parameters	Time After Street Cleaning or Significant Rain (Days)	lb/Curb-mile/day	Grams/Vehicle-mile	Increase Over Initial Rate
Lead	20 → 30	0.028	0.0031	1.9
	30 → 45	0.033	0.0036	2.2
	45 → 60	0.040	0.0044	2.7
	60 → 75	0.055	0.0060	3.7
	Average	0.026	0.0028	-
Zinc	2 → 4	0.0017	0.00019	-
	4 → 10	0.0017	0.00019	1.0
	10 → 20	0.0024	0.00026	1.4
	20 → 30	0.0030	0.00033	1.8
	30 → 45	0.0036	0.00039	2.1
	45 → 60	0.0044	0.00048	2.5
	60 → 75	0.0057	0.00062	3.3
	average	0.0028	0.00031	-
Chromium	2 → 4	0.0012	0.00013	-
	4 → 10	0.0012	0.00013	1.0
	10 → 20	0.0017	0.00019	1.4
	20 → 30	0.0021	0.00023	1.8
	30 → 45	0.0025	0.00027	2.1
	45 → 60	0.0030	0.00033	2.5
	60 → 75	0.0041	0.00045	3.4
	average	0.0020	0.00022	-
Copper	2 → 4	0.0014	0.00015	-
	4 → 10	0.0014	0.00015	1.0
	10 → 20	0.0028	0.00030	2.0
	20 → 30	0.0033	0.00036	2.4
	30 → 45	0.0041	0.00045	2.9
	45 → 60	0.0050	0.00055	3.6
	60 → 75	0.0069	0.00076	4.9
	average	0.0031	0.00034	-
Cadmium	2 → 4	0.000007	0.00000077	-
	4 → 10	0.000007	0.00000077	1.0
	10 → 20	0.000007	0.00000077	1.0
	20 → 30	0.000007	0.00000077	1.0
	30 → 45	0.000012	0.000013	1.7
	45 → 60	0.000016	0.000018	2.3
	60 → 75	0.000021	0.000023	3.0
	average	0.000010	0.000011	-

TABLE 6-6. FUGITIVE PARTICULATE EMISSION FACTORS FOR STREET SURFACE LOSSES KEYES-OIL AND SCREENS TEST AREA

Parameter	Time After Street Cleaning or Significant Rain (Days)	lb/Curb-mile/day	Grams/Vehicle-mile	Increase Over Initial Rate
Total Solids	2 → 4	<1	<4.5	--
	4 → 10	3	14	>3.1
	10 → 20	4	18	>4.0
	20 → 30	5	23	>5.1
	30 → 45	10	45	>10
	Average	4	18	--
Chemical Oxygen Demand	2 → 4	<0.1	<0.45	--
	4 → 10	0.1	0.45	>1.0
	10 → 20	0.2	0.91	>2.0
	20 → 30	0.3	1.4	>3.1
	30 → 45	0.7	3.2	>7.1
	Average	0.2	0.9	--
Kjeldahl Nitrogen	2 → 4	<0.001	<0.0045	--
	4 → 10	0.002	0.0091	>2.0
	10 → 20	0.004	0.018	>4.0
	20 → 30	0.005	0.023	>5.1
	30 → 45	0.010	0.045	>10
	Average	0.003	0.014	--
Orthophosphates	2 → 4	<0.0001	<0.00045	--
	4 → 10	0.0004	0.0018	>4.0
	10 → 20	0.0004	0.0018	>4.0
	20 → 30	0.0005	0.0023	>5.1
	30 → 45	0.0008	0.0036	>8.0
	Average	0.0004	0.0018	--
Lead	2 → 4	<0.001	<0.0045	--
	4 → 10	0.003	0.014	>3.1
	10 → 20	0.006	0.027	>6.0

(Continued)

TABLE 6-6. (Concluded)

Parameter	Time After Street Cleaning or Significant Rain (Days)	lb/Curb-mile/day	Grams/ Vehicle-mile	Increase Over Initial Rate
Lead	20 → 30	0.006	0.027	>6.0
	30 → 45	0.012	0.054	>12
	Average	0.004	0.018	--
Zinc	2 → 4	<0.0001	<0.00045	--
	4 → 10	0.0006	0.0027	>6.0
	10 → 20	0.0010	0.0045	>10
	20 → 30	0.0011	0.0050	>11
	30 → 45	0.0023	0.010	>22
	Average	0.0008	0.0036	--
Chromium	2 → 4	<0.0001	<0.00045	--
	4 → 10	0.0009	0.0041	>9.1
	10 → 20	0.0014	0.0064	>14
	20 → 30	0.0018	0.0082	>18
	30 → 45	0.0034	0.015	>33
	Average	0.0012	0.0054	--
Copper	2 → 4	<0.0001	<0.00045	--
	4 → 10	0.0015	0.0068	>15
	10 → 20	0.0020	0.0091	>20
	20 → 30	0.0025	0.011	>24
	30 → 45	0.0047	0.021	>47
	Average	0.0018	0.0082	--
Cadmium	2 → 4	<0.000001	<0.0000045	--
	4 → 10	<0.000001	<0.0000045	--
	10 → 20	0.000002	<0.0000091	> 2.0
	20 → 30	0.000003	0.000014	> 3.0
	30 → 45	0.000010	0.000045	>10
	Average	0.000001	0.0000045	--

TABLE 6-7. FUGITIVE PARTICULATE EMISSION FACTORS FOR STREET SURFACE LOSSES - TROPICANA-GOOD ASPHALT TEST AREA

Parameter	Time After Street Cleaning or Significant Rain (Days)	lb/Curb-Mile/day	Grams/ Vehicle-Mile	Increase Over Initial Rate
Total Solids	2→4	4	1.7	-
	4→10	4	1.7	1.0
	10→20	5	2.1	1.3
	20→30	7	2.9	1.8
	30→45	8	3.3	2.0
	45→60	9	3.7	2.3
	60→75	12	5.0	3.0
	Average	6	2.5	-
Chemical Oxygen Demand	2→4	0.4	0.17	-
	4→10	0.4	0.17	1.0
	10→20	0.6	0.25	1.5
	20→30	0.8	0.33	2.0
	30→45	0.9	0.37	2.3
	45→60	1.1	0.45	2.8
	60→75	1.4	0.58	3.5
	Average	0.7	0.29	-
Kjeldahl Nitrogen	2→4	0.006	0.0025	-
	4→10	0.006	0.0025	1.0
	10→20	0.010	0.0041	1.7
	20→30	0.012	0.0050	2.0
	30→45	0.015	0.0062	2.5
	45→60	0.017	0.0070	2.8
	60→75	0.023	0.0095	3.8
	Average	0.011	0.0045	-
Orthophosphates	2→4	0.0006	0.00025	-
	4→10	0.0006	0.00025	1.0
	10→20	0.0008	0.00033	1.3
	20→30	0.0010	0.00041	1.7
	30→45	0.0008	0.00033	1.3
	45→60	0.0013	0.00054	2.2
	60→75	0.0018	0.00074	3.0
	Average	0.0009	0.00037	-
Lead	2→4	0.015	0.0062	-
	4→10	0.015	0.0062	1.0
	10→20	0.026	0.011	1.7

(Continued)

TABLE 6-7. (Concluded)

Parameter	Time After Street Cleaning or Significant Rain (Days)	lb/Curb-Mile/day	Grams/ Vehicle-Mile	Increase Over Initial Rate
Lead	20→30	0.028	0.012	1.9
	30→45	0.033	0.013	2.2
	45→60	0.040	0.017	2.7
	60→75	0.055	0.023	3.7
	Average	0.026	0.011	-
Zinc	2→4	0.0017	0.00070	-
	4→10	0.0017	0.00070	1.0
	10→20	0.0024	0.0010	1.4
	20→30	0.0030	0.0012	1.8
	30→45	0.0036	0.0015	2.1
	45→60	0.0044	0.0018	2.6
	60→75	0.0057	0.0024	3.4
	Average	0.0028	0.0012	-
Chromium	2→4	0.0012	0.00050	-
	4→10	0.0012	0.00050	1.0
	10→20	0.0017	0.00070	1.4
	20→30	0.0021	0.00087	1.8
	30→45	0.0025	0.0010	2.1
	45→60	0.0030	0.0012	2.5
	60→75	0.0041	0.0017	3.4
	Average	0.0020	0.00083	-
Copper	2→4	0.0014	0.00058	-
	4→10	0.0014	0.00058	1.0
	10→20	0.0028	0.0012	2.0
	20→30	0.0033	0.0014	2.4
	30→45	0.0041	0.0017	2.9
	45→60	0.0050	0.0021	3.6
	60→75	0.0069	0.0028	4.9
	Average	0.0031	0.0013	-
Cadmium	2→4	0.000007	0.0000029	-
	4→10	0.000007	0.0000029	1.0
	10→20	0.000007	0.0000029	1.0
	20→30	0.000007	0.0000029	1.0
	30→45	0.000012	0.0000050	1.7
	45→60	0.000016	0.0000066	2.3
	60→75	0.000021	0.0000087	3.0
	Average	0.000010	0.0000041	-

beneficial air pollution effect in addition to the other environmental objectives described in Section 5.

STREET CLEANING EQUIPMENT CAB PARTICULATE CONCENTRATIONS

Tests were conducted to determine the concentrations of particulates (dust levels) inside the street cleaning equipment cabs and directly behind the state-of-the-art four-wheel mechanical street cleaner, both with and without using the water spray. Table 6-8 presents these data. The concentrations of particulates in the cab were not significantly different from the ambient concentrations when the windows were rolled up, the air conditioner was on, and the water spray was in use. When the water spray was not used, particulate concentrations in front of the equipment and within the cab increased significantly. In fact, the concentrations within the cab with the windows rolled up and with the air conditioner on (but without the water spray) were about equal to the concentrations directly behind the street cleaner. However,use of the water spray did not significantly change the high total particulate concentrations directly behind the street cleaner.

Most of these changes in particulate concentrations (by count) are in the smaller particle sizes. Concentrations of the larger particle sizes (greater than 10 microns) were not significantly affected by use of the water spray.

TABLE 6-8. DUST LEVELS IN AND BEHIND STREET CLEANER*

	Particle Size 0.5→1.0 μ	1.0→2.0 μ	2.0→5.0 μ	5.0→10.0 μ	>10.0 μ	Total (>0.5 μ)
Ambient (outside cab):						
With water spray (no./ft.^{3})	750	1950	74,500	100,800	270,000	448,000
(% in size range)	0.2	0.4	16.7	22.7	60.7	100.7
Without water (no./ft.^{3})	1130	17,570	390,300	577,000	534,000	1,520,000
(% in size range)	<0.1	1.2	25.7	38.0	35.1	100.1
Increase without water (factor)	1.5x	9.0x	5.2x	5.7x	2.0x	3.4x
Inside cab:						
With water spray (no./ft.^{3})	1960	0	35,230	150,900	371,000	559,000
(% in size range)	0.4	<0.1	6.3	27.0	66.4	100.1
Increase over ambient with water spray (factor)	2.6x	Large decrease	0.47x	1.5x	1.4x	1.3x
Without water (no./ft.^{3})	360	3040	328,600	1,188,000	1, 070.00	2,590,000
(% in size range)	<0.1	0.1	12.7	45.9	41.3	100.0
Increase without water spray (factor)	0.2x	Large decrease	9.3x	7.9x	2.9x	4.6x
Behind sweeper:						
With water spray (no./ft.^{3})	5850	26,350	662,800	745,000	1,210,000	2,650,000
(% in size range)	0.2	1.0	25.0	28.1	45.7	100.0
Increase over ambient with water spray (factor)	7.8x	14x	8.9x	7.4x	4.5x	5.9x
Without water (no./ft.^{3})	225,000	522,000	3,053,000	-570,000	40,000	3,270,000
(% in size range)	6.9	16.0	93.4	-17.4	1.2	100.1
Increase without water spray (factor)	38x	20x	4.6x	Large decrease	0.03	1.2

*4-wheel mechanical street cleaner test in Tropicana-good asphalt test area, 9/29/77.

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APPENDIX A

STREET SURFACE PARTICULTATE SAMPLING PROCEDURES

The sampling procedures described in this appendix were specifically developed for this study. The objectives of the study were different from those of past studies of street surface contaminants, so it was necessary to design special sampling procedures. These procedures were intended to maximize the accuracy and completeness of the information from the sampling program. The procedures are described here in detail so that they can be used by public works departments wishing to determine loading conditions, accumulation rates, and street cleaning effectiveness for their own cities.

EQUIPMENT DESCRIPTION

Figure A-1 shows the sampling trailer and major equipment components. A light-duty (half-ton capacity) trailer was used to carry the generator, tools, fire extinguisher, vacuum hose and wand, and two wet-dry vacuum units during sample collection.* A truck with a suitable hitch and signal light connections was used to pull the trailer. The truck also had warning lights, including a roof-top flasher unit. The truck operated with its headlights and warning lights on during the entire period of sample collection. The sampler and hose tender both wore orange, high-visibility vests. The trailer was equipped with a caution sign on its tailgate.

Both the truck and the street cleaner used to clean the test area were equipped with radios (CB radios were adequate), so that the sampling team could contact the street cleaner operator when necessary. Experiments were conducted to determine the most appropriate sampling vacuum and filter bag combination. Two-horsepower (hp) industrial vacuum cleaners with one secondary filter and a primary dacron filter bag were selected. The vacuum units were heavy duty and made of stainless steel to reduce contamination of the samples. Two 2-hp vacuums were used together by using a wye connector. This combination extended the useful length of the 1.5 in. vacuum hose to 35 ft. and increased the suction so that it was adequate to remove all particles of interest from the street

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*Dry vacuum sampling is capable of removing all of the particulates (>99%) from the street surface when compared to combination dry sampling and flushing sampling. It can also remove most of the other major pollutants from the street surface (>80% for volatiles, COD, phosphates and metals). Wet sampling is not an adequate procedure for comprehensive, large-scale programs of this nature.

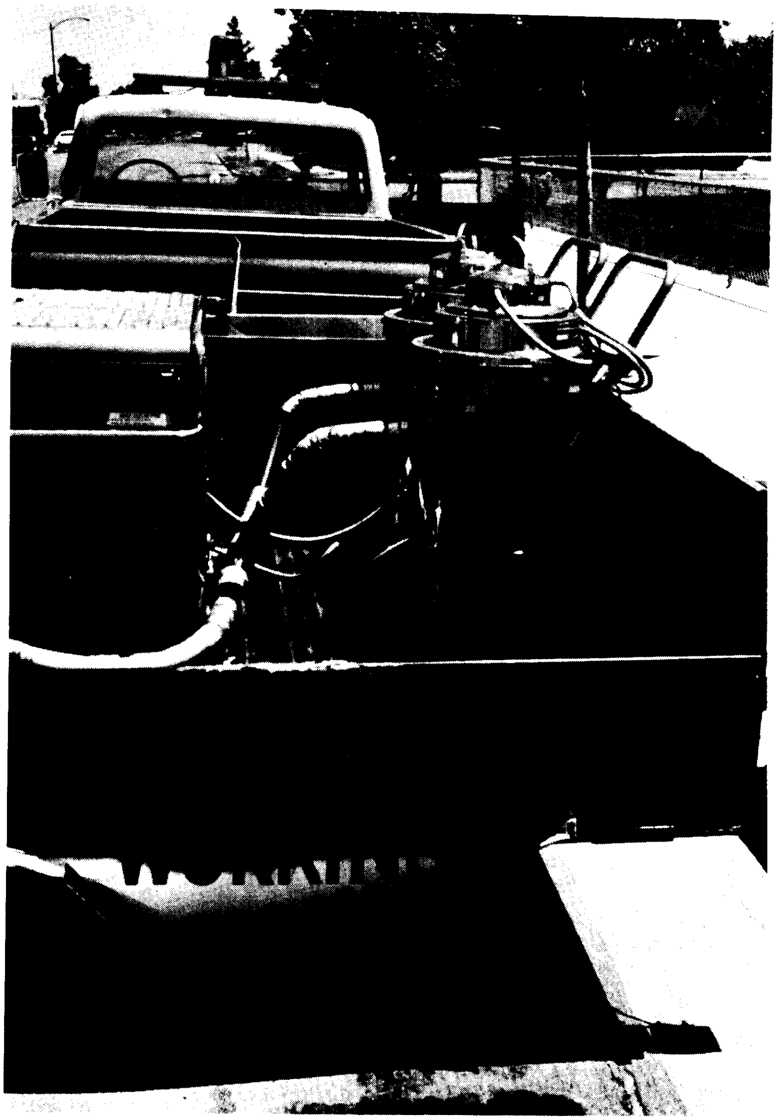

Figure A-1. Street sampling trailer and major equipment components.

surface. A wand and a gobbler* attachment were also needed. The generator used to power the vacuum units was of sufficient power to handle the electrical current load drawn by the vacuum units--about 5000 watts for two 2-hp vacuums. Finally a secure, protected garage was used to store the trailer and equipment near the study areas when not in use.

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*The gobbler attaches to the end of the wand and is triangular in shape and about 6 in. across.

SAMPLING PROCEDURE

Because the street surfaces were more likely to be dry during daylight hours (necessary for good sample collection), collection did not begin before sunrise nor continue after sunset, unless additional personnel were available for traffic control. Two people were required for sampling at all times--one acting as the sampler, the other acting as the vacuum hose tender and traffic controller. This lessened individual responsibility and enabled both persons to be more aware of traffic conditions.

Before each day of sampling, the equipment was checked to make sure that the generator's oil and gasoline levels were adequate, and that vacuum hose, wand, and gobbler were in good condition. A check was also made to ensure that the vacuum units were clean, the electrical cords were securely attached to the generator, and the trailer lights and warning lights were operable. The generator required about 3 to 5 minutes to warm up before the vacuum units were turned on one at a time (about 5 to 10 seconds apart to prevent excessive current loading on the generator). The amperage and voltage meters of the generator were also periodically checked.

Figure A-2 illustrates the general samping procedure. Each subsample included all of the street surface material that would be removed during a severe rain (including loose materials and caked-on mud in the gutter and street areas). The location of the subsample strip was carefully selected to ensure that it had no unusual loading conditions (e.g., a subsample was not collected through the middle of a pile of leaves; rather, it was collected where the

Figure A-2. Sub-sample collection.

leaves were lying on the street in their normal distribution pattern). When possible, wet areas were avoided. If a sample was wet and the particles caked around the intake nozzle, the caked mud from the gobbler was carefully scraped into the vacuum hose while the vacuum units were running.

Subsamples were collected in a narrow strip about 6 in. wide (the width of the gobbler) from one side of the street to the other (curb to curb) as shown in Figure A-3. In heavily traveled streets where traffic was a problem, some subsamples consisted of two separate one-half street strips (curb to crown). Traffic was not stopped for subsample collection; the operators waited for a suitable traffic break. On wide or busy roadways, a subsample was often collected from two strips several feet apart, halfway into the street. On busy roadways with no parking and good street surfaces, most particulates were found within a few feet of the curb, and a good subsample could be collected by vacuuming two adjacent strips from the curb as far into the traffic lanes as possible. A sufficient break in traffic allowed a subsample to be collected halfway across the street.

Subsamples taken in areas of heavy parking were collected between vehicles along the curb, as necessary. The sampling line across the street did not have to be a continuous line if a parked car blocked the most obvious and easiest subsample strip. A subsample could be collected in shorter strips, provided the combined length of the strip was representative of different distances from the curb. Again, in all instances, each subsample was representative of the overall curb-to-curb loading condition.

When sampling, the leading edge of the gobbler was slightly elevated above the street surface (0.125 in.) to permit an adequate air flow and to collect pebbles and large particles. The gobbler was lifted further to accept larger material as necessary. If necessary, leaves in the subsample strip were manually removed and placed in the sample storage container to prevent the hose from clogging. If a noticeable decrease in sampling efficiency was observed, the

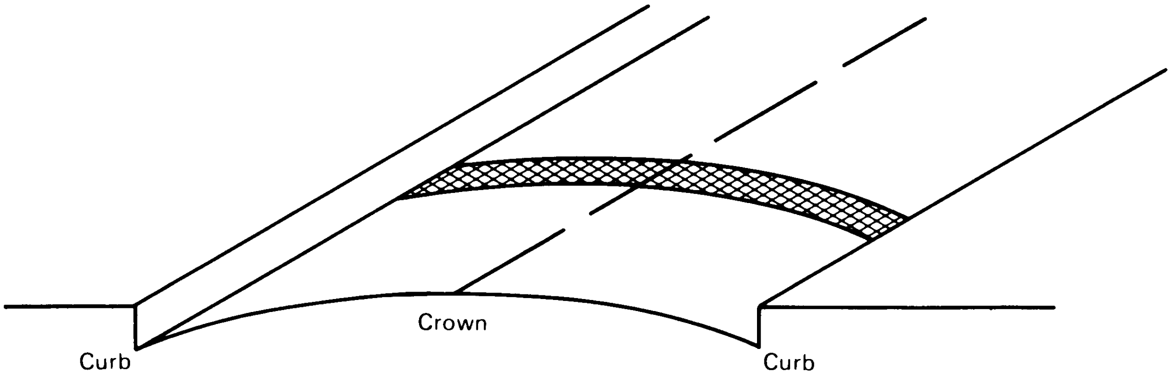

Figure A-3. Location of sub-sampling strips across a street.

vacuum hoses were cleaned immediately by disconnecting the hose lengths, cleaning out the connectors (placing the debris into the sample storage container), and reversing the air flows in the hoses (blowing them out by connecting the hose to the vacuum exhaust and directing the dislodged debris into the vacuum inlet). If any mud was caked on the street surface in the subsample strip, the sampler loosened it by scraping a shoe along the subsample path (being certain that street construction material was not removed from the subsample path unless it was very loose). Scraping caked-on mud was done after an initial vacuum pass. After scraping was completed, the strip was revacuumed. A rough street surface was sampled most easily by pulling (not pushing) the wand and gobbler toward the curb. Smooth and busy streets were usually sampled with a pushing action.

An important aspect of the sample collection was the speed at which the gobbler was moved across the street. A very rapid movement significantly decreased the amount of material collected; too slow a movement required more time than was necessary. The correct movement rate depended on the roughness of the street and the amount of material on it. When sampling a street that had a heavy loading of particulates, or a rough surface, the wand was pulled at a velocity of less than 1 ft. per second. In areas of lower loading and smoother streets, the wand was pushed at a velocity of 2 to 3 ft. per second. The best indication of the correct collection speed was by examining how well the street was visually being cleaned in the sampling strip and by listening to the collected material rattle up the wand and through the vacuum hose. The objective was to remove everything that was lying on the street that could be removed by a significant rainstorm. It was quite common to leave a visually cleaner strip on the street where the subsample was collected, even on streets that appeared to be clean.

In all cases of subsample collection, the sampler and hose tender continuously watched for oncoming vehicles. While working near the curb out of the traffic lane (typically an area of high loadings), the sampler visually monitored the performance of the vacuum sampler. In the street, he constantly watched traffic and monitored the collection process by listening to particles moving up the wand. A large break in traffic was required to collect dust and dirt from street cracks in the traffic lanes, because the sampler had to watch the gobbler to make sure that all of the loose material in the cracks was removed.

The hose tender also always watched for traffic. In addition, he played out the hose to the sampler as needed and kept the hose as straight as possible to prevent kinking. If a kink developed, sampling stopped until the hose tender straightened the hose.

When moving from one subsample location to another, the hose, wand, and gobbler were securely placed in the trailer. The hose was placed away from the generator's hot muffler to prevent hose damage. The generator and vacuum units were left on and in the trailer during the entire subsample collection period. This helped dry damp samples and reduced the strain on the vacuum and generator motors.

The length of time it took to collect the subsample varied with the number of subsamples and the test area. For the first phase of this study, the test areas required the following sampling effort:

Test Area	No. of Samples	Sampling Period
Downtown - poor asphalt street surface	14	0.5 hr.
Downtown - good asphalt street surface	35	1 hr.
Keyes Street - oil and screens street surface	10	0.5-1 hr.
Keyes Street - good asphalt street surface	36	1 hr.
Tropicana - good asphalt street surface	16	0.5-1 hr.

In the oil and screens test area, the sampling procedure was slightly different because of the relatively large amount of pea gravel (screens) that was removed from the street surface. The gobbler attachment was drawn across the street more slowly (at a rate of about 3 seconds per ft.). Each subsample was collected by a half pass (from the crown to the curb of the street) and contained one-half of the normal sample. Two curb-to-curb passes were made for each Tropicana subsample because of the relatively low particulate loadings in this area. Several hundred grams of sample material were needed for the laboratory tests. An after street cleaning subsample was not collected from exactly the same location as the before street cleaning subsample (they were taken from the same general area, but at least a few feet apart).

A field-data record sheet kept for each sample contained:

- Subsample numbers
- Dates and time of the collection period
- Any unusual conditions or sampling techniques.

Subsample numbers were crossed off as each subsample was collected. After-cleaning, subsample numbers were marked if the street cleaner operated next to the curb at that location. This differentiation enabled the effect of parked cars on street cleaning performance to be analyzed.

SAMPLE TRANSFER

After all subsamples for a test area were collected, the hose and wye connections were cleaned by disconnecting the hose lengths, reversing them, and holding them in front of the vacuum intake. Leaves and rocks that may have become caught were carefully removed and placed in the vacuum can, the generator was then turned off. The vacuums were either emptied at the last station or at a more convenient location.

To empty the vacuums, the top motor units were removed and placed out of the way of traffic, as shown in Figure A-4. The vacuum units were then disconnected from the trailer and lifted out. The secondary, coarse vacuum filters were removed from the vacuum can and were carefully brushed with a small whisk broom into a large funnel placed in the storage can, as shown in Figure A-5. The primary dacron filter bags were kept in the vacuum can and shaken carefully to knock off most of the filtered material. (Figure A-6 shows how the hose inlet was blocked with a leg or knee, and the primary filter bag was held onto the vacuum drum with arms and chest). The dust inside the can was allowed to settle for a few minutes, then the primary filter was removed and brushed carefully into the sample can with the whisk broom. Any dirt from the top part of the bag

Figure A-4. Disassembly of vacuum units for sample transfer.

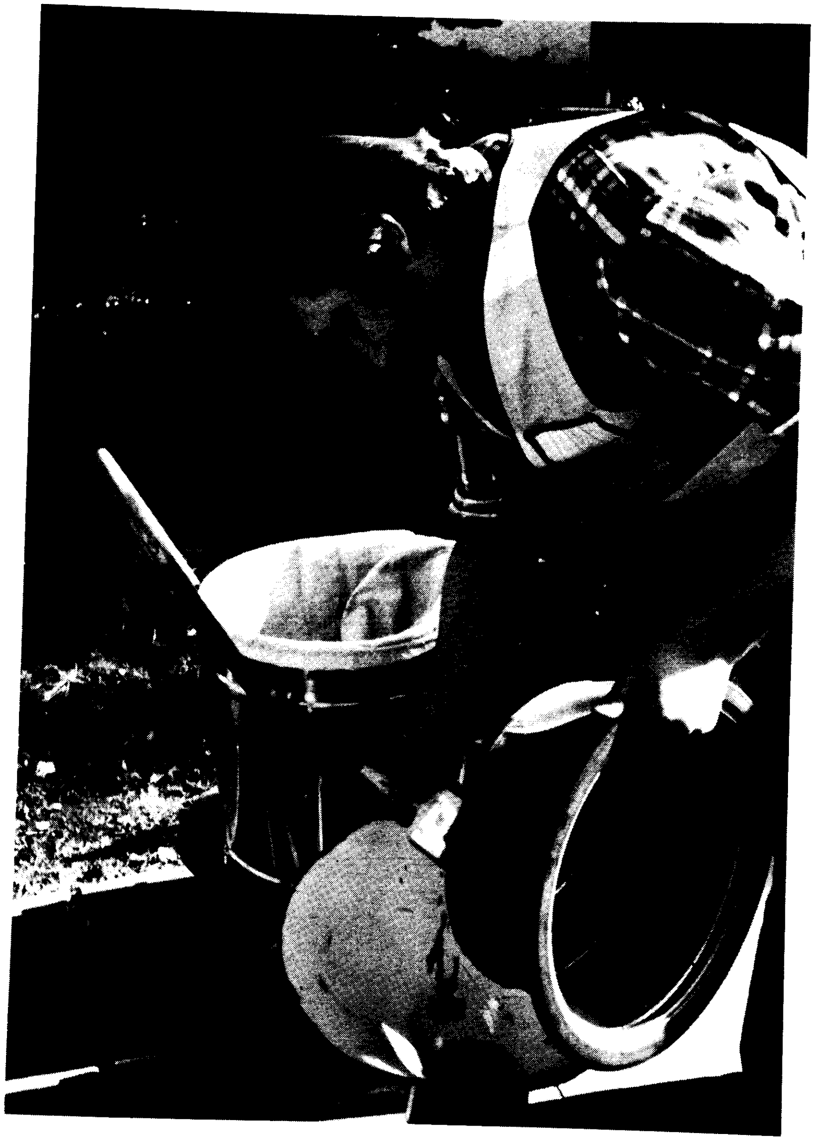

Figure A-5. Brushing some of the collected material from the secondary coarse filter.

Figure A-6. Shaking the primary dacron filter in the vacuum.

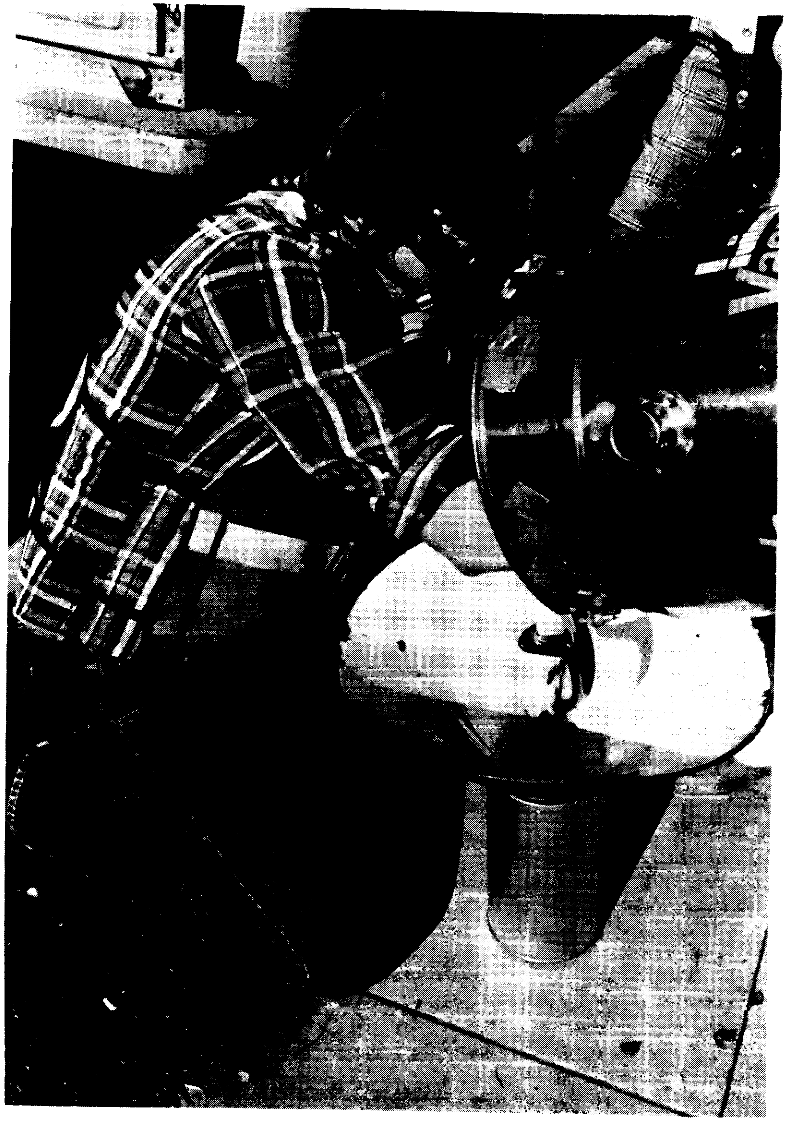

Figure A-7. Collected material transferred from vacuum units into a sample storage can.

where it was bent over the top of the vacuum was also carefully removed and placed into the sample can.

Figure A-7 shows how the material was transferred from the vacuum units into the sample can. After the filters were removed and cleaned, one person picked up the vacuum can and poured it into the large funnel on top of the sample can, while the other person carefully brushed the inside of the vacuum can with a soft 3- to 4-in. paint brush to remove the collected sample. In order to prevent excessive dust losses, the emptying and brushing was done in areas protected from the wind. To prevent inhaling the sample dust, both the sampler and the hose tender wore mouth and nose dust filters while removing the samples from the vacuums.

To reassemble the vacuum cans, the primary dacron filter bag was inserted into the top of the vacuum can with the filters's elastic edge bent over the top of the can. The secondary, coarse filter was placed into the can and assembled on the trailer. The motor heads were then carefully replaced on the vacuum cans, making sure that the filters were on correctly and the excessive electrical cord was wrapped around the handles of the vacuum units. The vacuum hoses and wand were attached so that the unit was ready for the next sample collection.

The storage cans were labled with the date, the test area's name, and an indication of whether the sample was taken before or after the street cleaning test or if it was an accumulation (or other type of) sample. Finally, the lids of the sample cans were taped shut and transported to the laboratory for logging-in and analysis or storage.

APPENDIX B

EXPERIMENTAL DESIGN

The samples were collected from narrow strips the width of the street from curb to curb, as described in Appendix A. The analytical procedure used to determine the number of subsamples needed involved weighing individual subsamples in the study area to calculate the standard deviation (σ) and the mean ($\bar{x}$) of the street surface loading values. From these two values, the number of subsamples necessary (N), depending on the allowable error (L), were determined. An allowable error value of about 25 percent, or less, was used. The formula used (after Cochran 1963) is

$$N = 4\sigma^2/L^2.$$

With 95 percent confidence, it calculates the number of sub-samples necessary to determine the true value for the loading within a range of $\pm$ L. Figure B-1 relates the ratio of the standard deviation to the mean for various allowable errors (as a percentage of the mean) to determine N.

As the $\sigma:\bar{x}$ ratio increases, more samples are required for a specific allowable error. Similarly, as the allowable error decreases for a specific $\sigma:\bar{x}$ ratio, more samples are required. Therefore, with an allowable error of 25 percent, the required number of subsamples for a study area with a $\sigma:\bar{x}$ ratio of 0.8 would be 36. For a test area with about 3 curb-miles, it then follows that a subsample would be taken about every 450 feet.

The total amount of street surface particulate sample removed during each test is insignificant when compared to the total street surface loadings in the whole test area. (In the above example, the sample would be 0.1 percent of the total street surface loadings for the area.)The number of sub-samples required was evaluated for each test area at the beginning of both sampling phases.

DETERMINING THE NUMBER OF SUBSAMPLES REQUIRED

Initially, individual samples were taken at 49 locations in the three study areas to determine the loading variability. Table B-1 presents the calculated loadings and the influential characteristic information for each sample. The loadings averaged about 2700 lb/curb-mile in the Downtown and Keyes Street areas, and were found to vary greatly within these two areas. The Tropicana area loadings were not as high, and averaged 310 lb/curb-mile.

The analytical procedure previously described was used to determine the required number of subsamples in each test area with an allowable error of 25

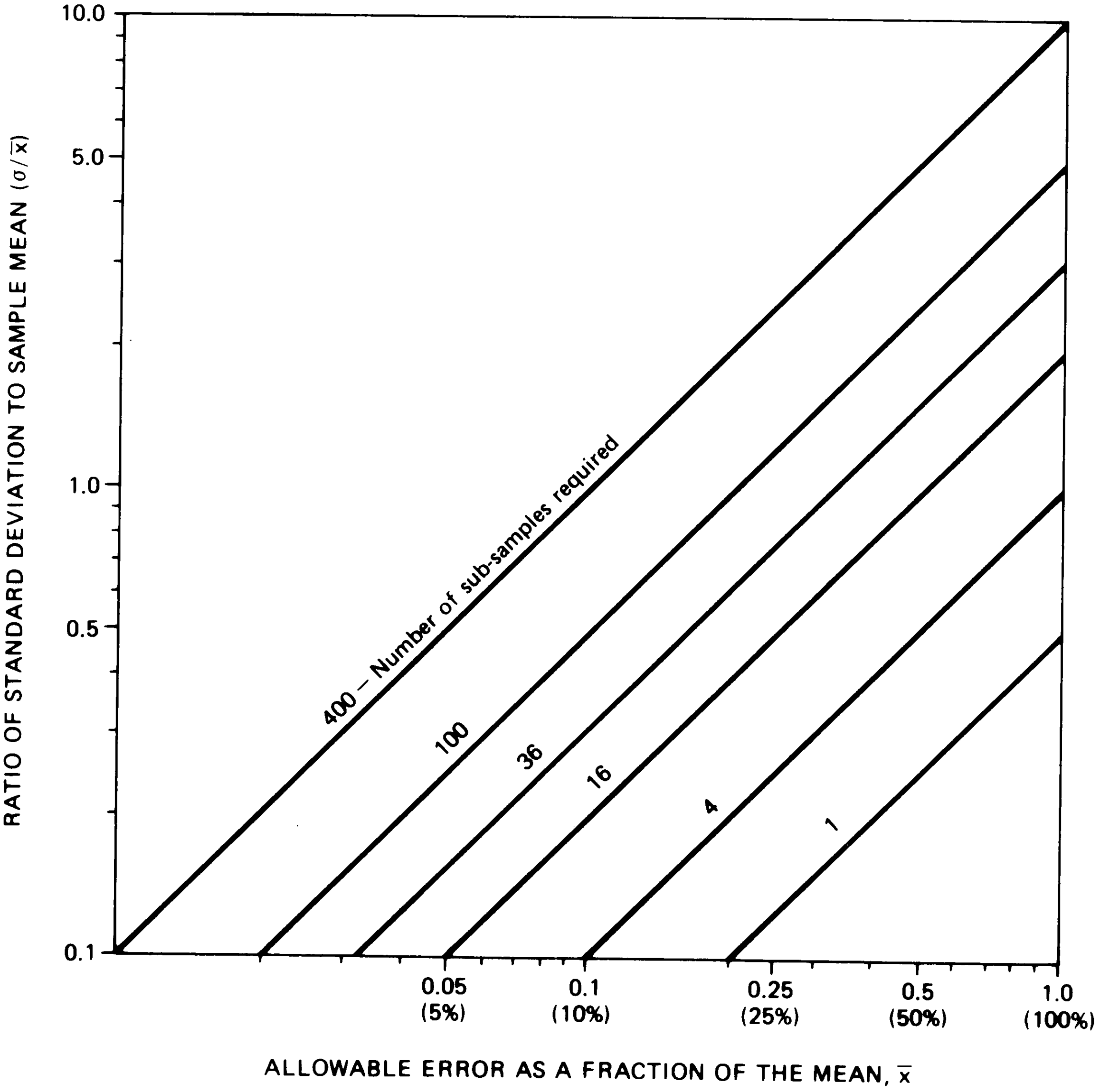

Figure B-1. Required number of sub-samples as a fuction of allowable error and standard deviation.

TABLE B-1. EXPERIMENTAL DESIGN SAMPLE INFORMATION(samples collected 11/29/76)

Study Area and Station Number	Location	Land Use[1]	Street Type[2]	Number of Curbs	Street Condition[3]	Traffic Density[4]	Street Width (ft.)	Dust/Dirt Particulate Loading (lb/curb-mile)
Downtown								
1	N. 1st @ Bassett	C	A	2	G	M/H	50	630
2	N. 1st @ Julian	C	A	2	G	M/H	50	47
3	N. 1st @ St. James	C	A	2	G	M/H	52	105
4	St. James between N. 1st & Market	C	A	2	G	M	40	220
5	Devine between N. 1st & Market	C	A	2	G	M/L	36	680
6	Julian between N. 1st & Market	C	A	2	G	M	40	262
7	Old Market	C	A	2	G	L	40	640
8	Market St. @ Devine	C	A	2	G	H	66	396
9	Market @ St. James	C	A	2	G	H	66	175
10[a]	Market @ Julian	I	A	0	P	L	29	3270
11[a]	Pleasant @ Bassett	I	A	0	P	L	40	20,000
12[a]	Bassett @ Pleasant	I	A	0	P	L	40	7600
13[a]	Bassett between Pleasant & Terraine	I	A	0	P	L	46	7400
14[a]	Bassett @ Terraine	I	A	0	P	L	48	5500
15	Bassett @ San Pedro	I	A	0	P	L	45	4025
16[a]	Terraine @ Bassett	I	A	0	P	L	60	9850
17	Terraine @ Julian	I	A	2	P	L	40	3050
18	San Pedro @ Bassett	I	A	2	P	L	45	3240
19	San Pedro @ Julian	I	A	2	P	L	45	2300
20[a]	Julian @ Pleasant	C/I	A	2	G	M	40	610
21[a]	Julian between Sta. Teresa and Terraine	C/I	A	2	G	M	40	303
22	Julian @ San Pedro	C/I	A	2	G	M	40	361
23	Devine between Sta. Teresa and Terraine	V	A	2	P	L	36	890
24	Devine between Market and N. 1st	I/V	A	2	G	L	38	580
25	St. James between Terraine & San Pedro	R/C	A	2	G	M	40	1740
26[a]	St. John between Pleasant & Santa Teresa	V	A	2	G	M	42	151
27[a]	St. John between Terraine & San Pedro	C	A	2	G	M	42	700
28	Pleasant between St. James & St. John	R	A	2	P	L	40	1570
29	Terraine @ Devine	V	A	2	P	L	40	995
Keyes								
1[a]	12th St. No. of Martha	R[b]	O&S	2	O&S	L	40	1733
2	12th @ Humboldt	R	O&S	2	O&S	L	40	3680
3	11th @ Keyes	R	A	2	G	H	50	582
4	10th @ Bestor	R	A	2	G	H	50	413
5	No. end of 9th St.	R	O&S	2	O&S	L	50	4380
6	9th @ Keyes	R	O&S	2	O&S	M	50	3760
7	9th @ Humboldt	R	O&S	2	O&S	L	50	6380
8	Martha @ 8th	R	A	2	G	L	40	262
9	Bestor @ 10th	R	O&S	2	O&S	L	40	2520
10[a]	Humboldt @ 8th	R	O&S	1	O&S	L	35	2860
Tropicana								
1	Cathay @ Naples	R[c]	A	2	G	L	36	220
2	Cathay @ Seaview	R	A	2	G	L	36	180
3	Palmview Way	R	A	2	G	L	36	145
4	Loyola Dr.	R	A	2	G	L	36	640
5	Darwin Way	R	A	2	G	L	36	174
6	Bal Harbor Way @ Everglade	R	A	2	G	L	36	407
7	Chiplay Dr.	R	A	2	G	L	36	424
8	Bermuda Way @ Ocala	R	A	2	G	L	36	366
9	Orlando @ Ocala	R	A	2	G	L	36	320
10	King Rd. @ Biscayne	R	A	2	G	H	60	233

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[1] Land uses:

C: commercial
I: industrial
V: vacant lots
R: residential

[2] Street types:

A: asphalt
O&S: oil and screens overlay

[3] Street condition:

G: good
P: poor
O&S: oil and screens

[4] Traffic density:

M: moderate
H: high
L: low

[a] Outside final study area.

[b] There is a substantial amount of commercial land use in this study area along Keyes.

[c] There is some commercial land use in this study area.

percent or less. This percentage was chosen to keep the precision and sampling effort at reasonable levels. The data were then examined to determine if the study areas should be divided into meaningful test area groups.

Table B-2 presents the results of grouping the data by influential parameters for each study area. It is interesting to note the similar groupings for much of the data: downtown streets in poor condition were generally in industrial areas, had low traffic, and had one or no curbs; the streets in good condition were generally in commercial areas, had moderate to high traffic, and had two curbs. The measured loading values within each of the different but related groupings were also similar. The purpose of the exercise was to identify a small number of meaningful test area groupings that required a reasonable number of subsamples and to increase the usefulness of the test data. Therefore, the Downtown study area was divided into two test areas: one with good asphalt street surface conditions and the other with poor asphalt street surface conditions. The Keyes Street study area was also divided into two test areas: good asphalt street surface and oil and screens street surface. The Tropicana study area was left undivided. There was reason to believe that the street cleaning equipment would perform significantly differently in each test area. This reasoning was based on the influencing external and uncontrollable operating conditions of street surface type, condition, and initial particulate loadings. Therefore the tests were started with five test areas, each with the number of subsamples and curb-mile lengths as listed below:

Downtown study area:

- good asphalt street surface (3.0 curb-miles) - 35 subsamples
- poor asphalt street surface (1.5 curb-miles) - 14 subsamples

Keyes Street study area:

- good asphalt street surface (2.7 curb-miles) - 36 subsamples
- oil and screens street surface (2.2 curb-miles) - 10 subsamples

Tropicana study area:

- good asphalt street surface (11.1 curb-miles) - 16 subsamples

In addition, buffer zones (Downtown: 5.1 curb-miles; Keyes: 2.7 curb-miles; and Tropicana: 7.0 curb-miles) were established around each study area to minimize tracking of particulates. A total of 20.5 curb-miles was included in all five test areas with about 15 curb-miles in the buffer zones. The downtown test areas were eliminated after the initial six weeks of testing because of an unauthorized plating discharge in the storm sewerage and excessive sampling requirements.

The second phase reevaluations resulted in slightly modifying the number of subsamples to be collected in each test area, but the physical test area divisions remained the same.

TABLE B-2. SAMPLING REQUIREMENTS FOR VARIOUS STUDY AREA GROUPINGS (Initial Test Phase)

Sample Group	Mean, $\bar{x}$, Loading (lb/curb-mile)	Number of Samples in Group	Standard Deviation, σ, of Loading (lb/curb-mile)	Standard Deviation to Mean Ratio, $\sigma/\bar{x}$	Approximate Number of Samples Needed for 25% Error
Downtown Study Area					
All samples	2700	29	4200	1.6	100
Good asphalt street surfaces*	470	13	440	0.9	35
Poor asphalt street surfaces*	2300	7	1200	0.5	16
Low traffic	4500	16	5000	1.1	80
Mod. traffic	540	8	520	1.0	60
High traffic	270	5	240	0.9	36
Commercial land use	390	10	260	0.7	30
Industrial land use	6600	10	5300	0.8	36
Other land uses	700	8	510	0.7	30
One or no curbs	8200	7	5600	0.7	30
Two curbs	890	22	920	1.0	60
Keyes St. Study Area					
All samples	2700	10	2000	0.7	30
Good asphalt streets, heavy traffic, good street conditions	750	4	670	0.9	36
Oil & screens streets, low traffic, poor street conditions	3900	6	1400	0.3	10
Tropicana Study Area					
All samples	310	10	150	0.5	16
All Study Areas Combined					
All samples	2200	49	3500	1.6	100

*Only those samples within the study area drainage are included.

APPENDIX C

SELECTION AND DESCRIPTION OF STUDY AREAS

Figure C-1 shows the San Francisco Bay Area and the general location of the Coyote Creek watershed. Figure C-2 is a more detailed map of the watershed and shows the locations of the study areas. All of the study areas are located within the urban area of San Jose, California. Figures C-3, C-4, and C-5 show detailed street maps of the three study areas and five test areas. Also shown are the buffer zones established around each study area. The buffer zones are cleaned at the same time and with the same number of passes as the test areas in order to prevent excessive tracking or blowing of street dirt into the test areas. Figures C-6 through C-10 are photographs of portions of the test areas.

In the process of selecting study areas, information on several potential study areas in the city of San Jose was collected. Eight areas that met many of the criteria necessary to conduct the field program were identified. These criteria included:

- Each study area must be at least 10 acres in size and have separated storm drainage and sanitary sewage systems.
- Each study area should have its own complete storm drain sewerage system.
- The surface drainage of each study area should closely coincide with the area drained by the stormwater sewerage system.
- The study areas should have little construction activity during the time of study and a minimum amount of vacant land area.
- The study sites should represent a cross-section of land uses and economic conditions in the city.
- The storm sewerage system must be well documented to show no cross connections between sanitary sewage and any upstream drainage areas, and should have no illegal discharges.
- The slope of the sewerage system should be small, with potential or known solids accumulation problems in the sewerage.
- The study sites should have a variety of traffic conditions, and should be located close to the City of San Jose Public Works Department main service yard.

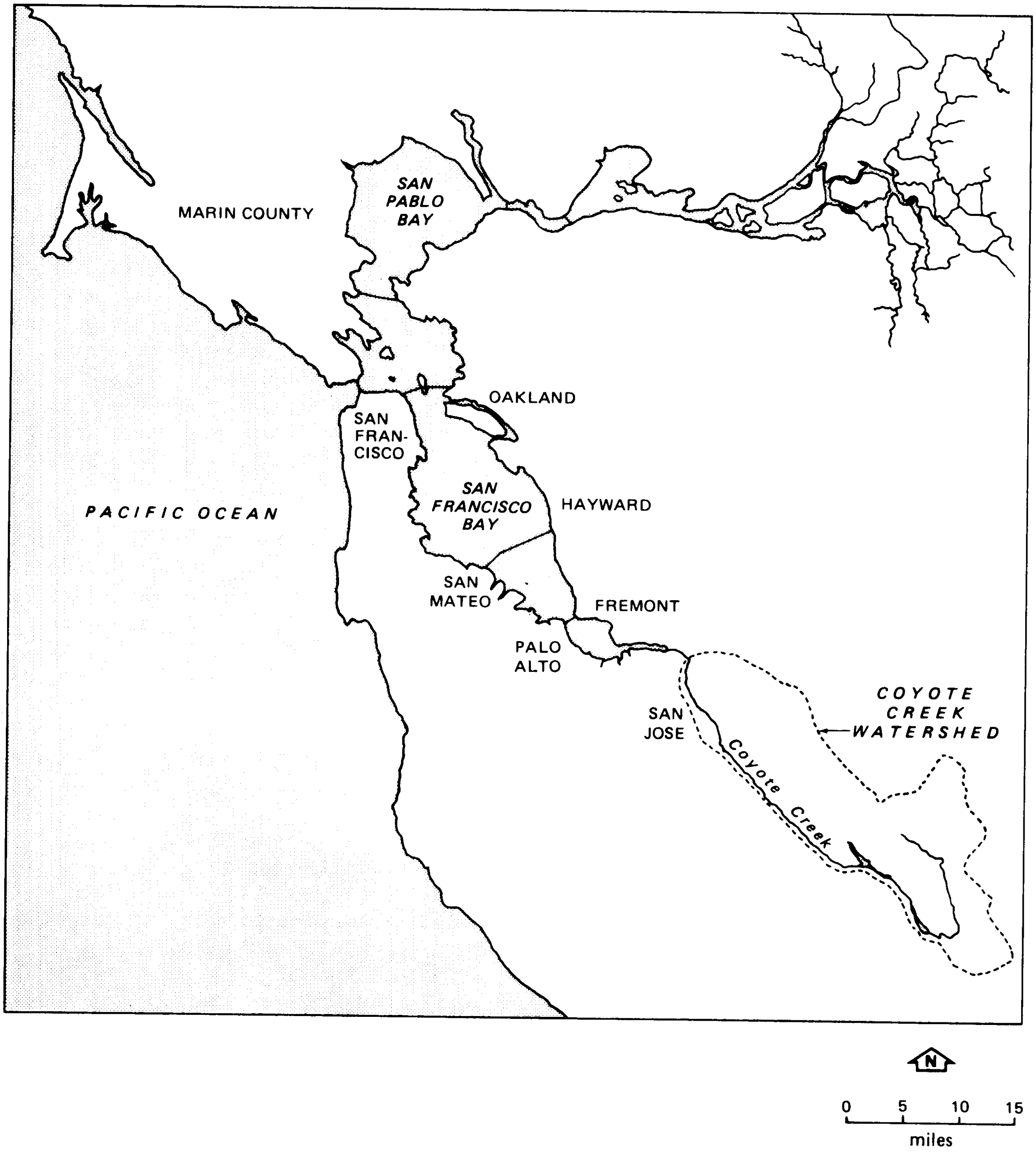

Figure C-1. San Francisco Bay Area showing the general location of the Coyote Creek watershed.

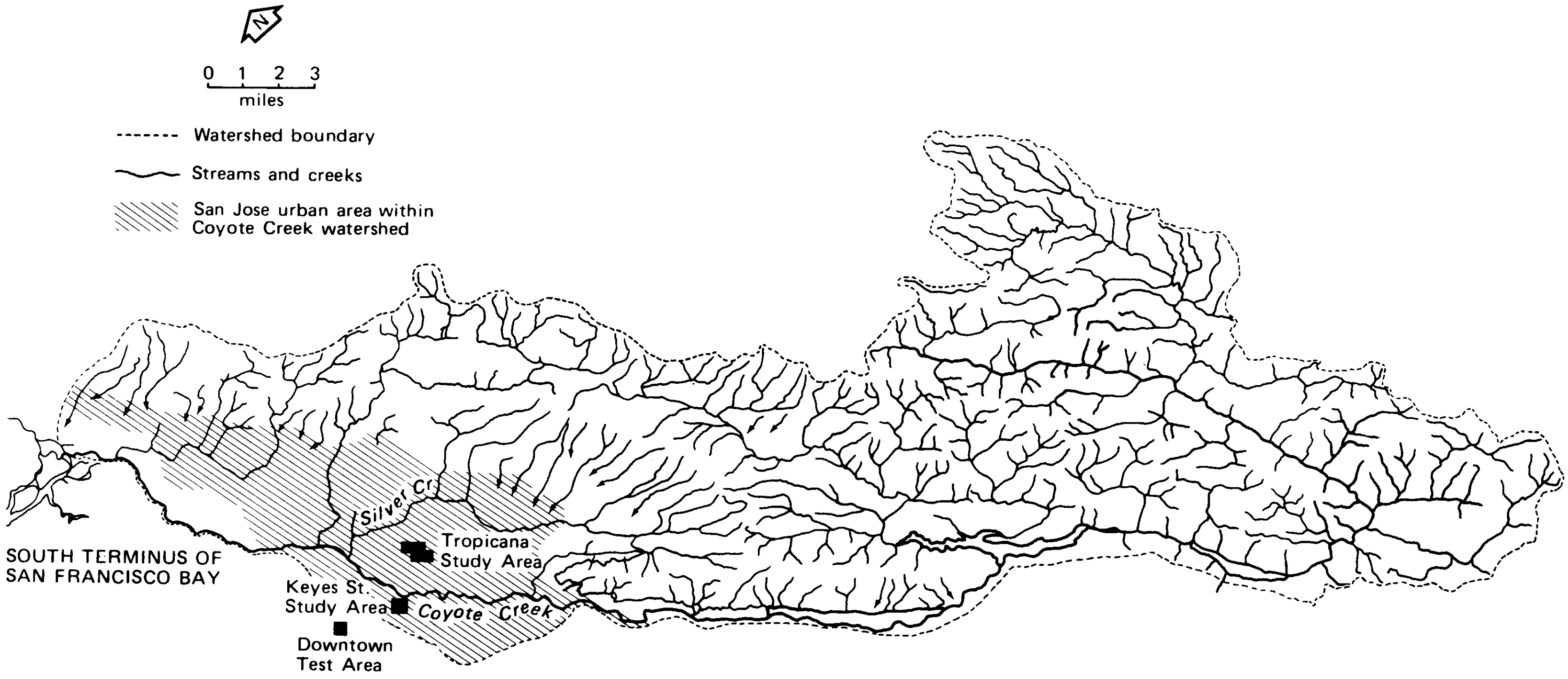

Figure C-2. Coyote Creek watershed and study areas.

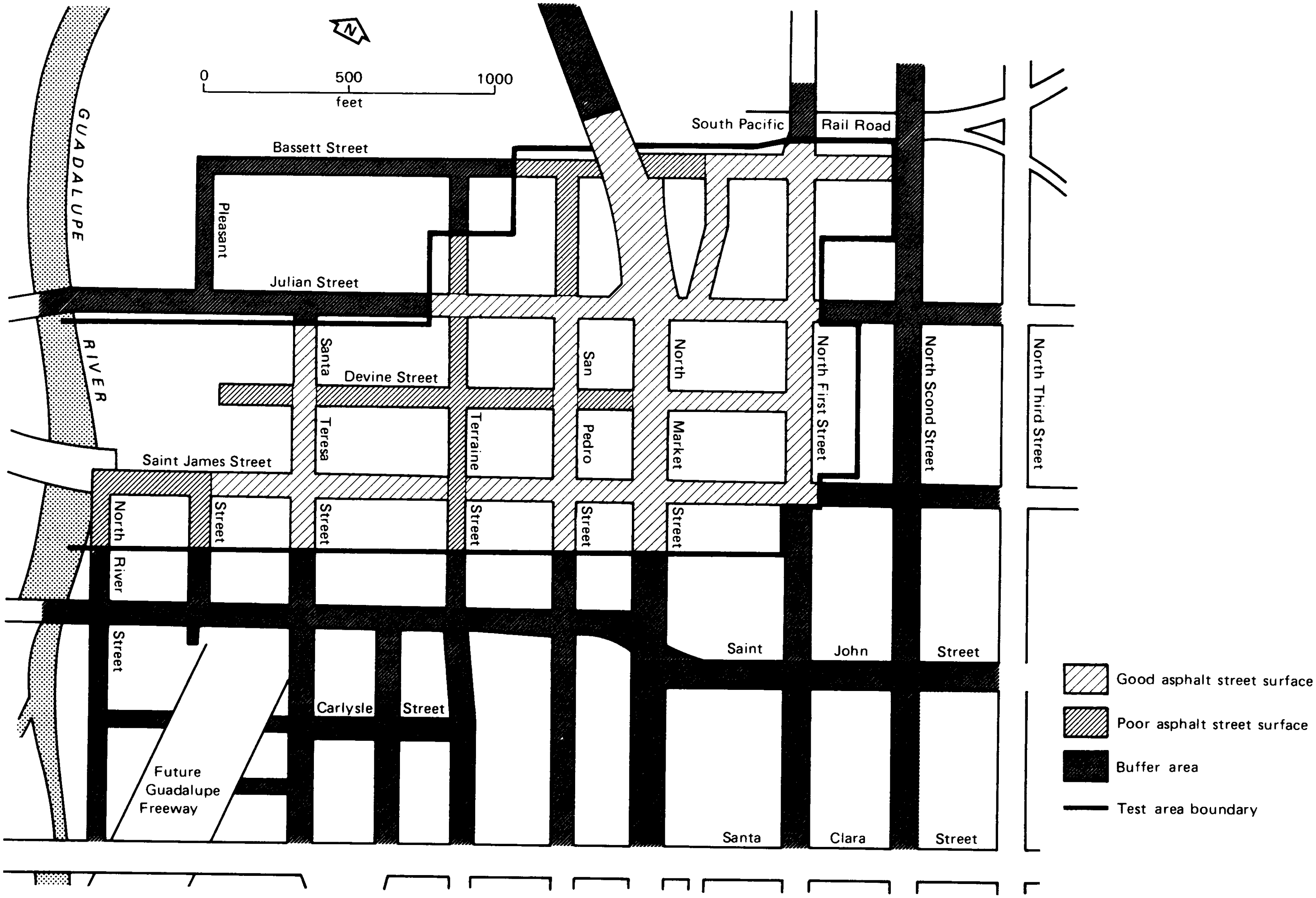

Figure C-3. Downtown buffer and test areas.

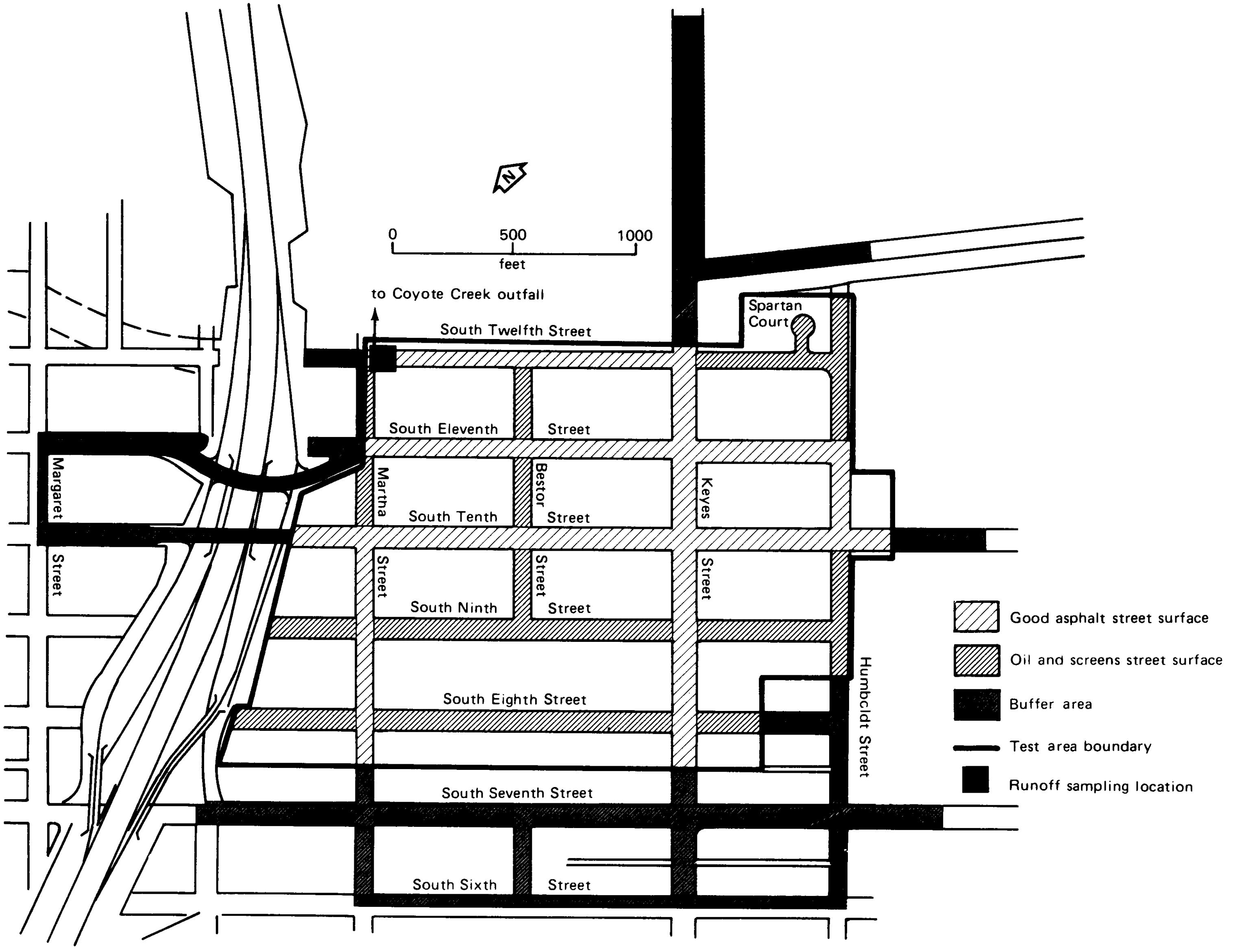

Figure C-4. Keyes street buffer and test areas.

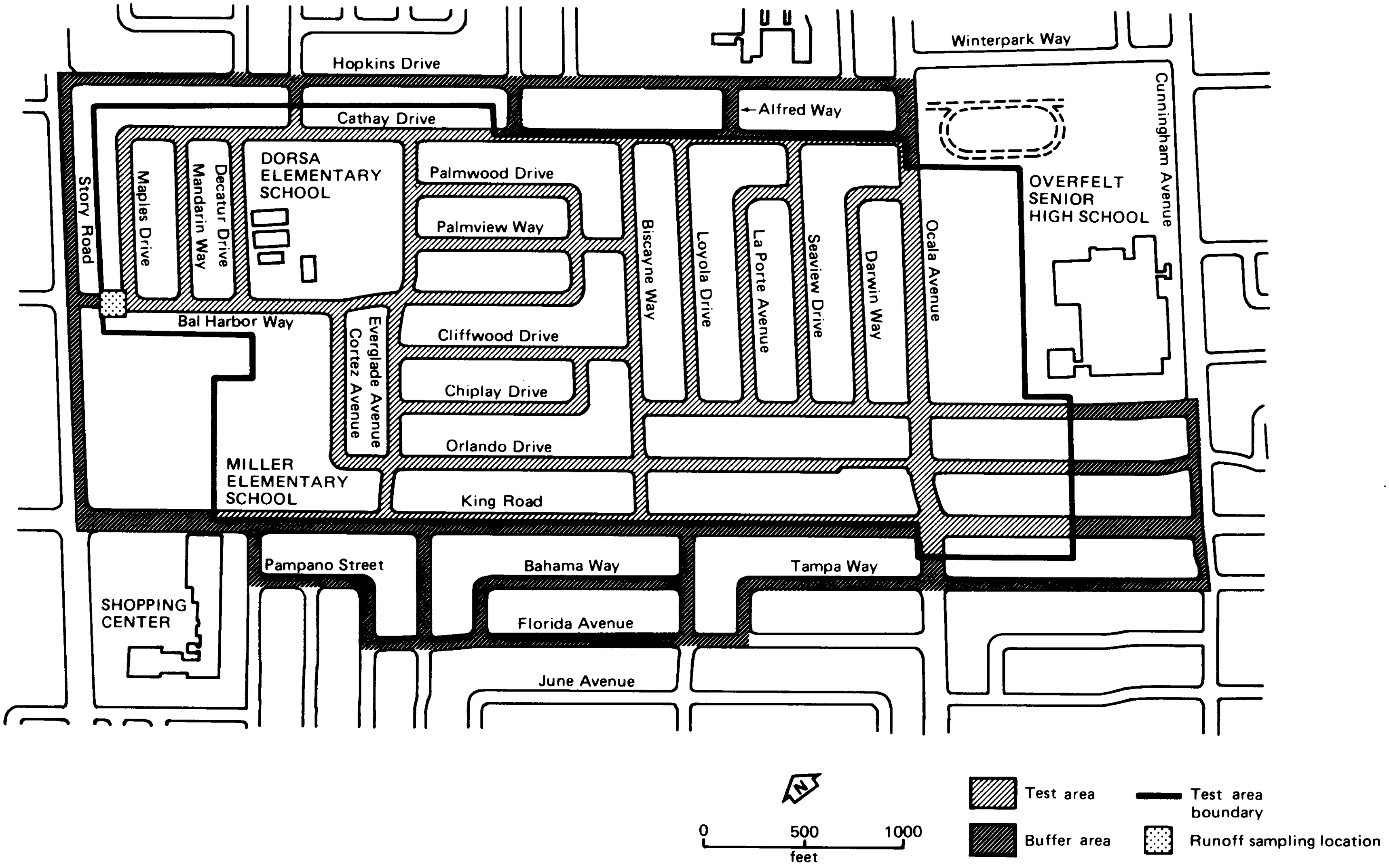

Figure C-5. Tropicana good asphalt buffer and test areas.

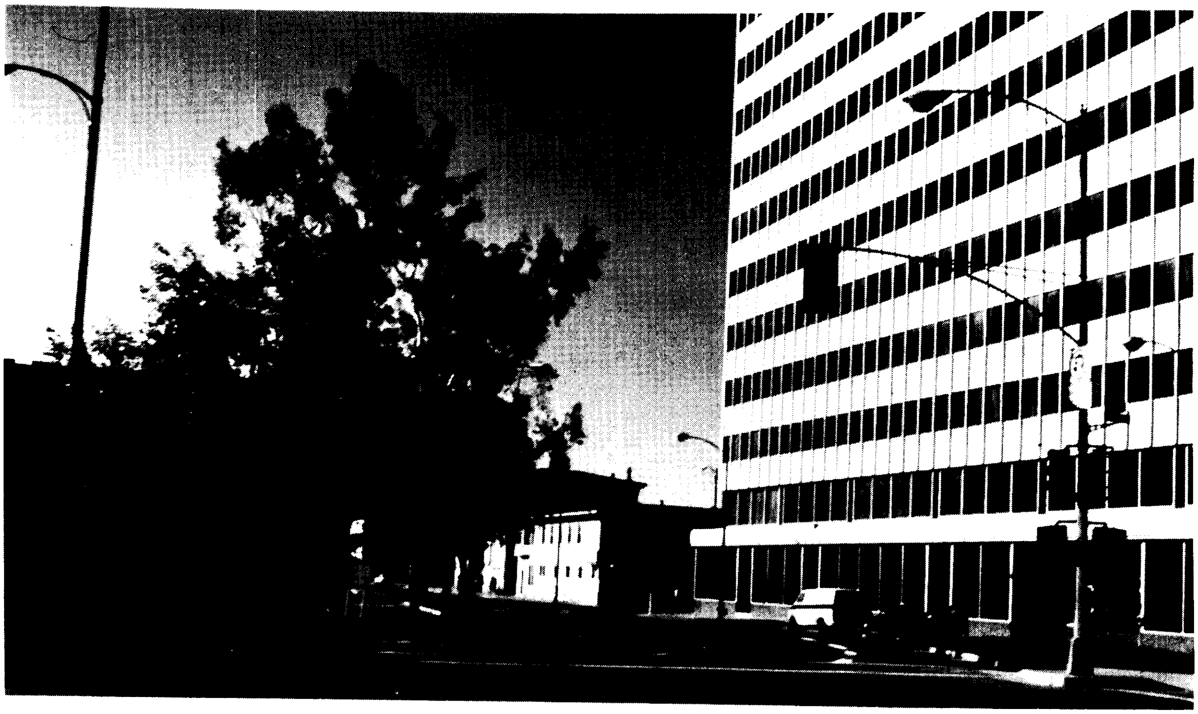

Figure C-6. Downtown - good asphalt test area.

Figure C-7. Downtown - poor asphalt test area.

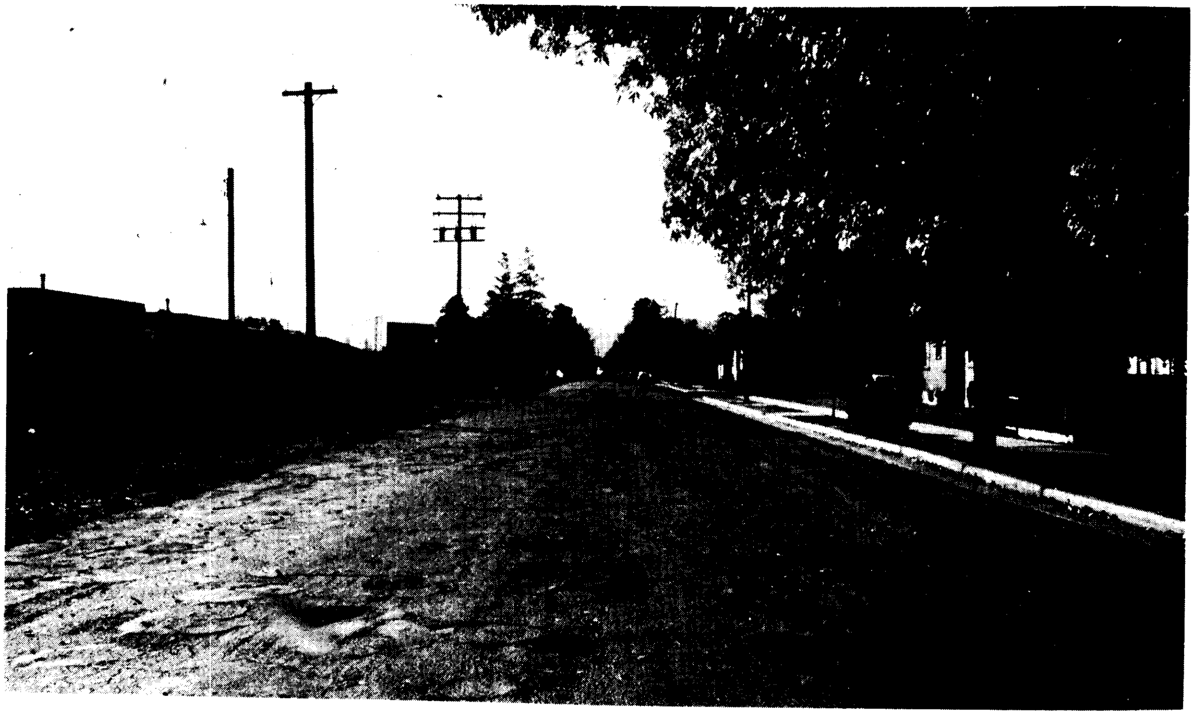

Figure C-8. Keyes - oil and screens test area.

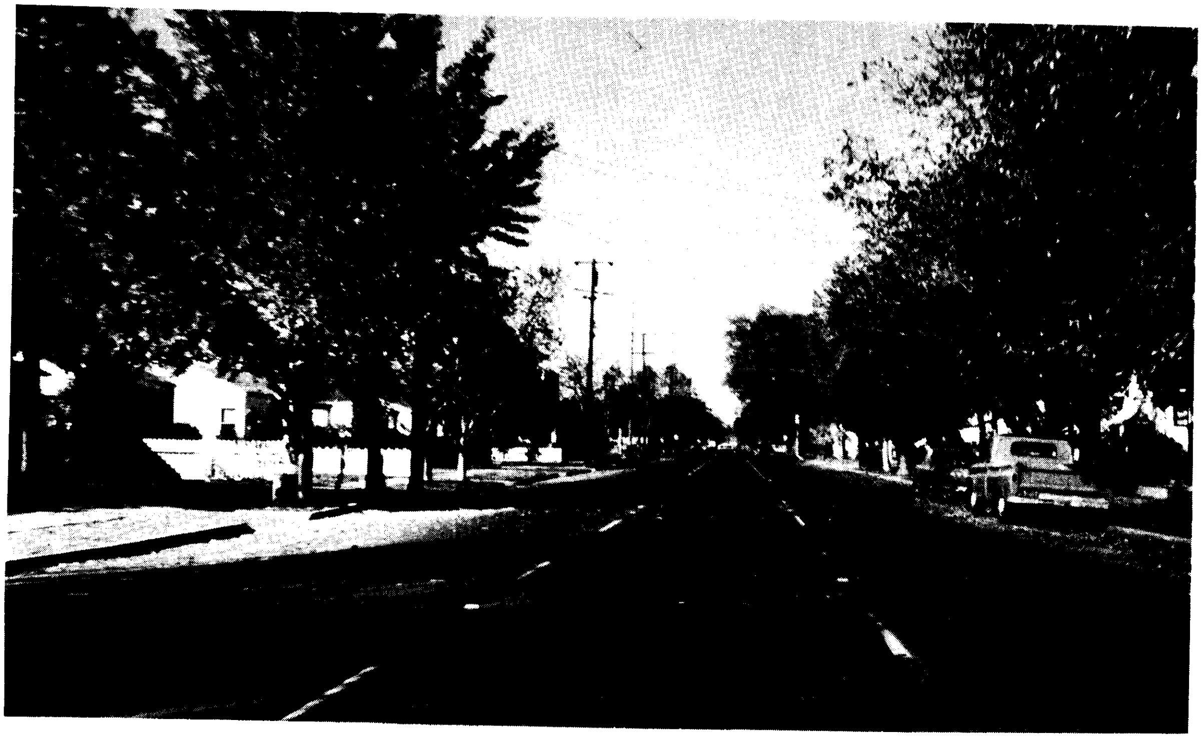

Figure C-9. Keyes - good asphalt test area.

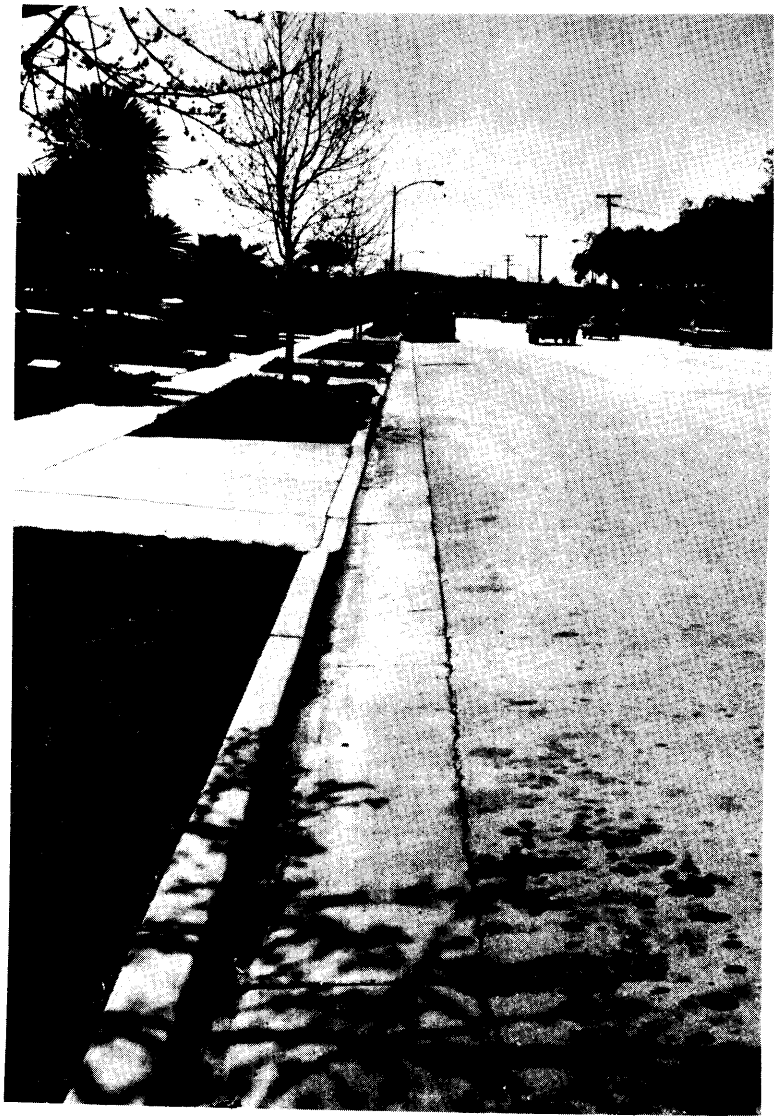

Figure C-10. Tropicana - good asphalt test area.

Table C-1 presents the information collected for the eight potential study areas; Figure C-11 shows their locations. The areas selected for initial study include the south Downtown area (site 2), the Keyes Street area (site 6), and the Tropicana area (site 8). These were chosen because they represent the variety of conditions found in San Jose and many other cities. As discussed in Appendix B, the Downtown and Keyes Street areas were found to be better represented by dividing each of them into two areas. Therefore, a total of five test areas was used in the initial field activities. Some data were collected from the five test areas, but most of the data are based on studies conducted in the two Keyes Street test areas and in the Tropicana test area. Other important study area characteristics that affect street cleaning operations include soil type (determines the erodability of adjacent land and the

TABLE C-1. INFORMATION ABOUT POTENTIAL STUDY AREAS*

	Potential Study Area Number							
	1	2	3	4	5	6	7	8
Area name	North Downtown Area	South Downtown Area	Julian St.	San Antonio St.	William St. Park	Keyes St.	Almaden Expwy.	Tropicana
Drainage area (acres)	110	100	31	51	85	92	69	195
Curb-miles	6.6	7.0	2.1	4.1	6.0	5.4	4.2	12.7
Number of inlets	36	25	7	11	16	17	24	55
Inlets/curb-mile	5.5	3.6	3.3	2.7	2.7	3.2	5.7	4.3
Inlets/acre	0.33	0.25	0.23	0.22	0.19	0.18	0.35	0.28
Acres/curb-mile	17	14	15	12	14	17	16	15
Land use	Commerical (business district), industrial (light), park	Commerical, industrial, older residential	Older residential, around 1920 construction	older residential, early 1900	Older residential, early 1900, park	Commercial and older residential, adjacent to school and fields	Residential 1950 →1960, park and elementary school, adjacent to orchard	Residential, low income, built 1960, some commercial, adjacent to 3 schools
Vacant lots in area	Many (redevelopment)	Many	None	None	None	Few	Adjacent	Few
Construction in area	Much (redevelopment)	Some	None	None	None	None	None	None
Traffic density	Heavy	Light→heavy	Light→heavy	Light→heavy	Light→moderate	Light→heavy	Light	Light→heavy
Major streets	1st St., Almaden Blvd., Santa Clara St., Market St.	1st St., Market St., Julian St.	Julian St., St. James St.	San Carlos St.	Williams St., 11th St.	Keyes, 10th & 11th Sts.	None	King Rd., Story Rd.
Outfall location	Santa Clara St., San Fernando St., Park Ave.	St. James St.	Julian St.	San Antonio St.	Williams St.	Martha St.	Between Redbird and Hummingbird Drs.	Manhole at Naples Dr. and Bal Harbor Way

(continued)

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*The pavement types and conditions were mixed asphalt and oil and screens that ranged from poor to good condition in most of the areas. See Appendix B, Table B-1 for street surface types and conditions for the selected study areas.

TABLE C-1. CONCLUDED

	Area Number							
	1	2	3	4	5	6	7	8
Receiving water	Guadalupe River	Guadalupe River	Coyote Creek	Coyote Creek	Coyote Creek	Coyote Creek	Canoas Creek	Silver Creek
Sewerage:								
Diam. (in.)	10 →33	8→33	10 →18	10 →21	10 →30	10 →27	10 →27	10 →36
Slope (%)	0.13→1.4	0.07→1.2	0.12 →0.8	0.13 →0.6	0.098 →1.5	0.17→0.9	0.2→1.0	0.11→0.85
Length (ft.)	10,550	6860	2300	3490	5580	6560	5050	8850
Parking regulations	Some (meters)	Some (meters)	None	None	None	None	None	None
Sewerage (ft./acre)	96	67	74	68	66	71	73	45
Street Cleaning frequency	Some daily, the rest every 5 weeks	Some daily, the rest every 5 weeks	Every 5 weeks	Every 5 weeks	Every 5 weeks	Every 5 weeks	Every 5 weeks	Every 5 weeks
Driving distance to corp. yard (mi.)	1-1/2	1	1-1/4	1-1/2	2	2-1/4	5	3-1/2
Curbside vegetation	Minor	Much (vacant lots)	Many trees	Many trees	Many trees	Some trees	Many trees	Some trees
Air quality sampling sites	None	In front of Superior Court Bldg. at Julian & Second St.	At cross streets with Julian St.	At cross streets with San Carlos St.	At cross streets with William St.	At Co. admin. bldg., Martha & 11th Sts.	None	Along King Rd.
Notes:	3 outfalls for this area; too much construction and too many vacant lots	Good overall site; land-use variety and AQ* sampling pt.	Leaf-fall problem during the fall	Leaf-fall problem during the fall	Great variety of residential (moderate → high); good area, but no good AQ* sampling area	Adjacent to Spartan Stadium and subject to heavy traffic and parking periodically; good area	Surrounded by orchards and fields on 1-1/2 sides; too far from corp. yard	Good area; good air sampling sites; moderate vegetation, few large trees, and minimal leaf removal problem

*Air quality.

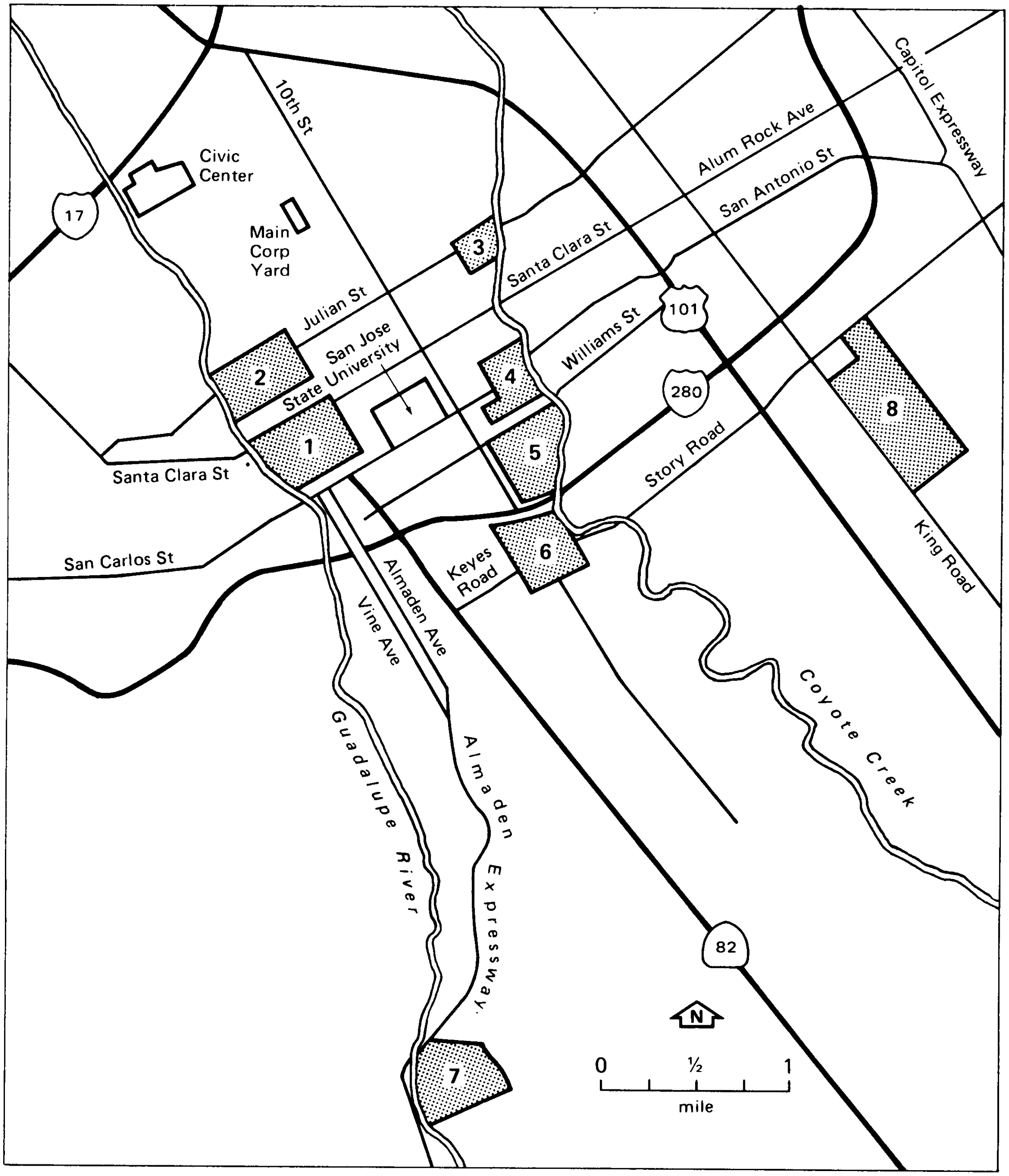

Figure C-11. Area map showing potential test site locations.

chemical make-up of erosion products that can wash onto the streets during major rains), topography, and gutter type. These characteristics were very similar for all of the study areas: the topography was flat, and most of the gutters were made of concrete with straight sides (very few rolled asphalt gutters were present). Table B-1 in Appendix B describes the gutter presence within the selected test areas.

Table C-2 shows the land use and surface area compositions for the three study areas selected. In the Downtown area, vacant spaces and rooftops make up most of the area, while landscaped areas are most predominant in the Keyes and and Tropicana Study areas. Street surfaces composed between 14 and 21 percent of the three areas. Buildings greater than three stories tall only existed in the Downtown area. The Downtown area was also significantly different in that only 1 percent of the total area consisted of lawns or otherwise planted. The Downtown area had few residential areas, but quite a bit of institutional areas and vacant lots. About 1/3 of the Downtown area was commercial. Most of the land use in the Keyes and Tropicana areas was residential.

Table C-3 presents the estimated annual average daily traffic conditions for the test areas. The weighted average for all street segments in each test area ranged from about 200 cars/day in the Keyes-oil and screens test area to about 10,000 cars/day in the Downtown-good asphalt test area. Those street segments having the most traffic also had the best street conditions.

TABLE C-2. STUDY AREA SURFACE AND LAND USE COMPOSITIONS (%)

	Downtown	Keyes	Tropicana
<u>Surface Area</u>			
Rooftops (<3 stories tall)	24	19	17
Rooftops (>3 stories tall)	2	0	0
Lawn/landscaped area	1	44	39
Vacant space	34	4	18
Sidewalks	4	5	4
Street	21	21	15
Parking lots	14	7	7
<u>Land Use</u>			
Commercial	33	11	0
Residential	2	86	83
Industrial	31	0	(some)
Other (institutional, vacant land, etc.)	34	3	17
<u>Total Acreage</u>	100 acres	92 acres	195 acres

TABLE C-3. ESTIMATED DAILY TRAFFIC VOLUMES IN TEST AREAS

	Weighted Average Daily Traffic*	Estimated Minimum Daily Traffic**	Estimated Maximum Daily Traffic***
Downtown-overall	7700	500	25,000
Downtown-good asphalt street surfaces	10,000	1500	25,000
Downtown-poor asphalt street surfaces	2800	500	7500
Keyes-overall	4600	50	26,000
Keyes-good asphalt streets	8300	200	26,000
Keyes-oil and screens surfaced streets	200	50	1000
Tropicana-good asphalt street surfaces	2200	100	18,000

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*Estimated based on some field measurements. Weighted by representative street segment lengths.

**Minimum estimated daily traffic for any one street segment in test area.

***Maximum estimated daily traffic for any one street segment in test area.

APPENDIX D

RAINFALL AND ACCUMULATION RATE HISTORY

Figures D-1 through D-5 present the rainfall history in the study areas as a function of time. These figures include a bar graph on each day that rainfall occurred (>0.01 in.) along with values for the total rain, the hours of rain, and the rainfall intensities.

Figures D-6 through D-22 present total street surface particulate loading and median particle sizes as a function of time. The dates with significant rains are also shown with a solid vertical line and the dates of street cleaning are designated with a code showing the type of street cleaning equipment used and the number of passes made that day. The values of total particulate loading and particle size for each day of sampling are connected by straight lines. Solid lines signify a positive slope (an increase in median particle size or an increase in total solids loading). Dashed and dotted lines show a decrease in median particle size or total solids loading.

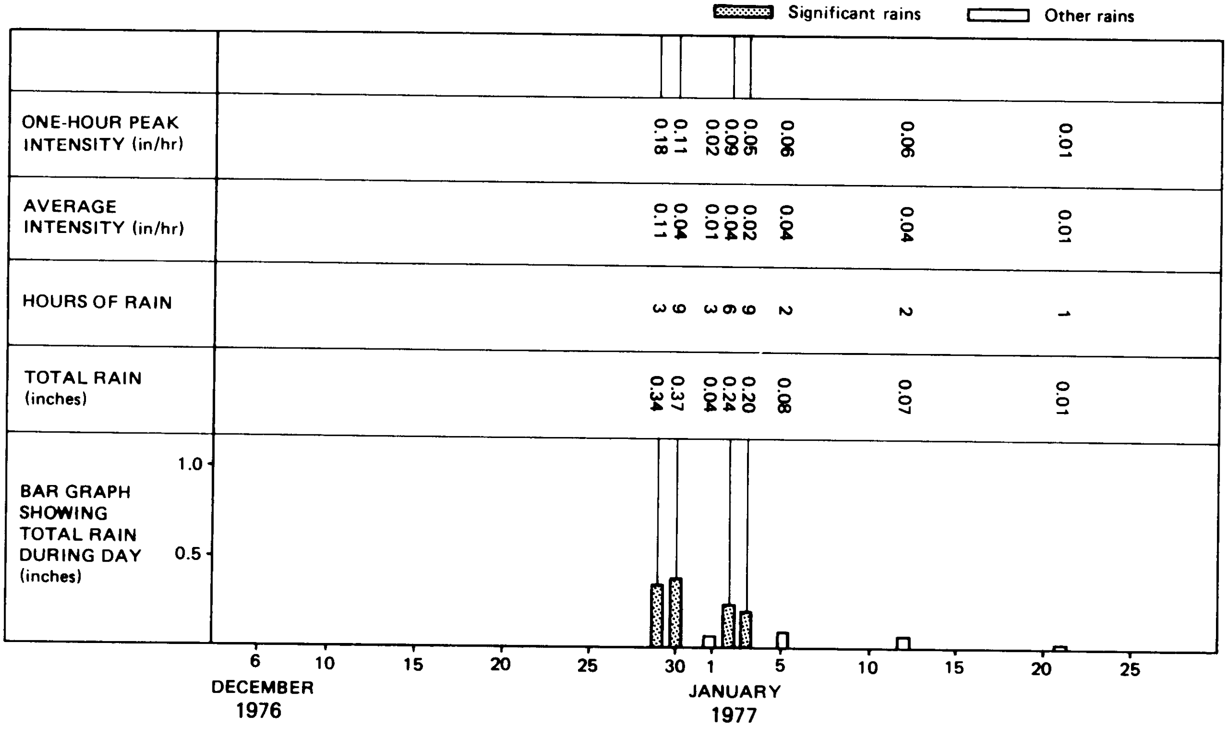


Figure D-1. Rainfall history.

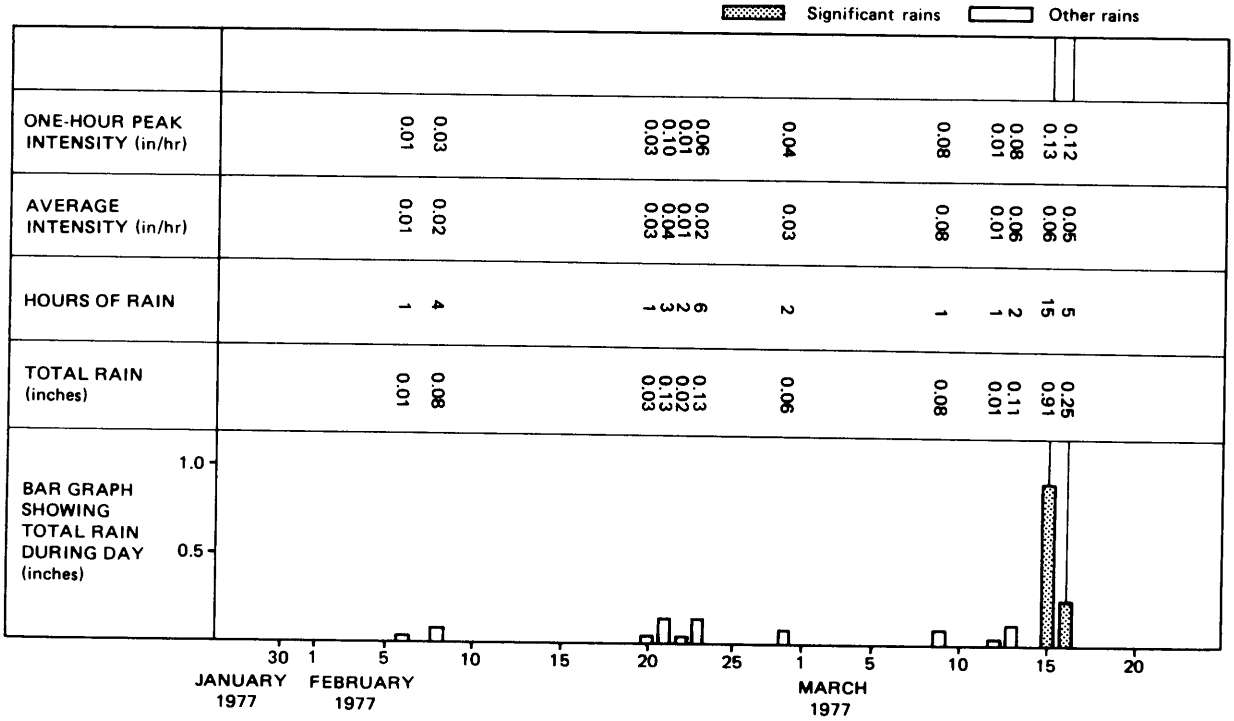
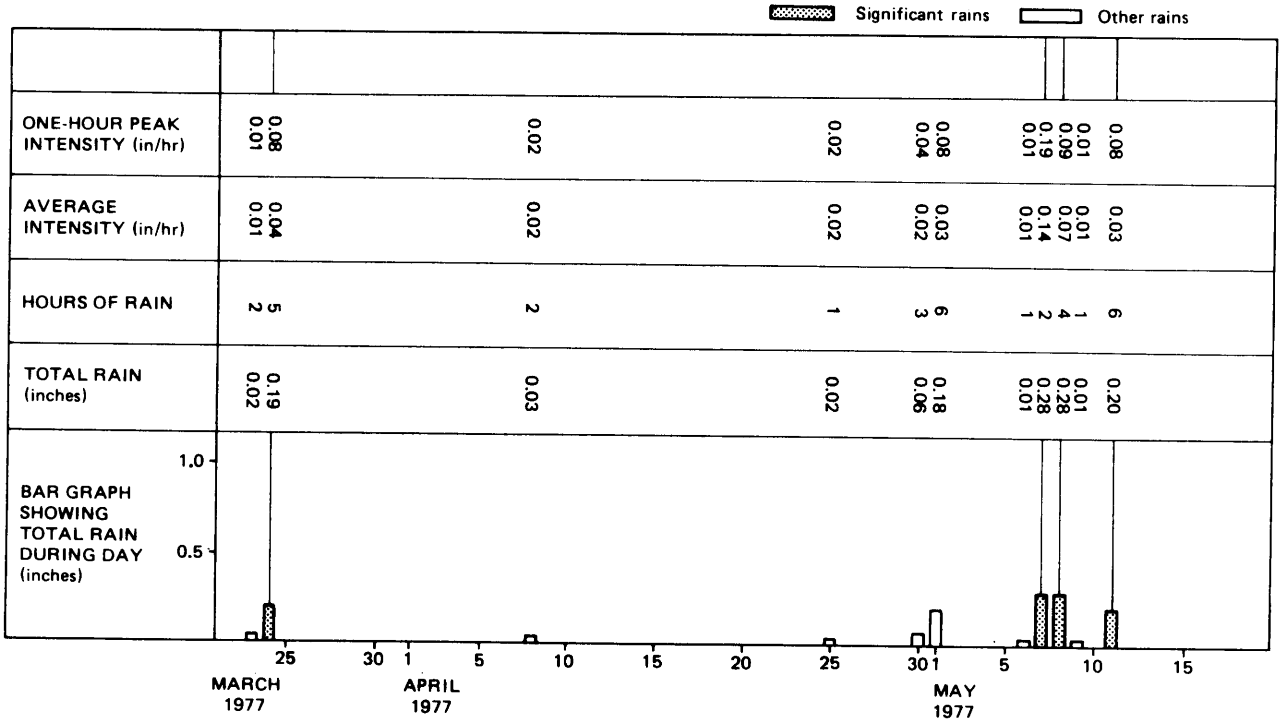
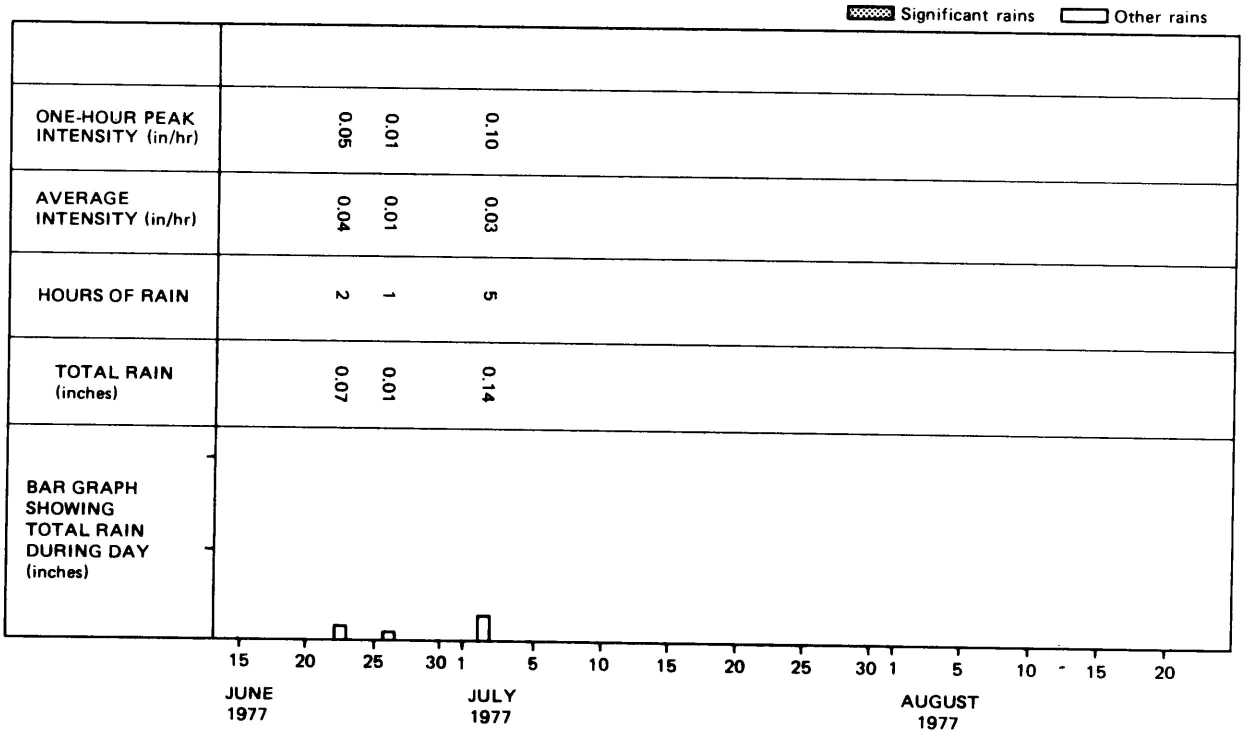


Figure D-2. Rainfall history (continued).



ONE-HOUR PEAK INTENSITY (in/hr)	0.01	0.08	0.02	0.02	0.04	0.08	0.01	0.19	0.09	0.01	0.08
AVERAGE INTENSITY (in/hr)	0.01	0.04	0.02	0.02	0.02	0.03	0.01	0.14	0.07	0.01	0.03
HOURS OF RAIN	2	5	2	1	3	6	1	2	4	1	6
TOTAL RAIN (inches)	0.02	0.19	0.03	0.02	0.06	0.18	0.01	0.28	0.28	0.01	0.20

Figure D-3. Rainfall history (continued).



ONE-HOUR PEAK INTENSITY (in/hr)	0.05	0.01	0.10
AVERAGE INTENSITY (in/hr)	0.04	0.01	0.03
HOURS OF RAIN	2	1	5
TOTAL RAIN (inches)	0.07	0.01	0.14

Figure D-4. Rainfall history (continued).

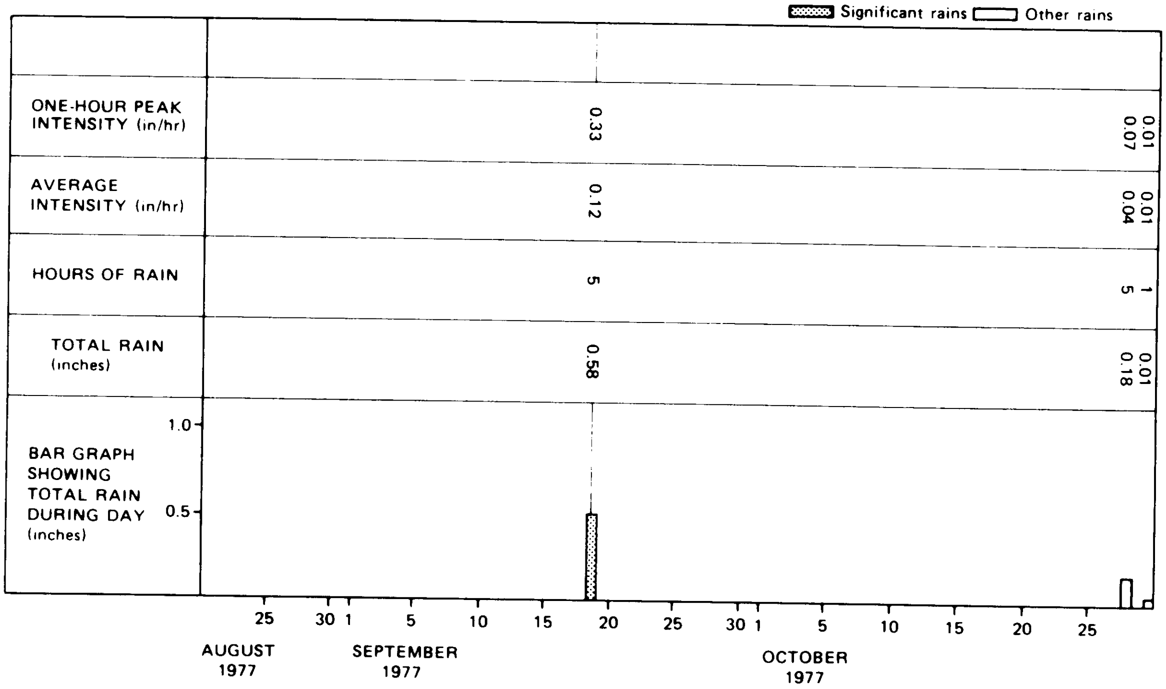


Figure D-5. Rainfall history (concluded).

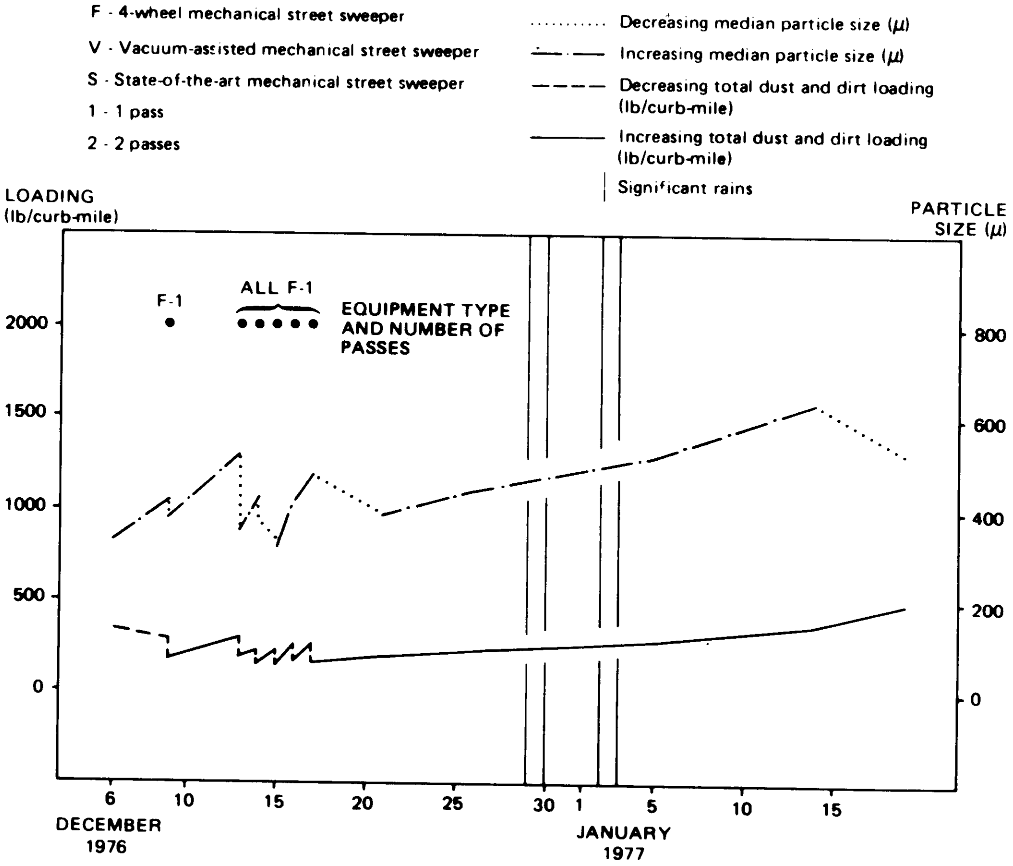


Figure D-6. Total particulate loading and median particle size as a function of time - Downtown - good asphalt test area.

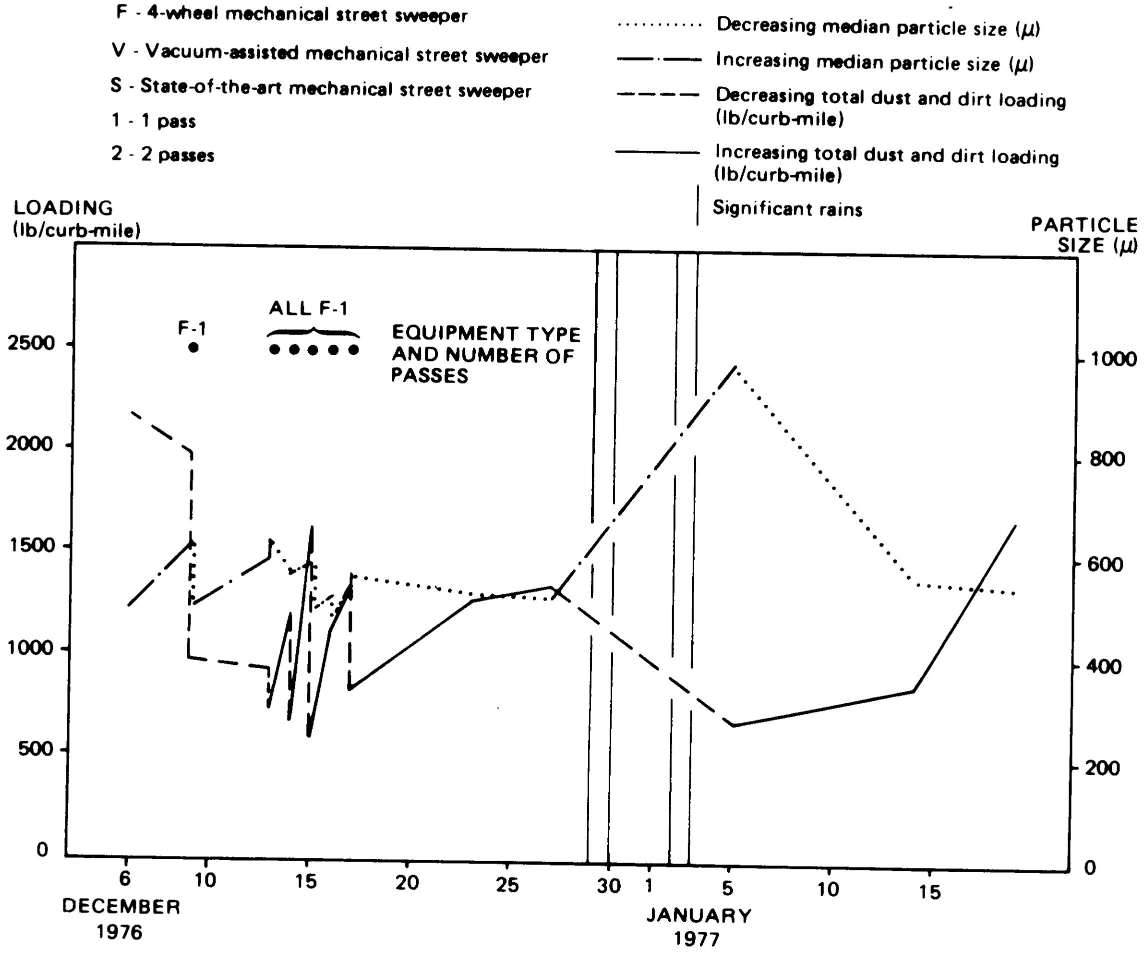


Figure D-7. Total particulate loading and median particle size as a function of time - Downtown - poor asphalt test area.

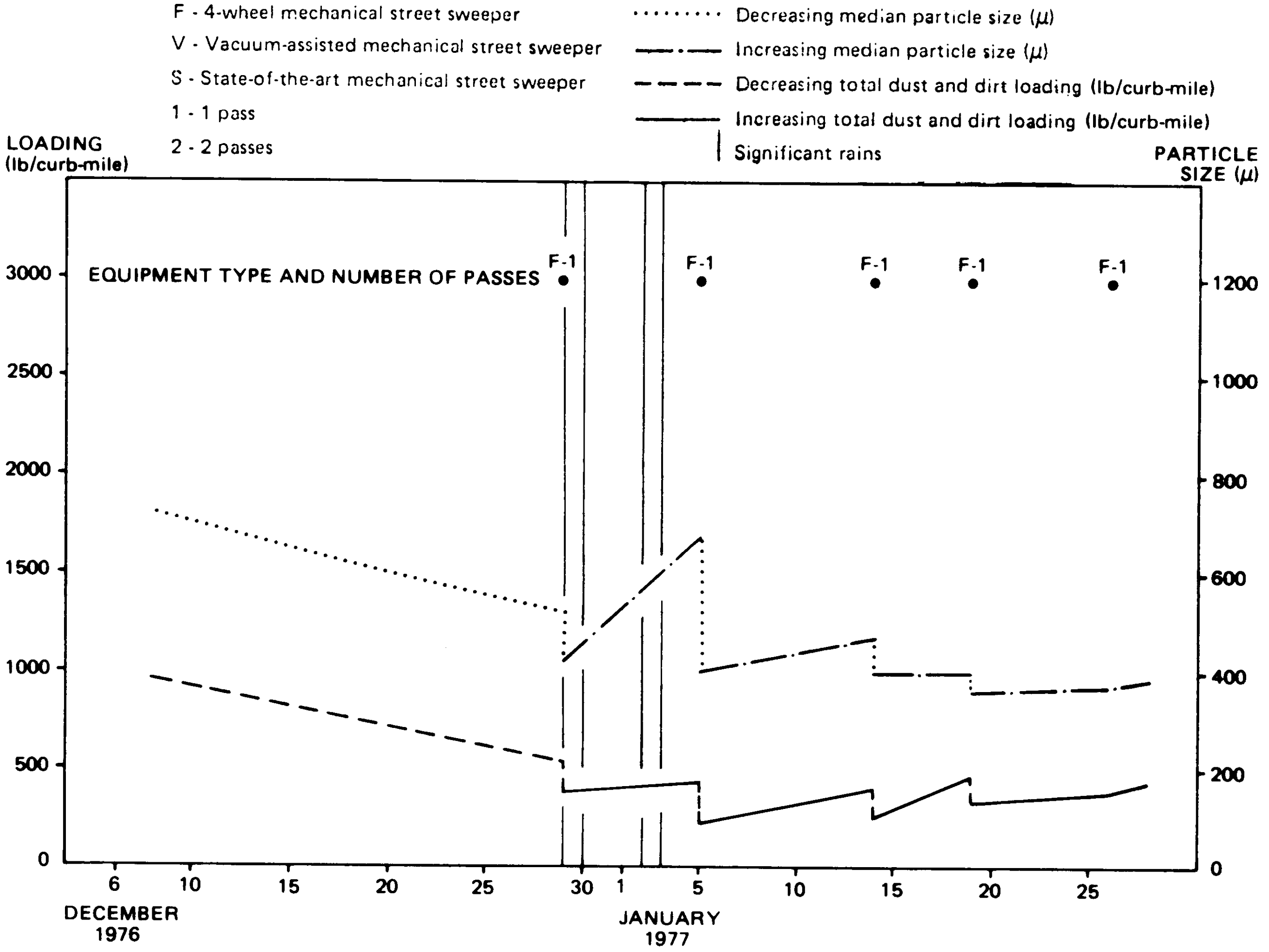


Figure D-8. Total particulate loading and median particle size as a function of time - Keyes - good asphalt test area.

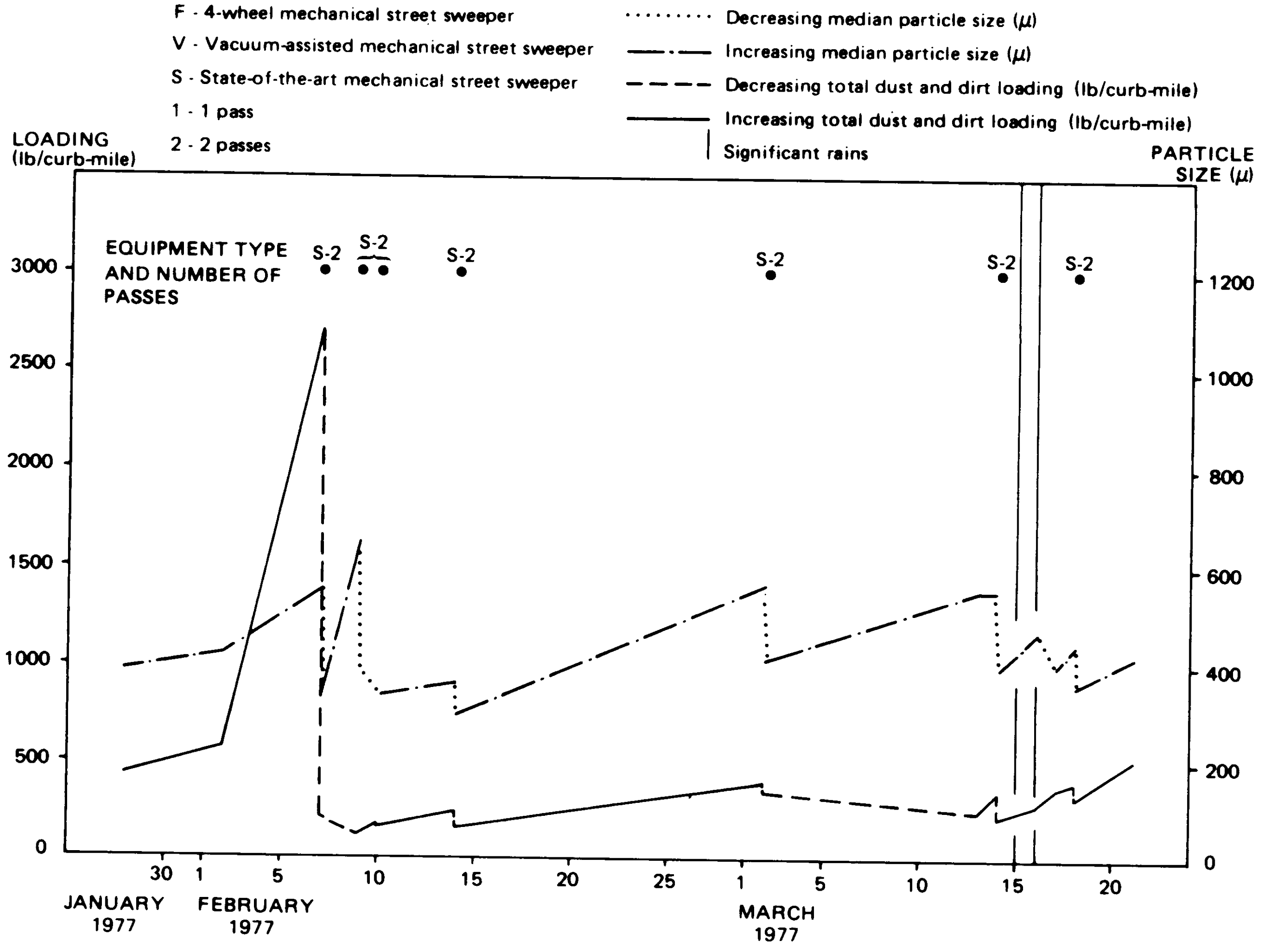


Figure D-9. Total particulate loading and median particle size as a function of time - Keyes - good asphalt test area (continued).

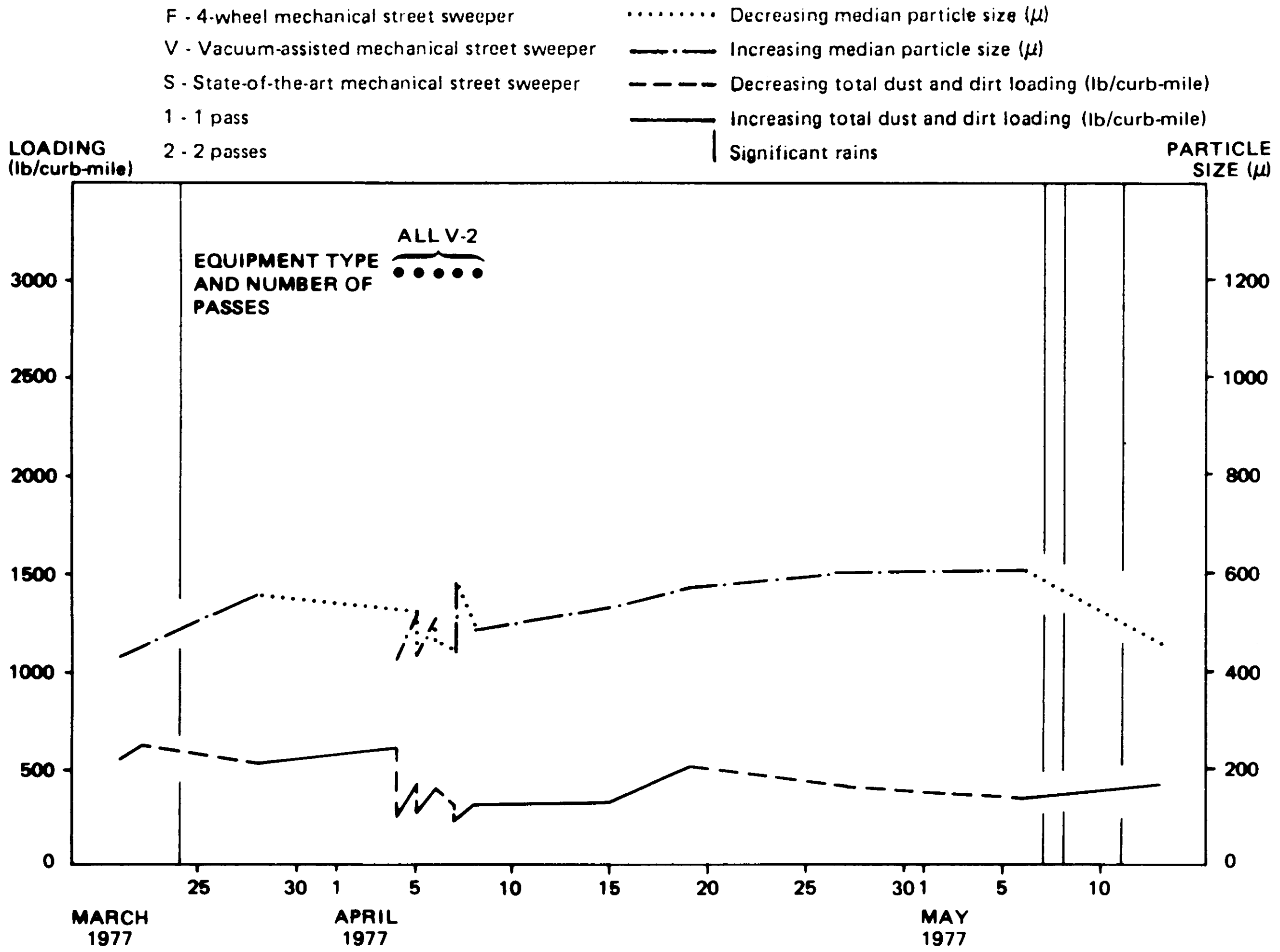


Figure D-10. Total particulate loading and median particle size as a function of time - Keyes - good asphalt test area (continued).

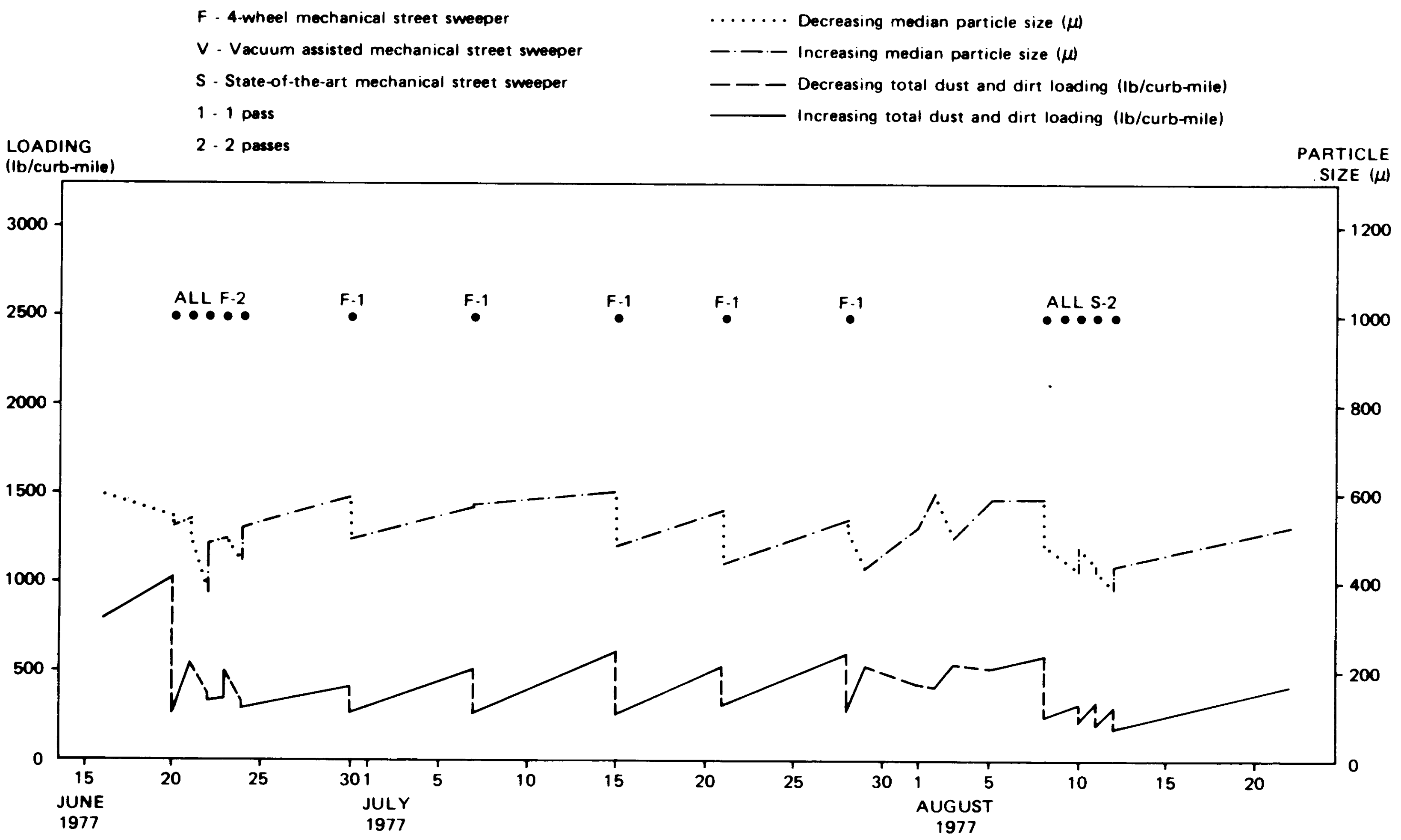


Figure D-11. Total particulate loading and median particle size as a function to time - Keyes - good asphalt test area (continued).

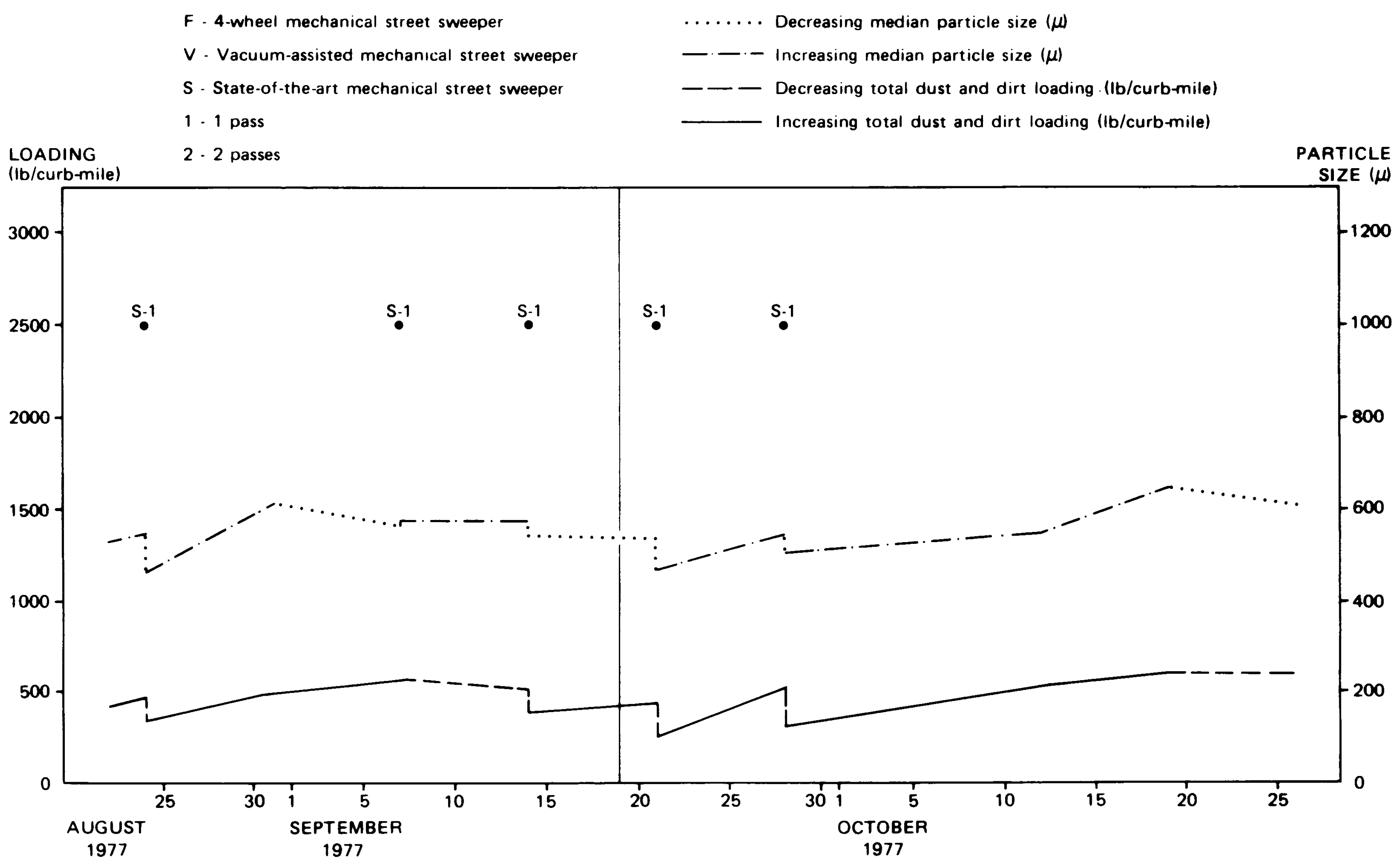


Figure D-12. Total particulate loading and median particle size as a function of time - Keyes - good asphalt test area (concluded).

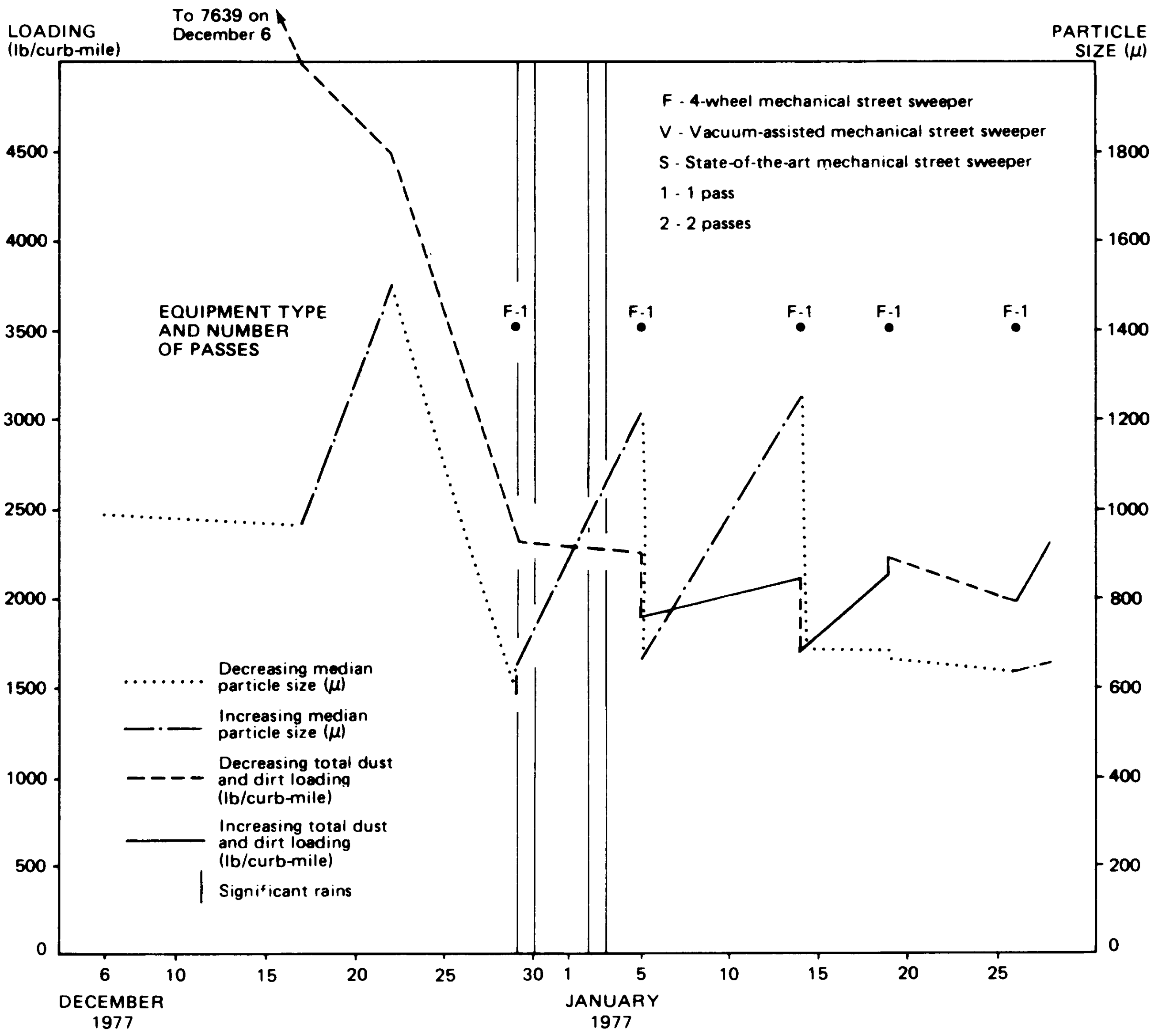


Figure D.13. Total particulate loading and median particle size as a function of time - Keyes - oil and screens test area.

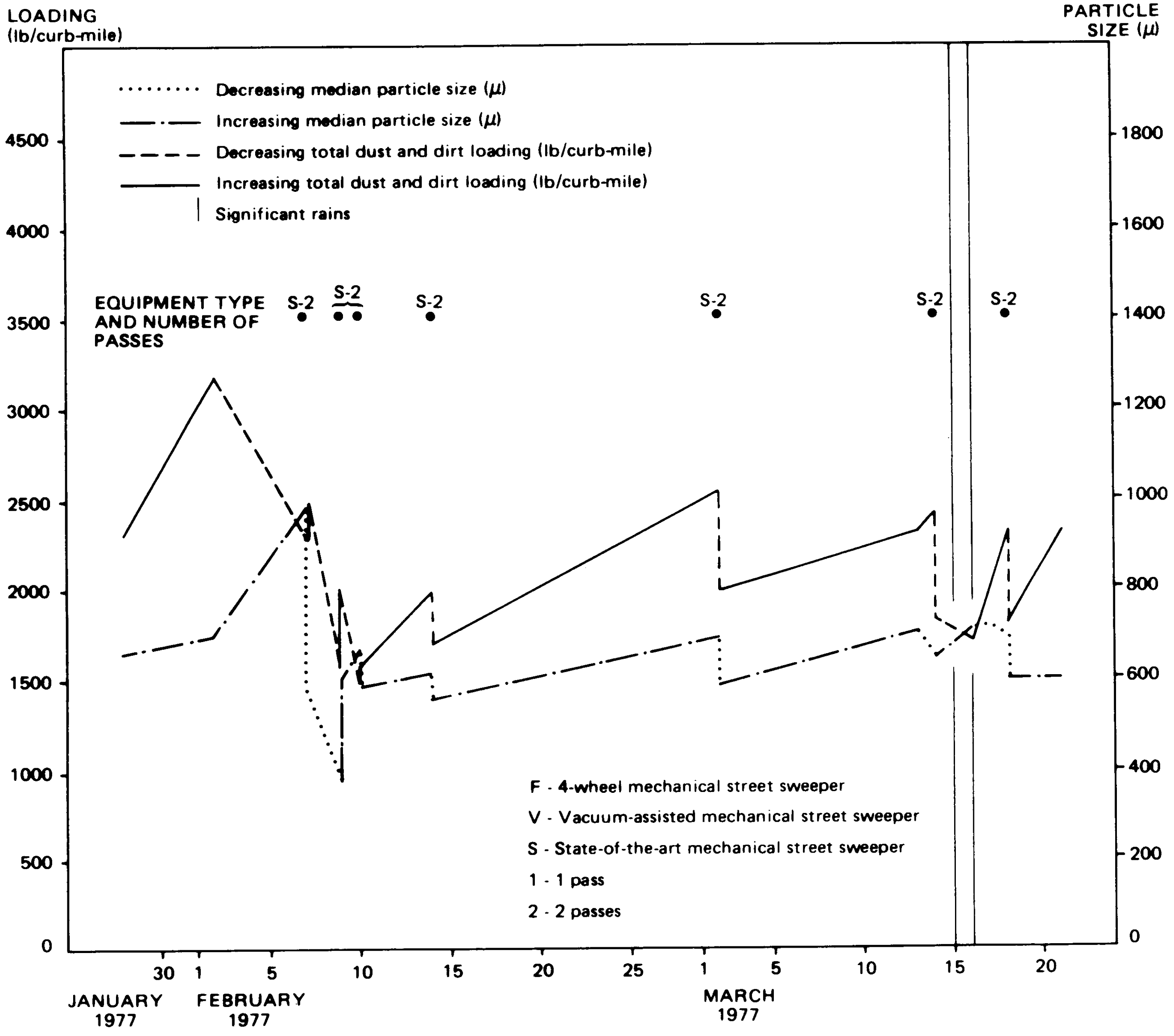


Figure D-14. Total particulate loading and median particle size as a function of time - Keyes - oil and screens test area (continued).

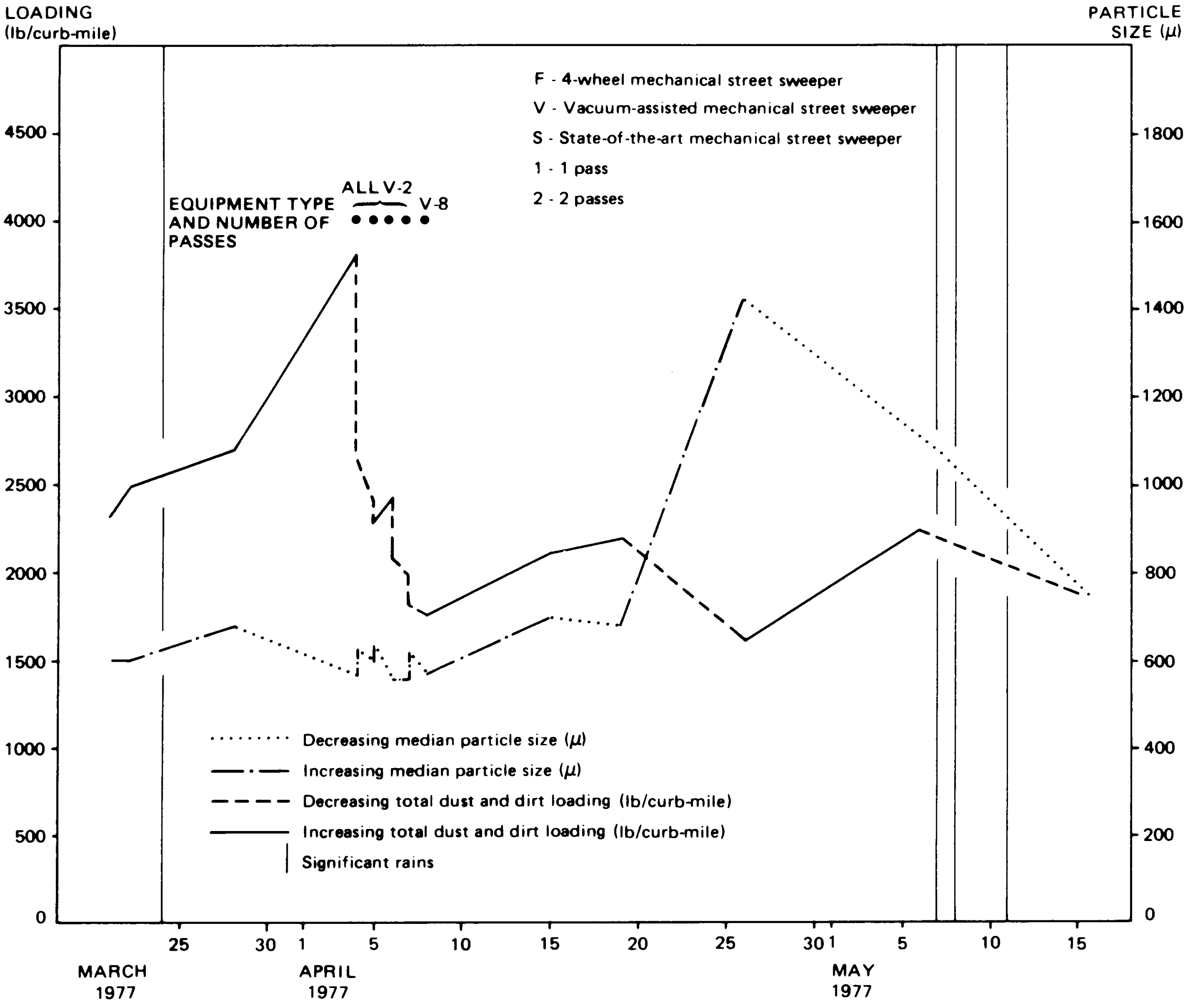


Figure D-15. Total particulate loading and median particle size as a function of time - Keyes - oil and screens test area (continued).

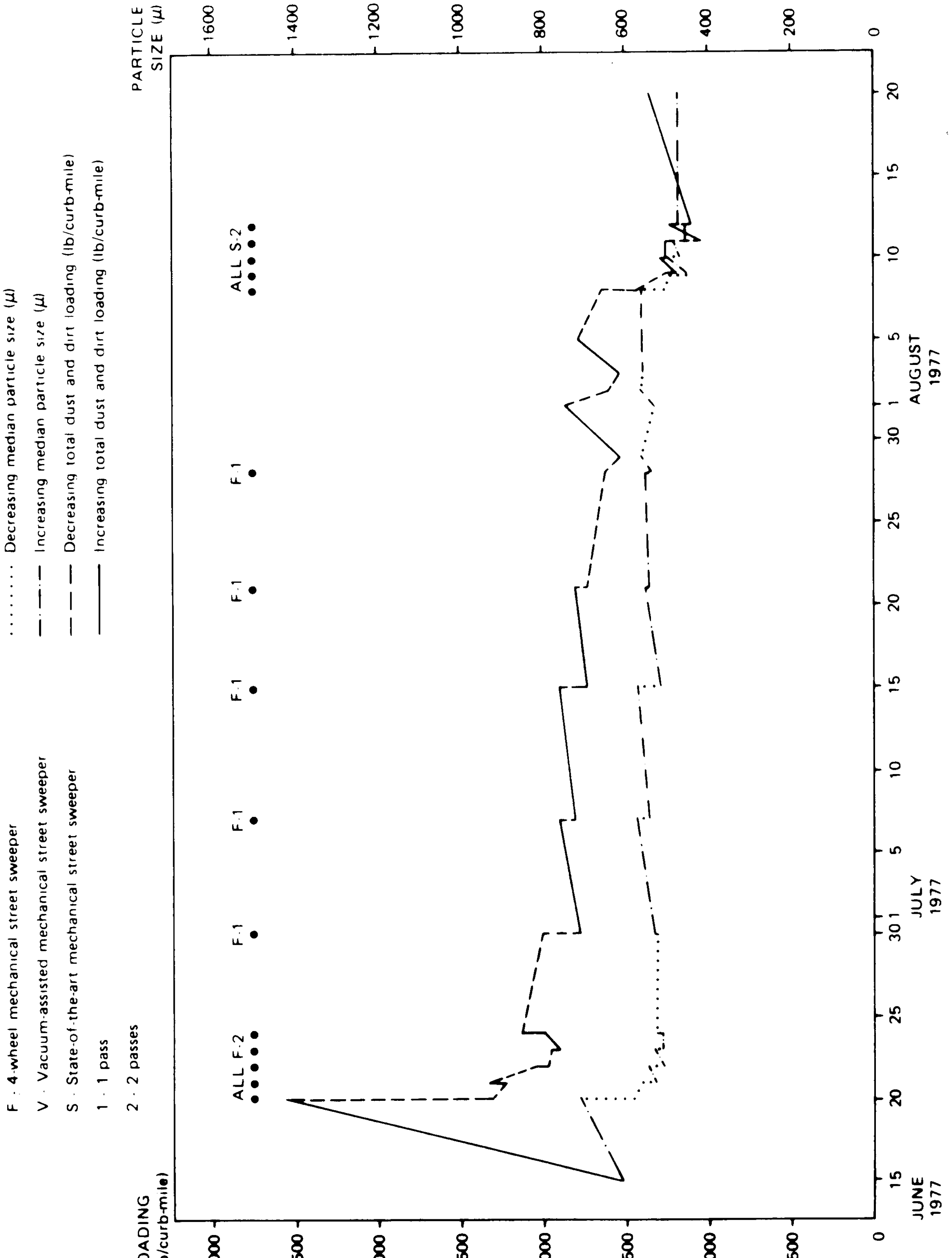


Figure D-16. Total particulate loading and median particle size as a function of time - Keyes - oil and screens test area (continued).

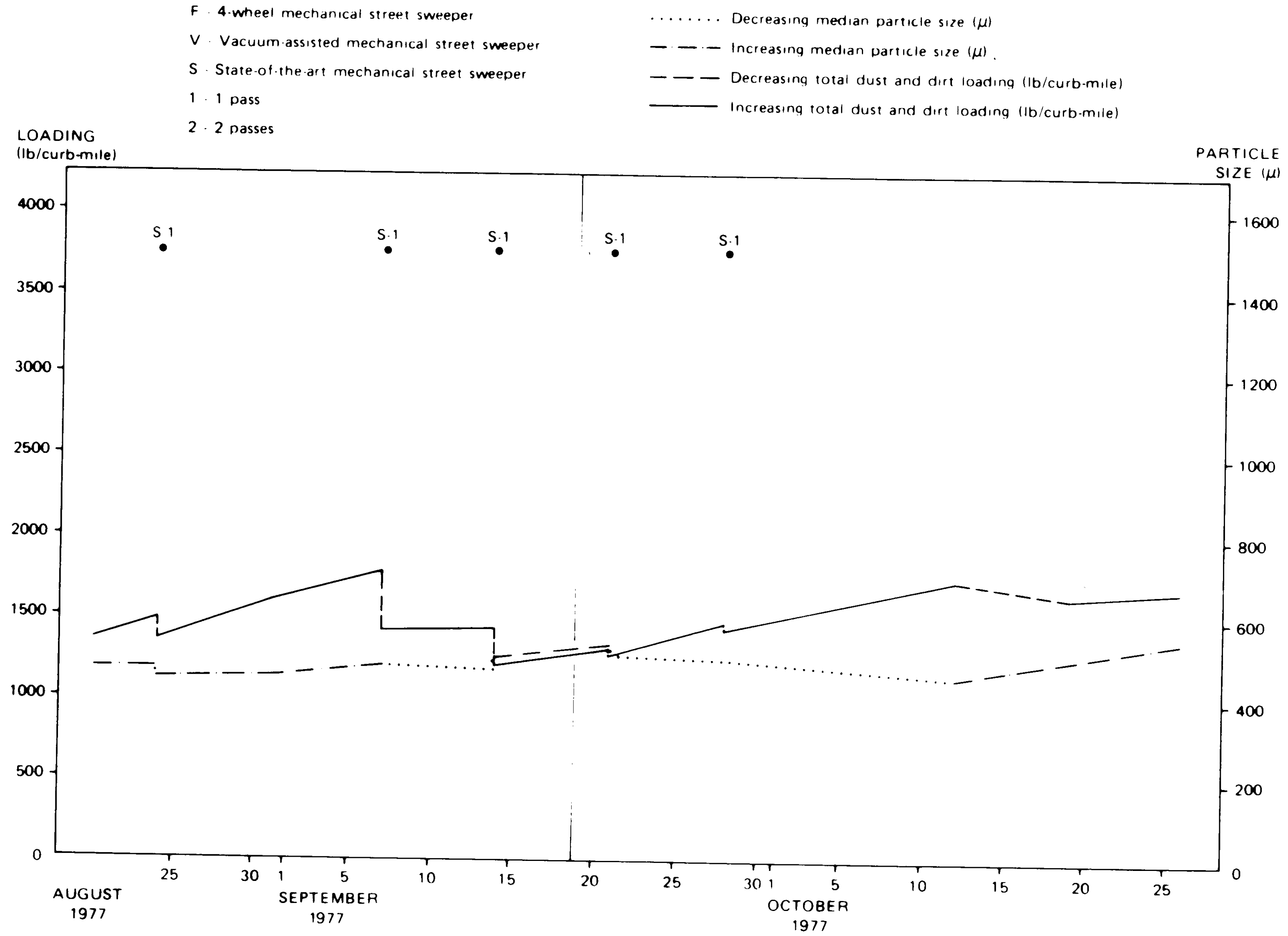


Figure D-17. Total particulate loading and median particle size as a function of time - Keyes - oil and screens test area (concluded).

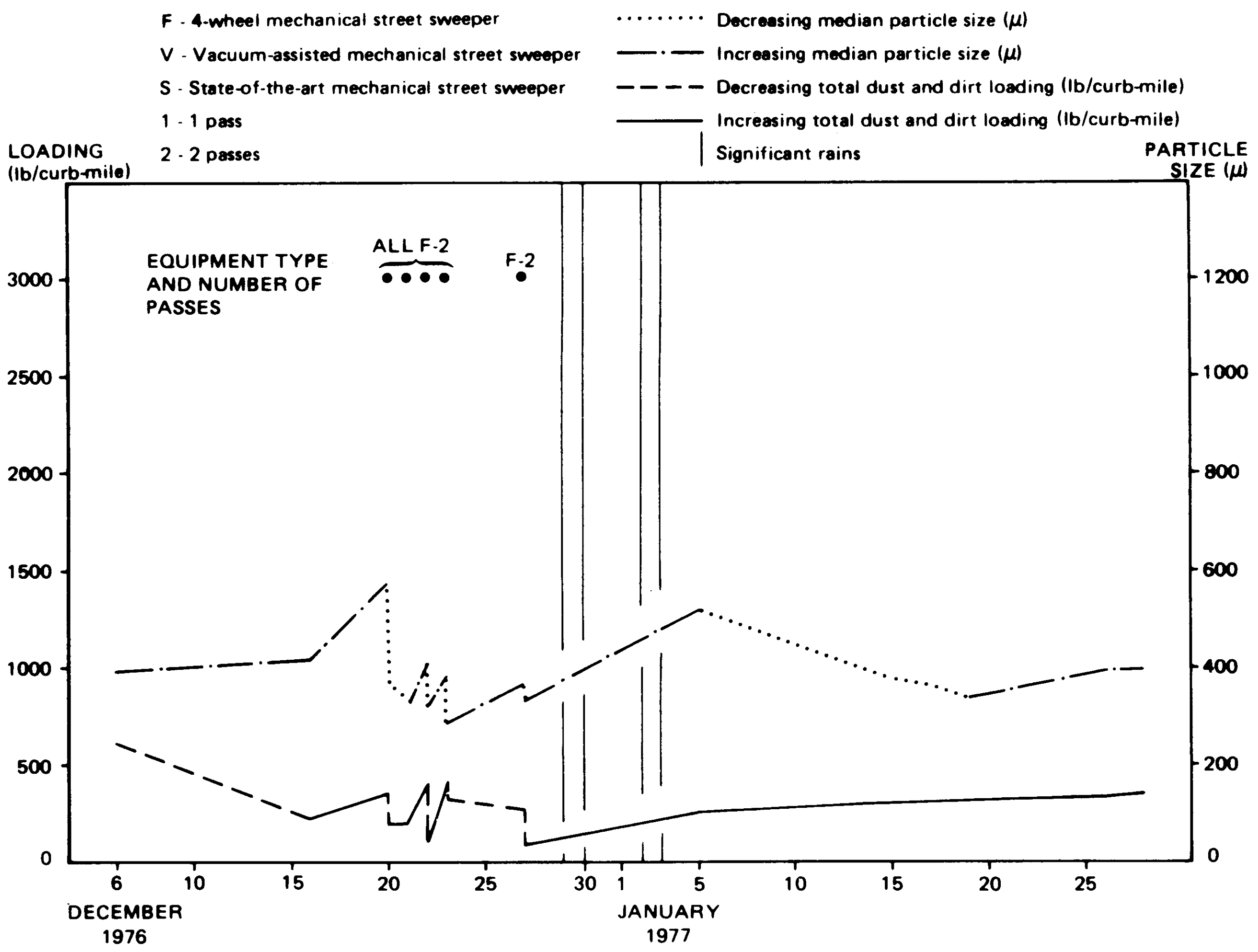


Figure D-18. Total particulate loading and median particle size as a function of time - Tropicana - good asphalt test area.

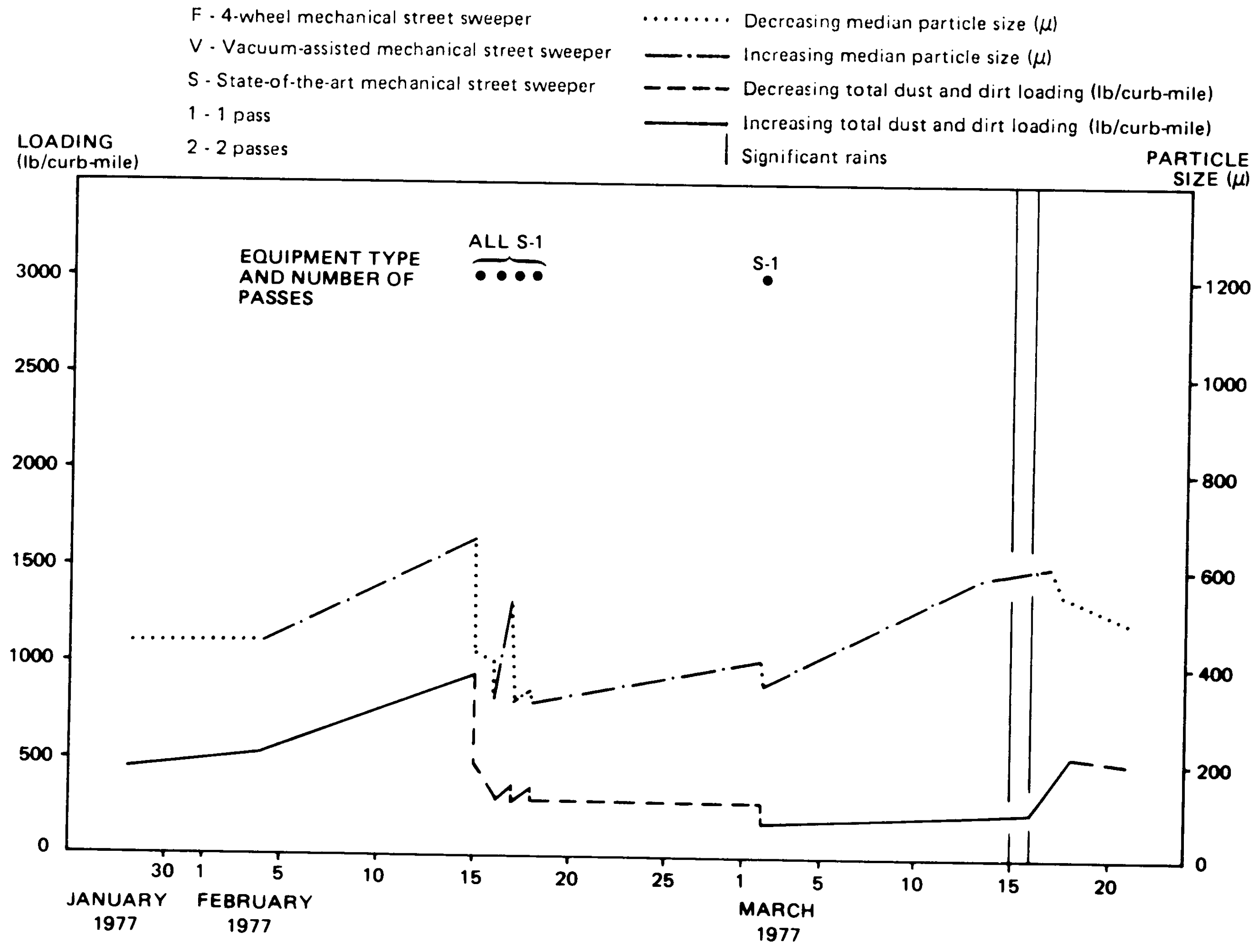


Figure D-19. Total particulate loading and median particle size as a function of time - Tropicana - good asphalt test area (continued).

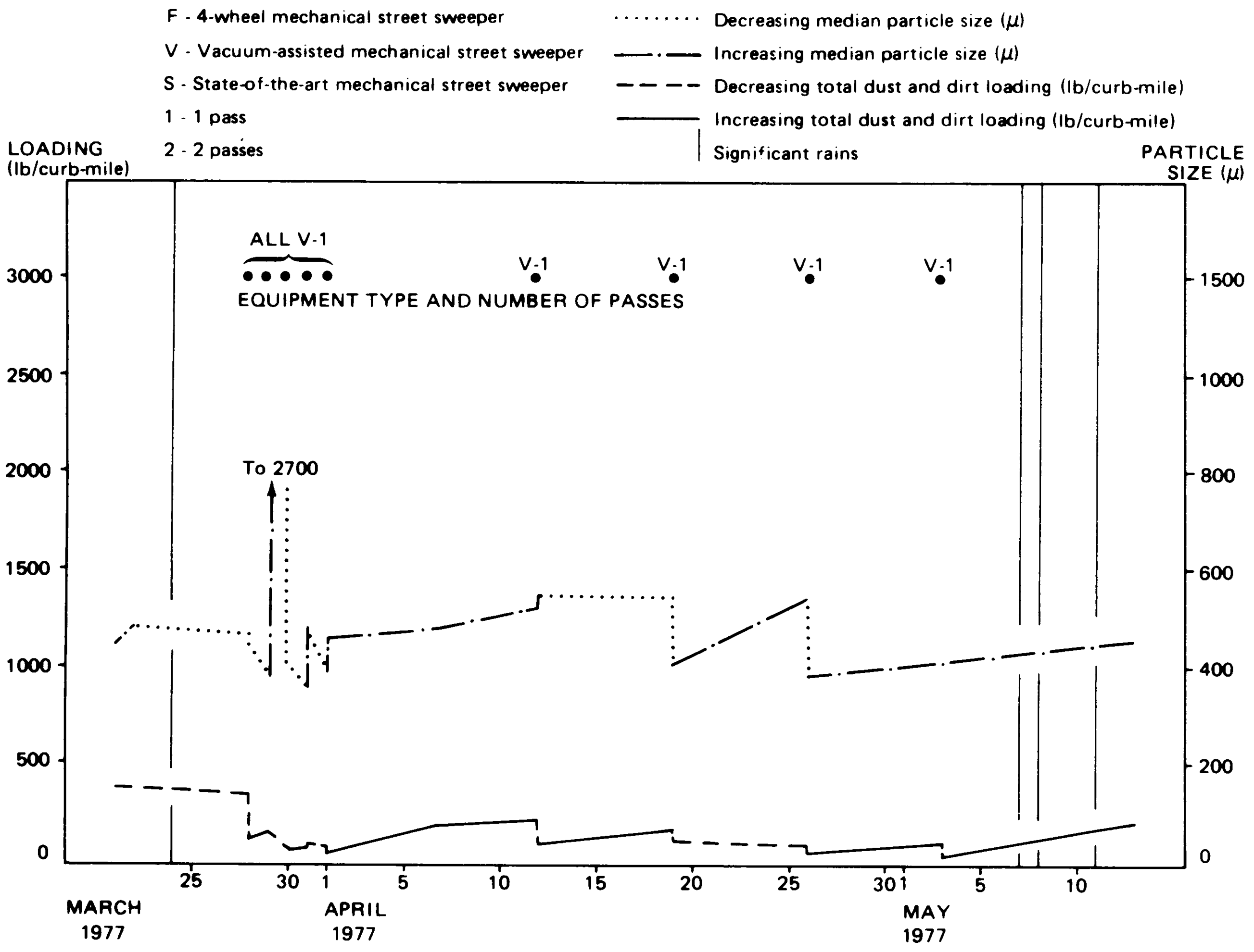


Figure D-20. Total particulate loading and median particle size as a function of time - Tropicana - good asphalt test area (continued).

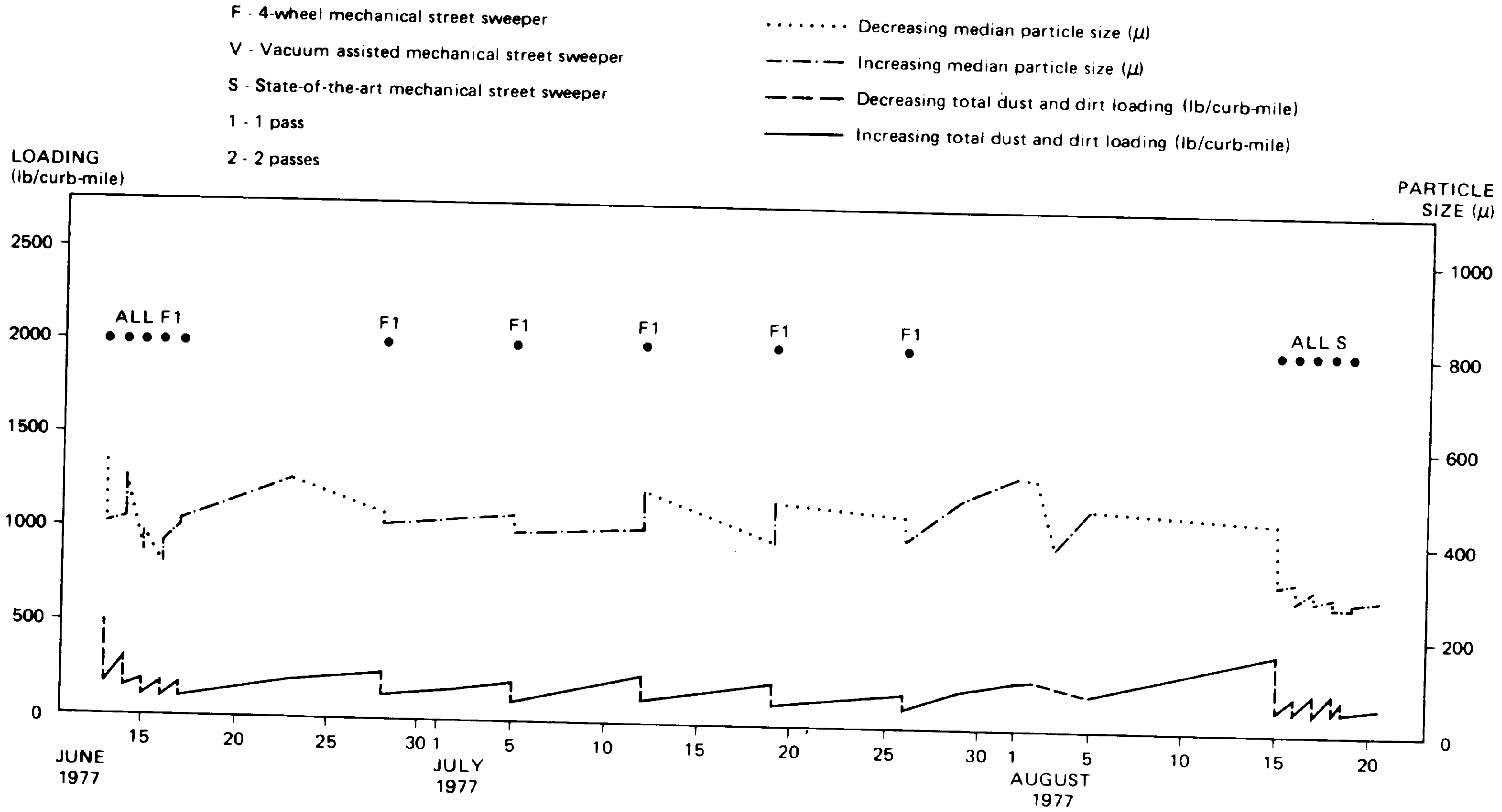


Figure D-21. Total particulate loading and median particle size as a function of time - Tropicana - good asphalt test area (continued).

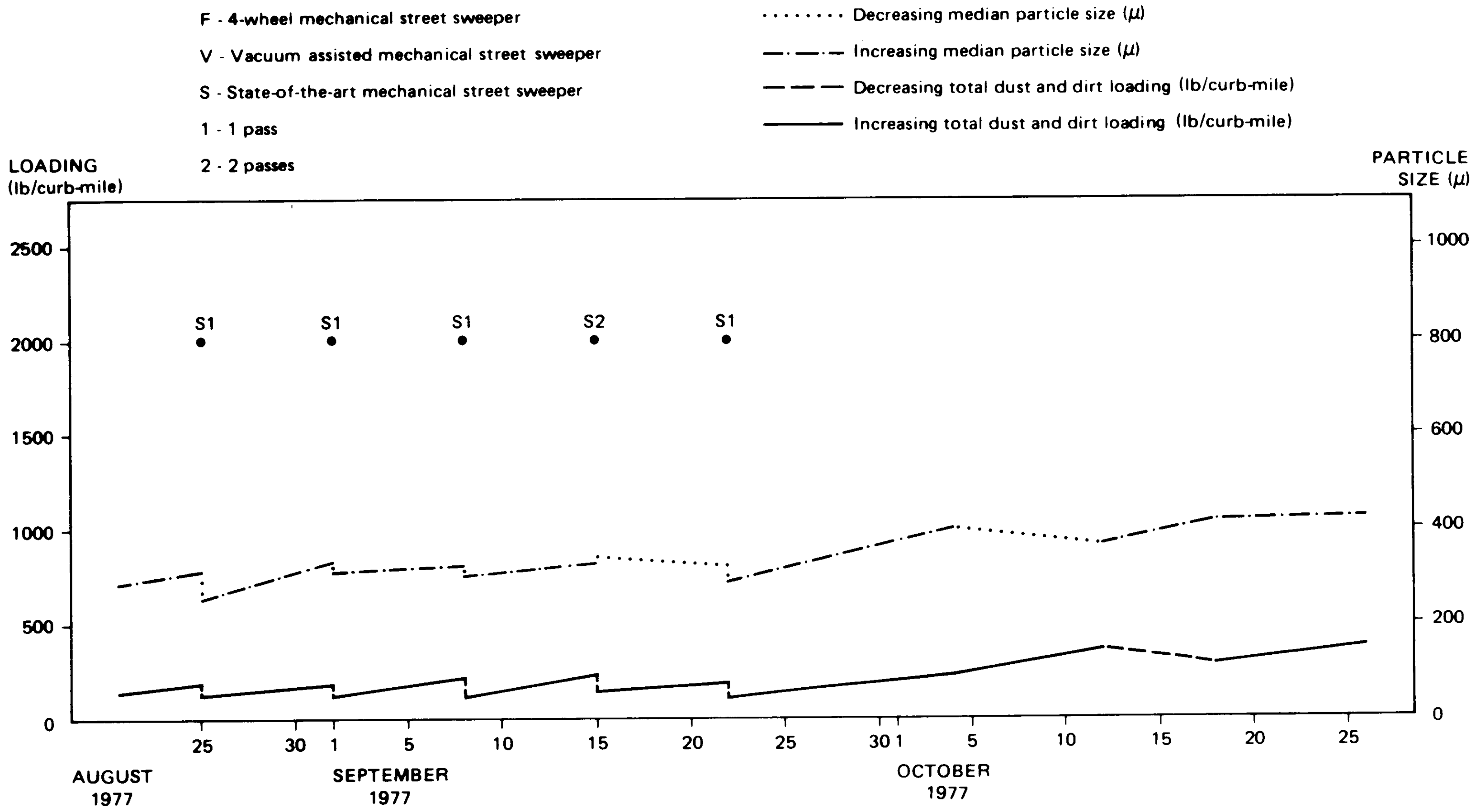


Figure D-22. Total particulate loading and median particle size as a function of time - Tropicana - good asphalt test area (concluded).

APPENDIX E

POLLUTANT STRENGTHS AS A FUNCTION OF PARTICLE SIZE

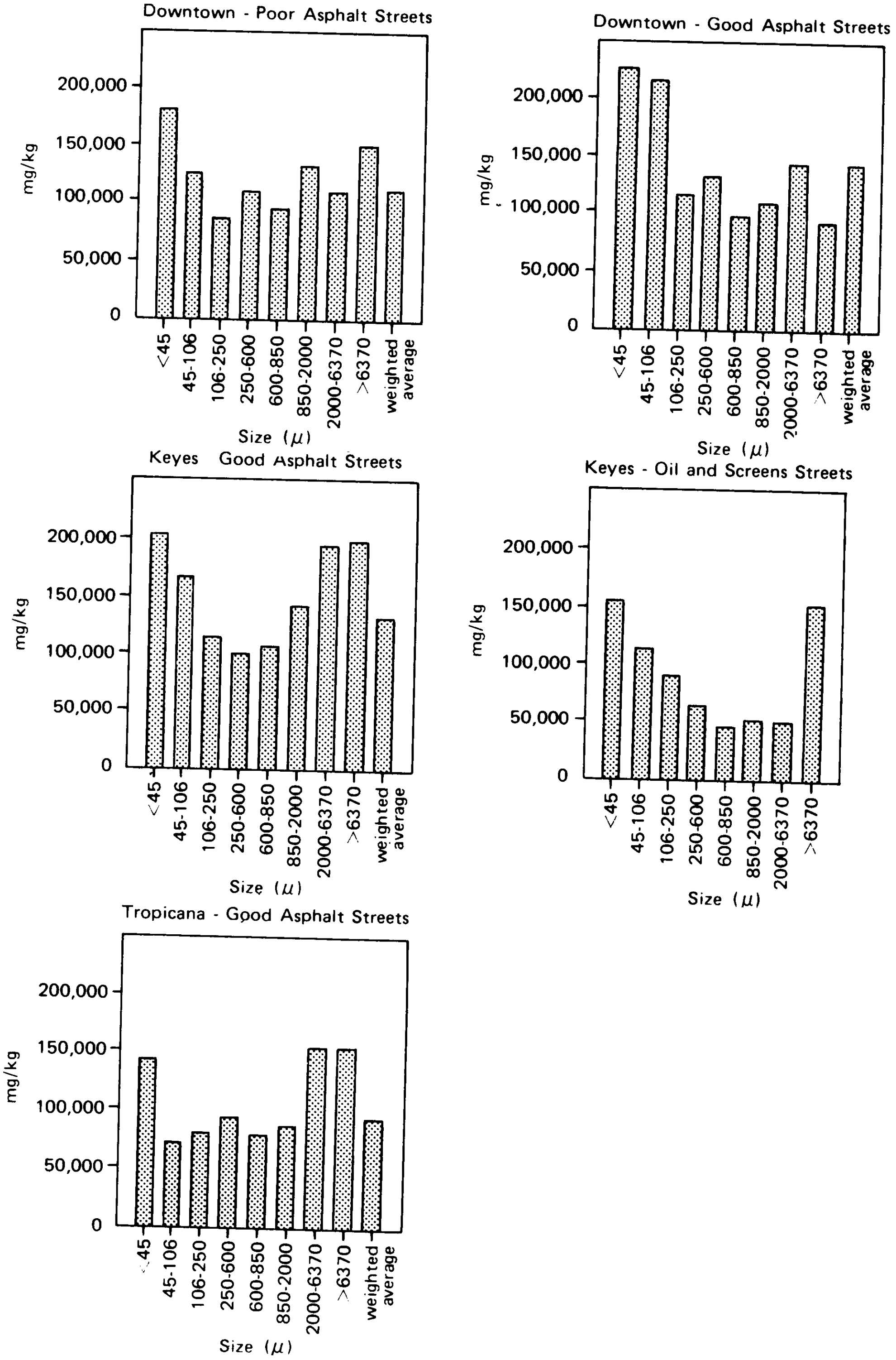
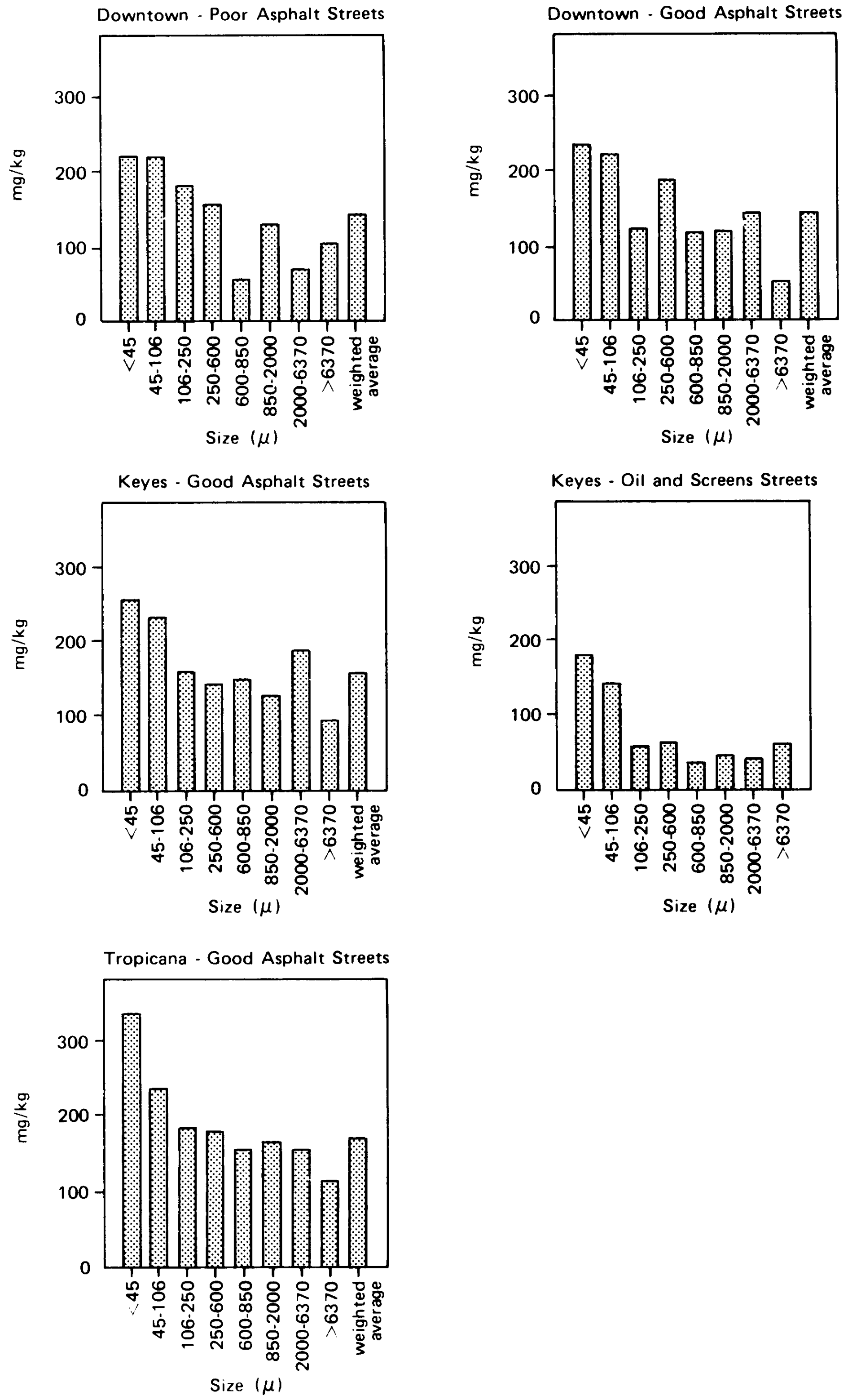


Figure E-1. COD Concentrations as a function of particle size (mg COD / kg total solids) - 12 / 13 / 76 through 5 / 15 / 77 average.



Downtown - Poor Asphalt Streets

Downtown - Good Asphalt Streets

Keyes - Good Asphalt Streets

Keyes - Oil and Screens Streets

Tropicana - Good Asphalt Streets

Figure E-2. Total orthophosphate concentrations as a function of particle size (mg OPO_4/kg total solids) - 12/13/76 through 5/15/77 average.

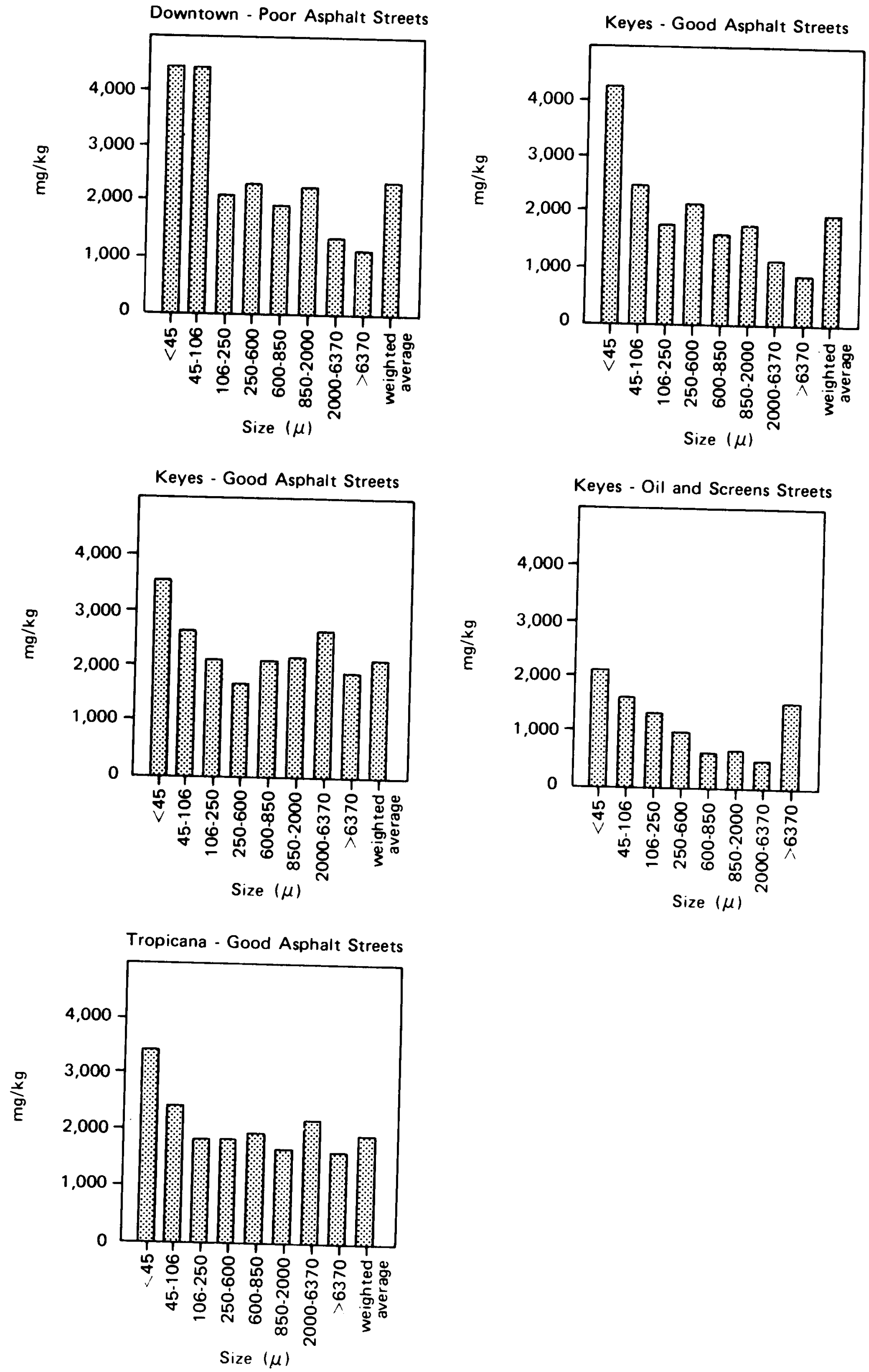


Figure E-3. Kjeldahl nitrogen concentrations as a function of particle size (mg KN/kg total solids) - 12/13/76 through 5/15/77 average.

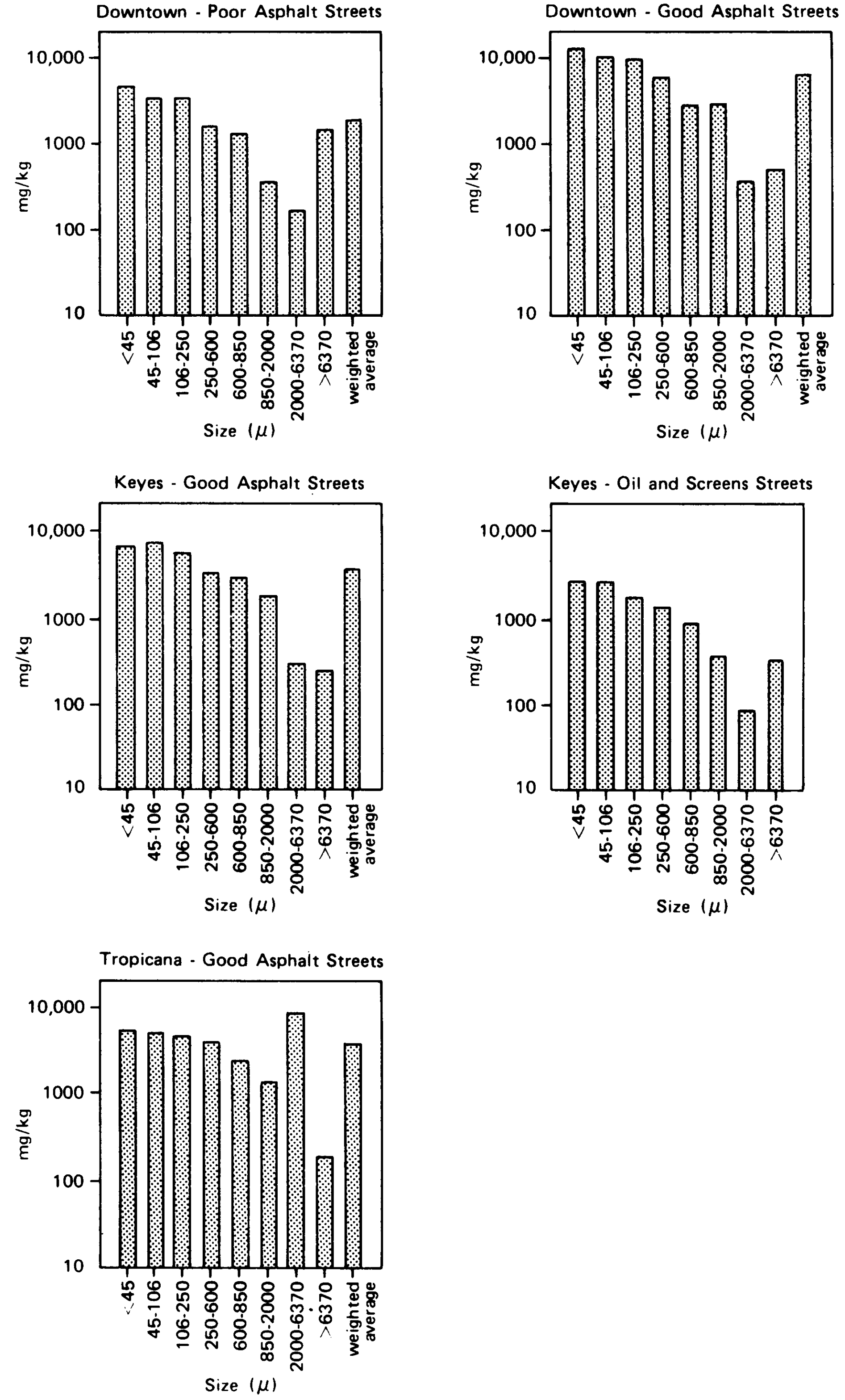


Figure E-4.. Lead concentrations as a function of particle size (mg Pb/kg total solids) - 12/13/76 through 5/15/77 average.

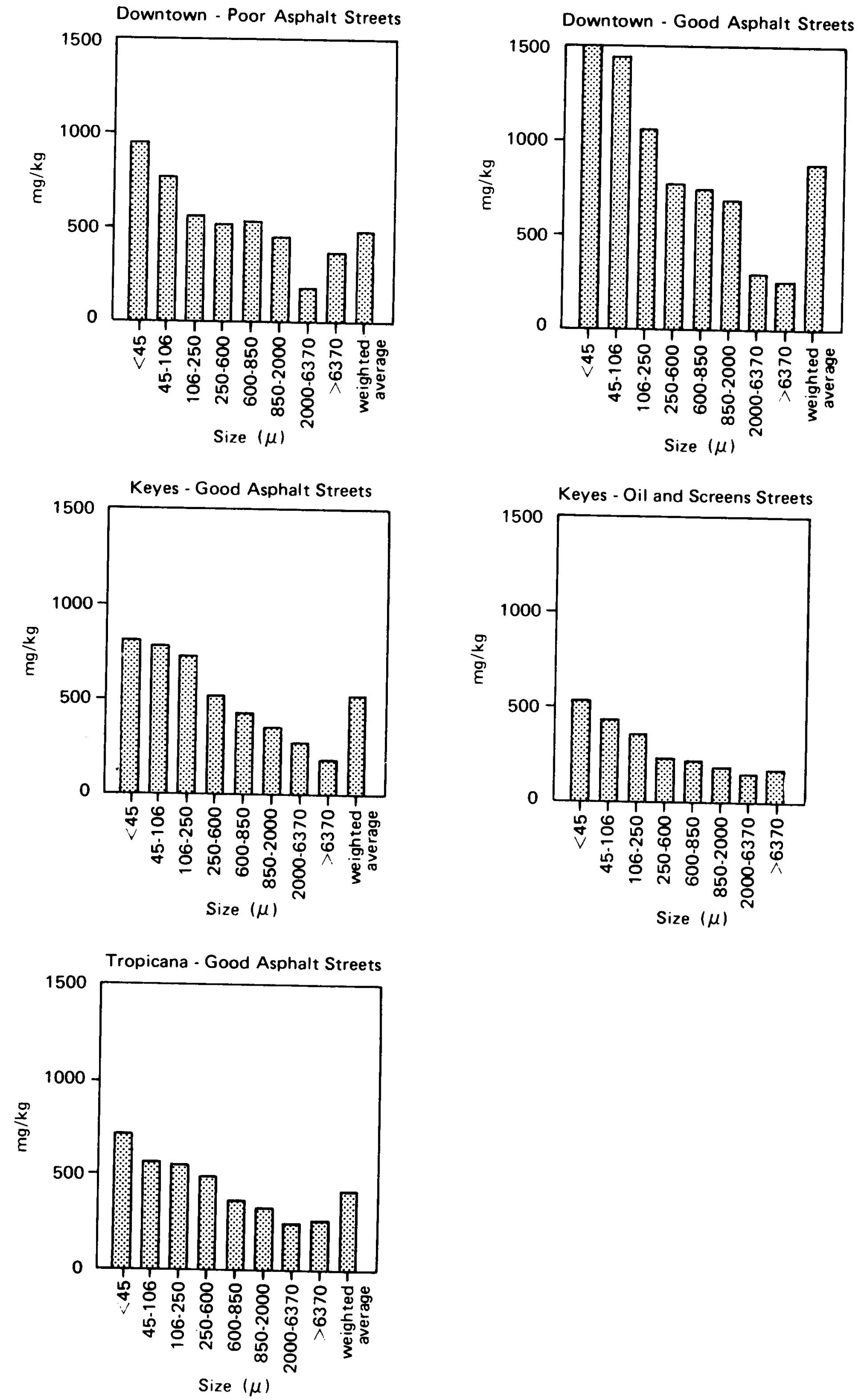
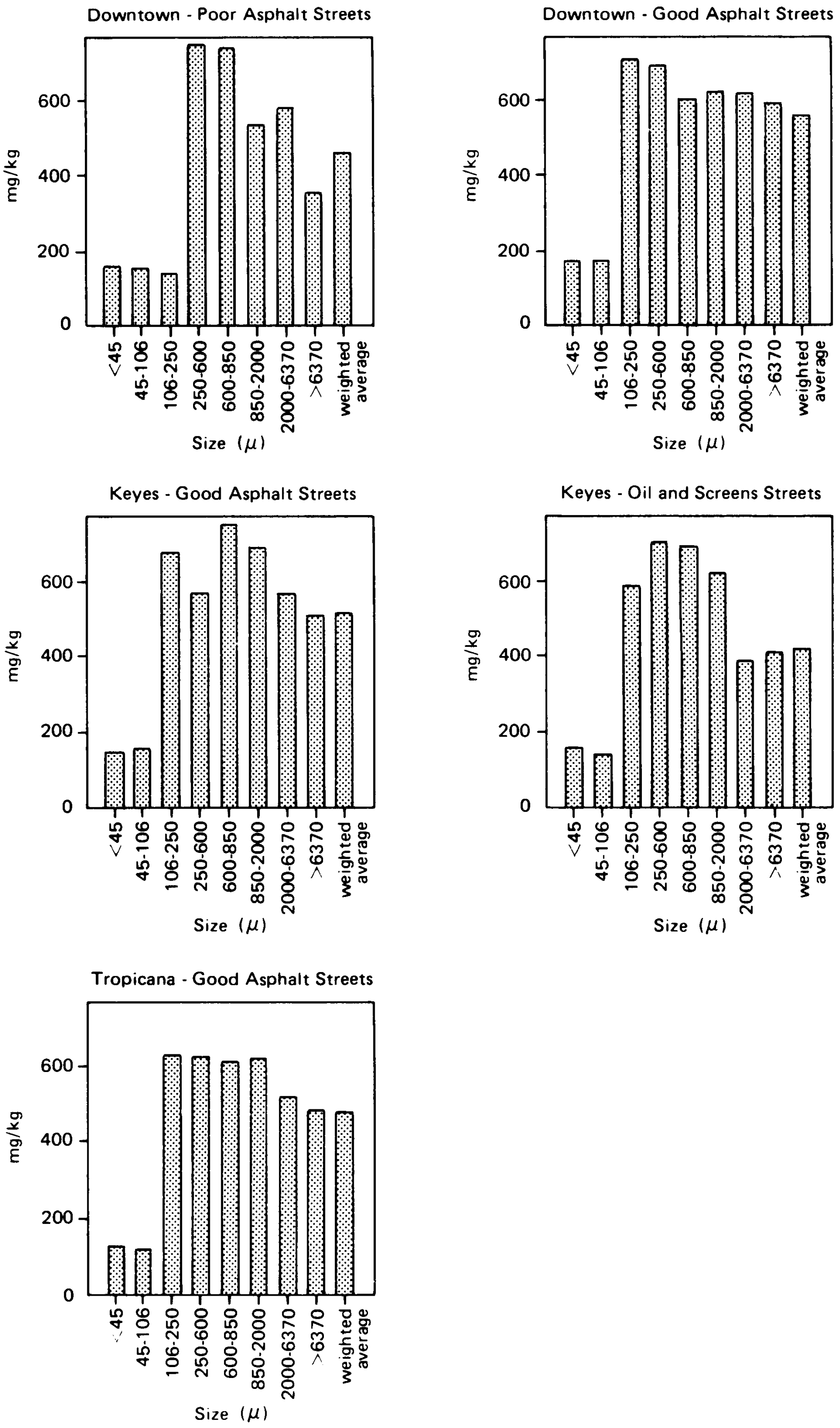


Figure E-5. Zinc concentrations as a function of particle size (mg Zn/kg total solids) - 12/13/76 through 5/15/77 average.



Downtown - Poor Asphalt Streets

Downtown - Good Asphalt Streets

Keyes - Good Asphalt Streets

Keyes - Oil and Screens Streets

Tropicana - Good Asphalt Streets

Figure E-6. Chromium concentrations as a function of particle size (mg Cr/kg total solids) - 12/13/76 through 5/15/77 average.

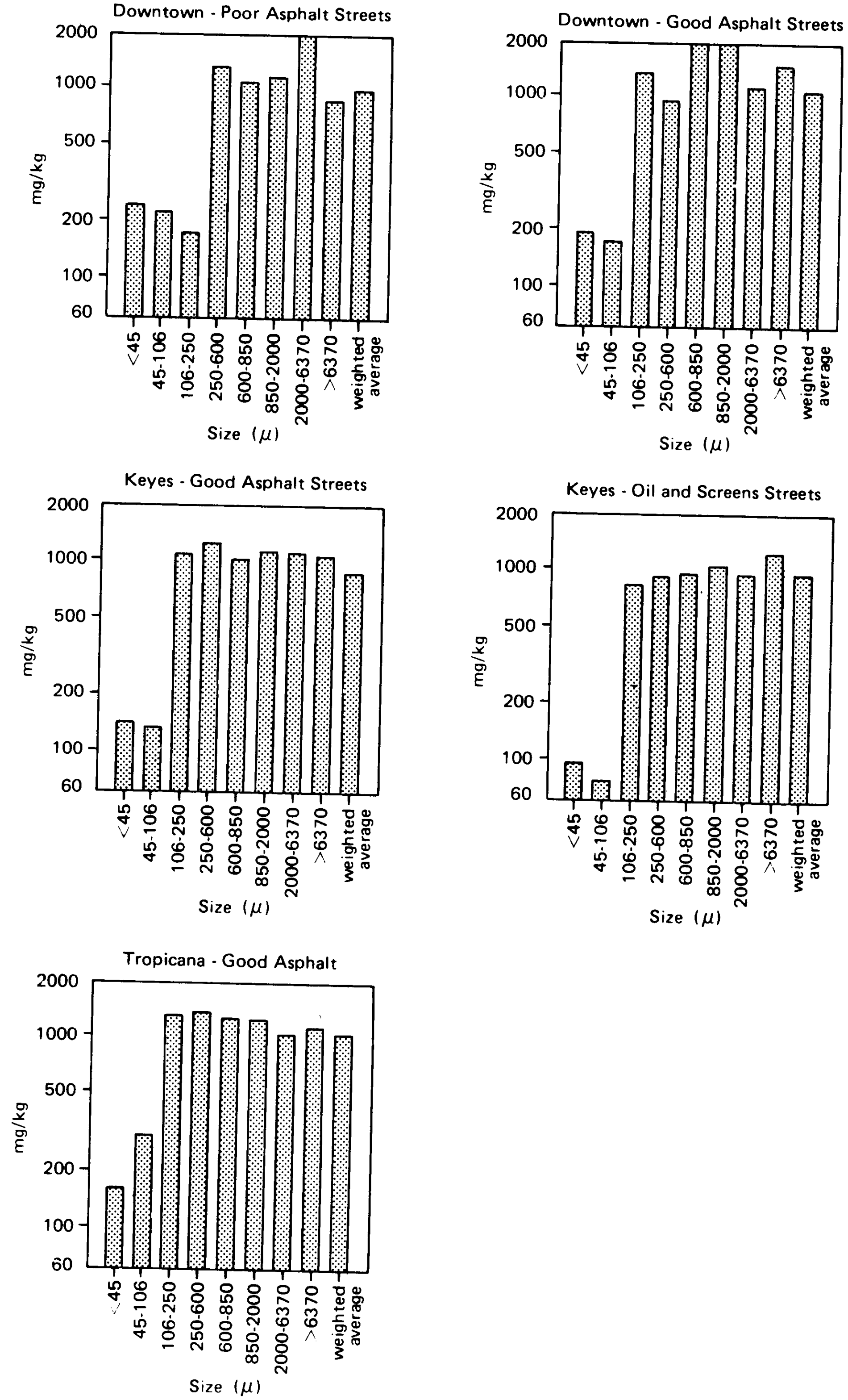


Figure E-7. Copper concentrations as a function of particle size (mg Cu/kg total solids) - 12/13/76 through 5/15/77 average.

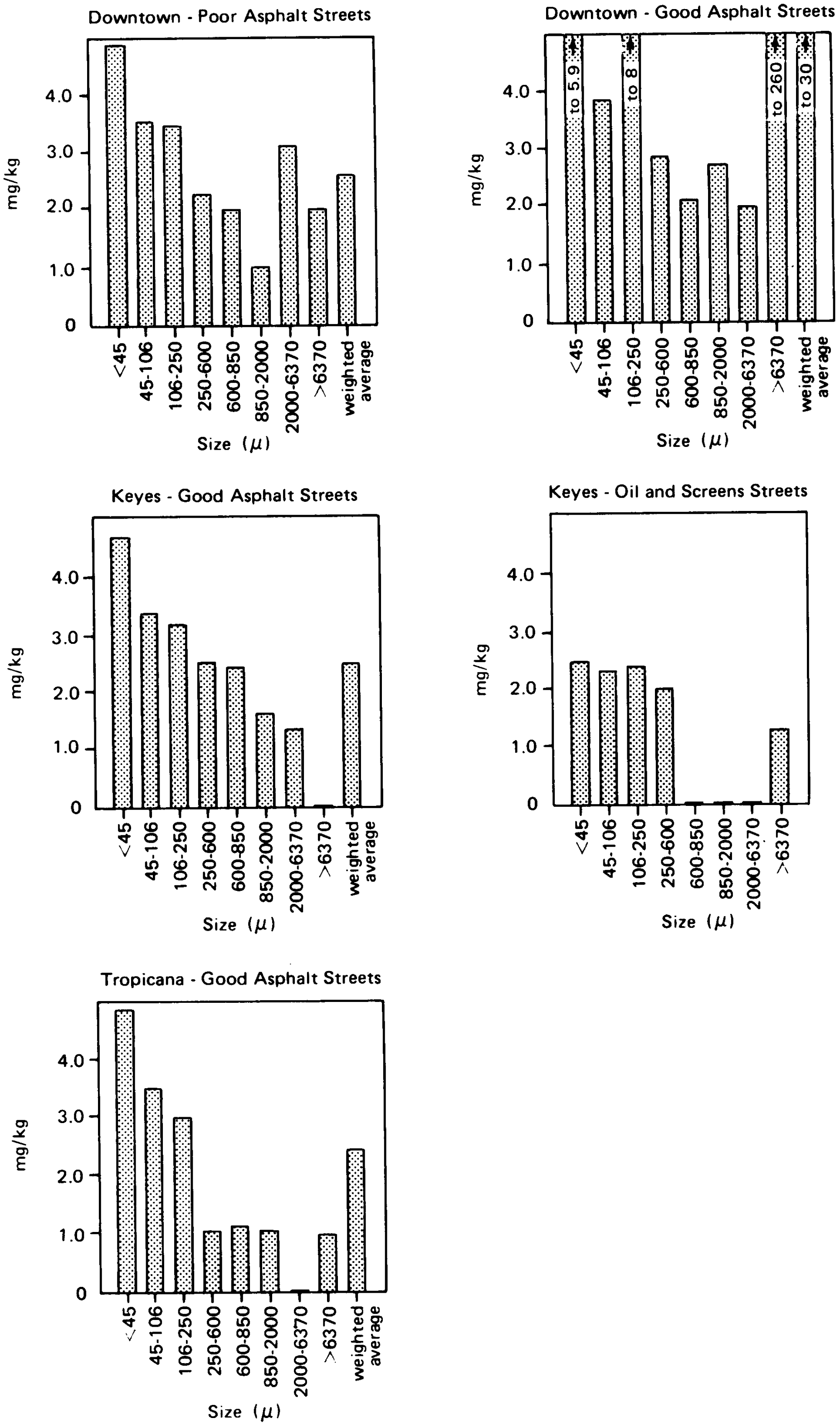


Figure E-8. Cadmium concentrations as a function of particle size (mg Cd/kg total solids) - 12/13/76 through 5/15/77 average.

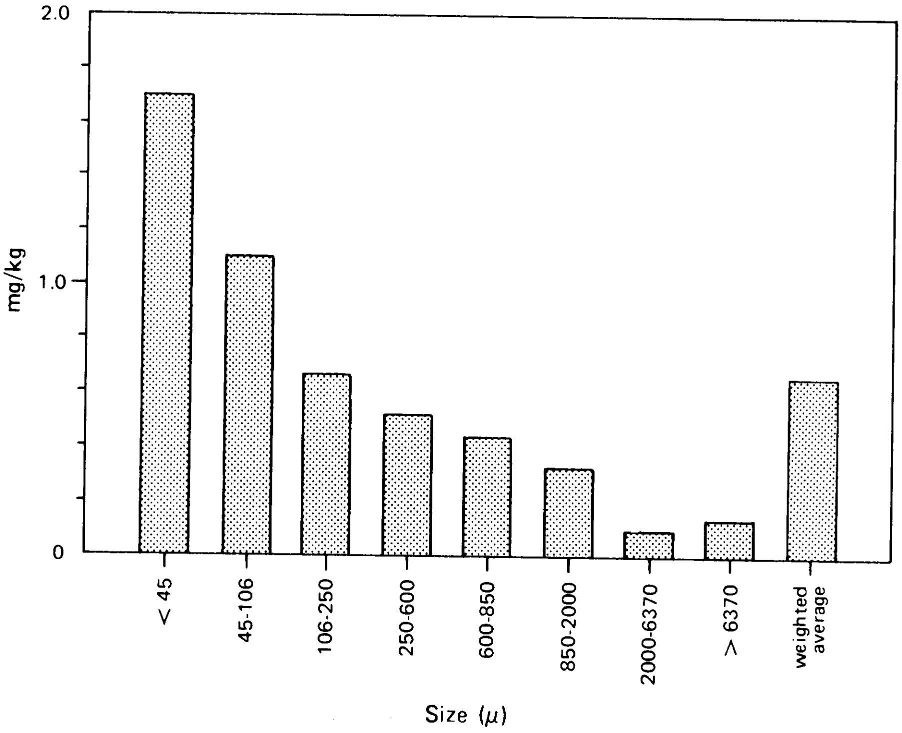


Figure E-9. Mercury concentrations as a function of particle size - all test areas combined - (mg Hg/kg total solids) - 12/13/76 through 5/15/77 average.

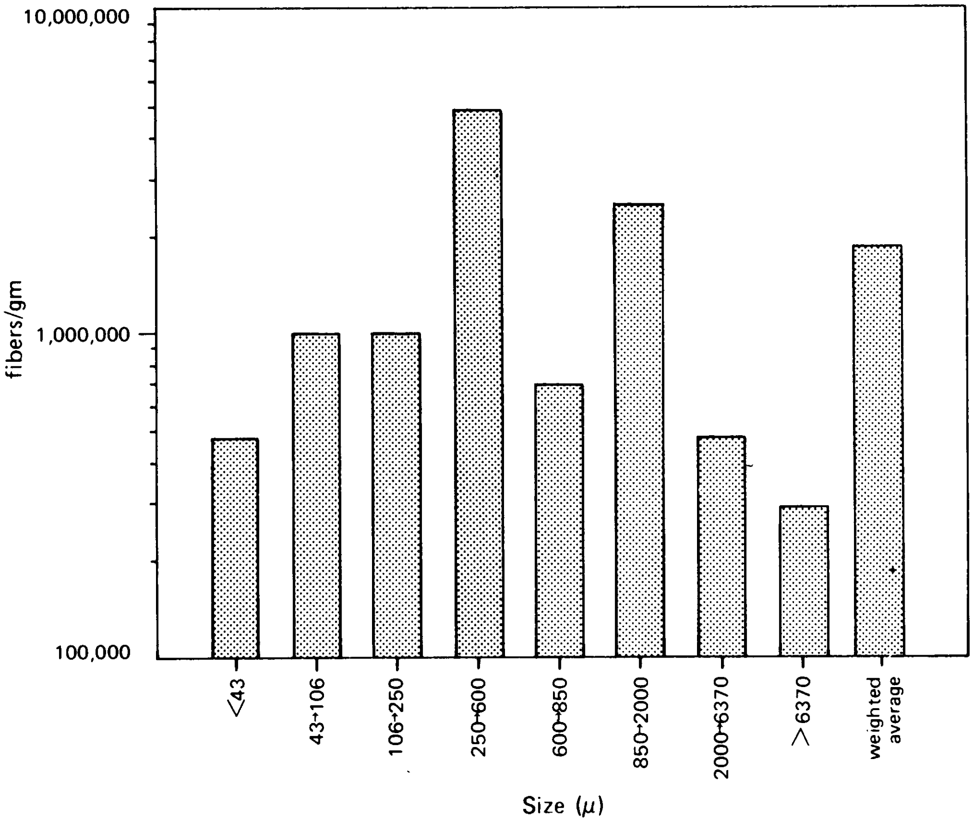


Figure E-10. Asbestos concentrations as a function of particle size - all test areas combined - (fibers/gram total solids) - 12/13/76 through 5/15/77 average.

TABLE E-1. CHEMICAL CONCENTRATIONS BY PARTICLE SIZE - DOWNTOWN TEST AREAS

Parameter (ppm, by weight) and dates	Downtown-Poor Asphalt Street Surface Condition-Study Area							
	Particle Sizes (μ)							
	>6370	2000→ 6370	850→ 2000	600→ 850	250→ 600	106 250	45→ 106	<45
12/13/76 → 1/23/77								
COD	151,000	111,000	134,000	93,400	107,000	84,700	124,000	176,000
Total Kjeldahl Nitrogen	1210	1360	2260	1920	2300	2010	4190	4390
Phosphate, total Ortho (as $PO_4^{\equiv}$)	104	74	129	61	159	184	221	221
Lead, total	1530	155	465	1240	1670	3560	3450	4540
Zinc, total	340	190	445	520	510	545	740	930
Chromium, total	365	580	535	705	755	150	165	175
Copper, total	830	2010	1140	1020	1260	170	220	235
Cadmium, total	2.0	3.1	1.0	2.0	2.3	3.4	3.5	4.8
	Downtown-Good Asphalt Street Surface Condition-Study Area							
12/13/76 → 1/23/77								
COD	90,000	139,000	110,000	98,900	129,000	119,000	215,000	225,000
Total Kjeldahl Nitrogen	860	1150	1790	1630	2060	1750	2460	4240
Phosphate, total Ortho (as $PO_4^{\equiv}$)	55	147	116	116	184	123	208	215
Lead, total	490	320	2540	2470	5710	9150	10,300	12,100
Zinc, total	250	290	690	675	770	1095	1465	1530
Chromium, total	590	615	620	600	690	720	180	175
Copper, total	1430	1100	1960	1910	950	1310	175	195
Cadmium, total	260	2.0	2.7	2.1	2.8	8.1	3.8	5.9

TABLE E-2. CHEMICAL CONCENTRATIONS BY PARTICLE SIZE - TROPICANA GOOD ASPHLAT TEST AREA

Parameter (ppm,)by weight) and dates	Particle Sizes (μ)							
	>6370	2000→ 6370	850→ 2000	600→ 850	250→ 600	106→ 250	45→ 106	<45
1/13/76 → 1/23/77								
COD	190,000	266,000	86,200	83,000	93,800	94,400	51,800	87,500
Total Kjeldahl Nitrogen	2460	4140	2080	2690	2060	2030	2480	3400
Phosphate, total Ortho (as $PO_4^{\equiv}$)	178	282	184	233	178	202	257	276
Lead, total	230	280	2240	3040	5720	6990	7000	7140
Zinc, total	180	205	315	350	465	670	645	755
Chromium, total	425	415	555	530	580	610	125	125
Copper, total	765	1180	1500	1030	1170	1240	155	150
Cadmium, total	1.0	<1.0	2.2	2.3	2.1	4.0	4.9	4.7
1/24/ → 3/20/77								
COD	160,000	105,000	86,900	50,700	84,200	72,900	109,000	166,000
Total Kjeldahl Nitrogen	1160	1410	1690	1010	1086	1240	1980	2470
Phosphate, total Ortho (as $PO_4^{\equiv}$)	61	98	178	104	116	159	178	429
Lead, total	164	220	615	1500	2660	3300	4950	5350
Zinc, total	470	385	285	470	445	455	550	725
Chromium, total	495	645	620	655	700	585	110	130
Copper, total	1390	1020	1000	1340	1520	1210	145	155
Cadmium, total	1.0	2.0	2.0	2.0	2.3	2.0	2.9	5.4
3/21 → 5/15/77								
COD	102,000	82,200	74,700	93,900	96,400	85,100	58,500	170,000
Total Kjeldahl Nitrogen	1090	1130	1340	1920	2270	2100	2720	4320
Phosphate, total Ortho (as $PO_4^{\equiv}$)	98	80	147	123	233	178	264	288
Lead, total	135	28200	790	2370	4180	4100	5130	5050
Zinc, total	175	180	320	345	570	520	575	695
Chromium, total	525	460	675	645	595	685	120	125
Copper, total	1170	895	1230	1400	1480	1500	310	175
Cadmium, total	1.0	<1.0	2.0	2.2	2.0	2.9	2.6	4.4
5/16 → 7/31/77								
COD	228,000	136,000	133,000	128,000	86,300	60,200	59,500	72,200
Total Kjeldahl Nitrogen	24	997	474	3220	2620	1960	2320	696
Phosphate, Ortho (as $PO_4^{\equiv}$)	130	120	154	156	132	113	146	199
Lead	240	185	1280	3210	5360	6450	5320	5090
Zinc	104	95	168	214	497	606	716	845
Chromium	81	160	195	195	240	265	200	205
Copper	52	31	615	365	255	245	175	165
Cadmium	0.60	1.10	1.39	1.59	1.98	5.36	3.78	4.99
8/1 → 9/23/77								
COD	234,000	104,000	155,000	118,000	80,700	65,200	68,000	78,600
Total Kjeldahl Nitrogen	473	2140	3300	3025	2390	2370	2420	691
Phosphate, Ortho (as $PO_4^{\equiv}$)	96	125	161	172	131	161	205	246
Lead	255	180	630	1880	3550	4420	3830	4100
Zinc	177	149	149	199	441	540	638	852
Chromium	125	180	165	220	190	235	210	190
Copper	37	33	32	46	245	255	180	155
Cadmium	1.29	1.69	1.39	1.39	1.99	2.39	3.19	4.27

TABLE E-3. CHEMICAL CONCENTRATIONS BY PARTICLE SIZE - KEYES GOOD ASPHALT TEST AREA

Parameter (ppm, by weight) and dates	Particle Sizes (μ)							
	>6370	2000→ 6370	850→ 2000	600→ 850	250→ 600	106→ 250	45→ 106	<45
12/13/76 → 1/23/77								
COD	197,000	229,000	158,000	150,000	104,000	116,000	167,000	196,000
Total Kjeldahl Nitrogen	1800	3680	2670	2980	2080	2070	2920	3730
Phosphate, total Ortho (as $PO_4^{\equiv}$)	86	202	129	159	129	141	227	233
Lead, total	175	240	1180	2500	4330	5220	6800	7010
Zinc, total	195	325	465	470	560	760	785	820
Chromium, total	435	565	680	640	785	705	150	155
Copper, total	1290	1430	1180	950	1210	1260	120	130
Cadmium, total	1.0	2.0	2.9	3.2	4.4	3.2	5.1	4.1
1/24 → 3/20/77								
COD	204,000	170,000	117,000	115,000	98,200	111,000	159,000	208,000
Total Kjeldahl Nitrogen	1640	1900	1870	2020	1420	1520	2170	2550
Phosphate, total Ortho (as $PO_4^{\equiv}$)	86	178	129	153	141	172	239	300
Lead, total	376	237	1410	2780	3650	5320	7150	7380
Zinc, total	185	225	280	375	485	680	815	865
Chromium, total	505	600	690	770	840	670	185	170
Copper, total	920	1090	920	985	1150	980	135	155
Cadmium, total	<1.0	1.0	1.0	2.0	2.0	2.9	<1.0	4.8
3/21 → 5/15/77								
COD	193,000	187,000	144,000	60,100	95,700	111,000	168,000	203,000
Total Kjeldahl Nitrogen	2100	2660	2080	1360	1770	2750	2930	4220
Phosphate, total Ortho (as $PO_4^{\equiv}$)	116	184	54	141	165	172	245	233
Lead, total	185	420	635	3030	1970	7410	7200	6560
Zinc, total	190	235	280	465	515	710	770	775
Chromium, total	575	545	725	795	94	655	160	150
Copper, total	1040	845	1300	1110	1280	980	140	140
Cadmium, total	2.0	1.0	1.0	2.1	1.0	3.4	4.2	5.3
5/16 → 7/31/77								
COD	379,000	217,000	214,000	93,300	91,600	92,800	84,000	87,500
Total Kjeldahl Nitrogen	5490	3380	4730	2720	3680	2010	1800	647
Phosphate, Ortho (as $PO_4^{\equiv}$)	108	108	131	113	107	114	153	178
Lead	1200	210	775	6650	11,700	13,200	10,000	8650
Zinc	84	141	211	568	846	970	1015	996
Chromium	110	170	235	351	285	345	245	260
Copper	3460	29	480	530	270	180	175	160
Cadmium	0.99	0.99	1.38	2.09	2.07	3.08	2.97	4.06
8/1 → 9/23/77								
COD	98,100	21,800	106,500	88,100	73,500	83,300	74,600	83,600
Total Kjeldahl Nitrogen	119	272	179	200	219	1830	1970	2770
Phosphate, Ortho (as $PO_4^{\equiv}$)	47	90	334	99	21	123	165	189
Lead	295	445	2200	9050	14,600	15,700	11,400	10,100
Zinc	163	303	582	539	765	1064	1060	1047
Chromium	155	235	265	425	320	360	255	275
Copper	34	26	745	560	385	235	175	180
Cadmium	0.69	0.79	1.18	1.99	1.89	3.50	3.85	5.16

TABLE E-4. CHEMICAL CONCENTRATIONS BY PARTICLE SIZE KEYES-OIL AND SCREENS TEST AREA

Parameter (ppm, by weight) and dates	Particle Sizes (μ)							
	>6370	2000→ 6370	850→ 2000	600→ 850	250→ 600	106→ 250	45→ 106	<45
12/13/76 → 1/23/77								
COD	117,000	53,900	55,000	56,000	74,800	102,000	126,000	125,000
Total Kjeldahl Nitrogen	1310	520	710	770	1130	1600	2080	2560
Phosphate, total Ortho (as $PO_4^{\equiv}$)	49	74	31	37	49	18	147	178
Lead, total	115	80	315	660	1000	1430	2450	2700
Zinc, total	210	175	195	220	240	340	480	530
Chromium, total	485	460	635	710	685	580	160	145
Copper, total	1380	940	1030	1080	990	780	84	83
Cadmium, total	1.0	<1.0	2.0	1.0	2.0	2.0	2.2	2.8
1/24 → 3/20/77								
COD	96,400	57,500	49,000	41,800	70,100	82,200	125,000	168,000
Total Kjeldahl Nitrogen	564	540	640	590	920	1440	2315	1450
Phosphate, total Ortho (as $PO_4^{\equiv}$)	22	25	43	31	61	80	159	215
Lead, total	120	100	520	1060	1230	1720	2310	3120
Zinc, total	205	165	205	195	265	345	390	595
Chromium, total	310	480	565	605	635	535	130	165
Copper, total	1270	930	1100	860	840	800	68	115
Cadmium, total	2.0	1.0	<1.0	<1.0	2.0	2.1	2.0	2.7
3/21 → 5/15/77								
COD	242,000	36,400	45,200	34,100	53,500	63,600	93,000	174,000
Total Kjeldahl Nitrogen	2890	390	650	540	920	1090	830	2660
Phosphate, total Ortho (as $PO_4^{\equiv}$)	129	18	74	43	74	80	129	165
Lead, total	770	70	255	920	1250	1750	2520	2430
Zinc, total	235	170	200	310	270	350	385	455
Chromium, total	420	165	680	675	690	665	155	160
Copper, total	1060	1040	1070	995	980	1070	81	83
Cadmium, total	1.0	<1.0	2.0	1.0	2.0	2.8	2.4	2.0
5/16 → 7/31/77								
COD	162,000	72,500	47,500	45,300	38,200	46,200	64,100	76,300
Total Kjeldahl Nitrogen	1550	331	790	771	613	1390	2120	3270
Phosphate, Ortho (as $PO_4^{\equiv}$)	57	22	29	15	35	49	80	113
Lead	150	110	1380	290	2420	3070	3410	3970
Zinc	74	83	172	100	171	373	540	613
Chromium	250	175	280	235	285	235	220	175
Copper	26	34	99	33	140	94	125	150
Cadmium	0.30	0.79	0.99	0.90	1.38	1.30	2.29	2.67
8/1 → 9/23/77								
COD	119,000	104,000	74,200	43,400	32,700	46,400	61,300	73,400
Total Kjeldahl Nitrogen	1220	402	1300	1067	860	1360	1820	2900
Phosphate, Ortho (as $PO_4^{\equiv}$)	50	56	50	45	49	60	92	156
Lead	130	120	250	1760	2670	4290	4160	4290
Zinc	99	87	111	185	184	488	655	708
Chromium	120	145	220	265	190	215	250	210
Copper	27	36	33	60	99	115	160	160
Cadmium	0.50	1.19	1.29	1.28	0.79	1.29	2.68	3.46

TABLE E-5. ASBESTOS AND MERCURY CONCENTRATIONS BY PARTICLE SIZE ALL TEST AREAS COMBINED

	Particle Sizes (μ)							
Parameter	>6370	2000→ 6370	850→ 2000	600→ 850	250→ 600	106→ 250	45→ 106	<45
12/13/76 → 5/15/77								
Mercury (ppm by weight)	0.19	0.11	0.21	0.25	0.30	0.43	0.69	0.86
Asbestos (fibers/ gram)	2.9×10^5	4.7×10^5	2.5×10^6	7.0×10^5	4.8×10^6	1.0×10^6	1.0×10^6	4.6×10^5

APPENDIX F

RUNOFF DATA

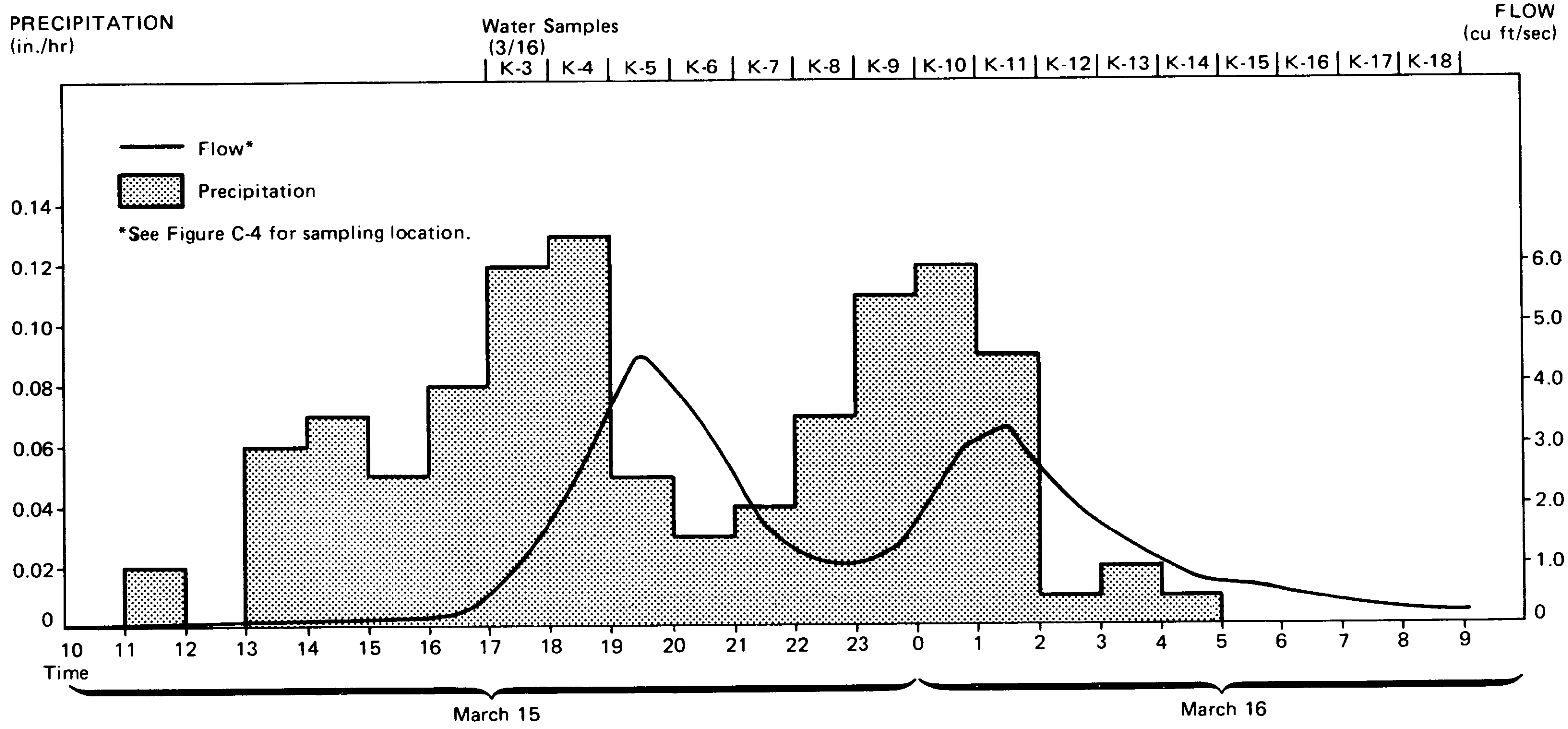


Figure F-1. Runoff from Keyes street study area during the rains of March 15 and 16, 1977.

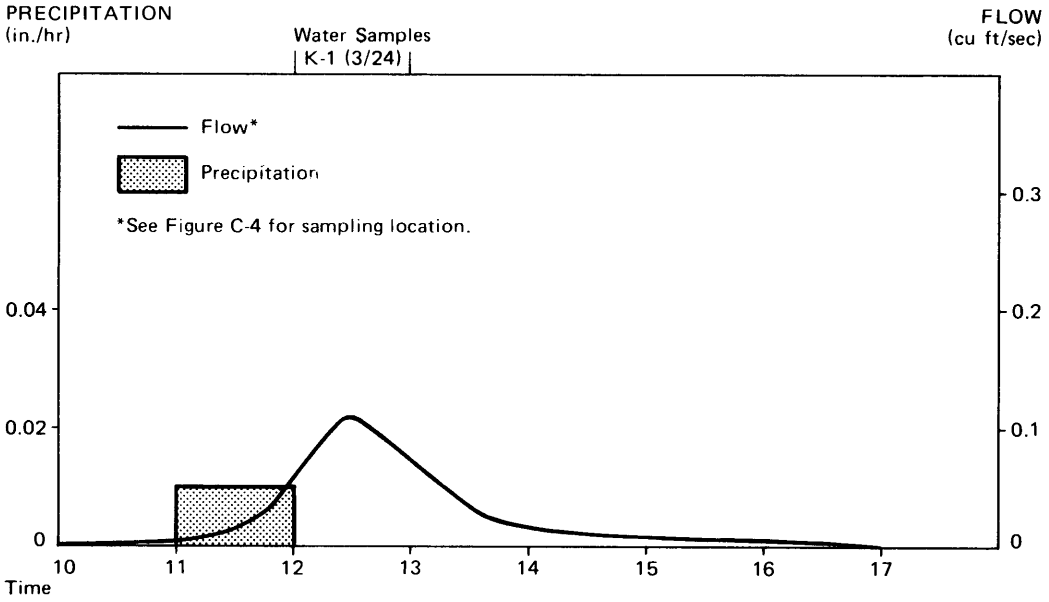


Figure F-2. Runoff from Keyes street study area during the rains of March 23, 1977.

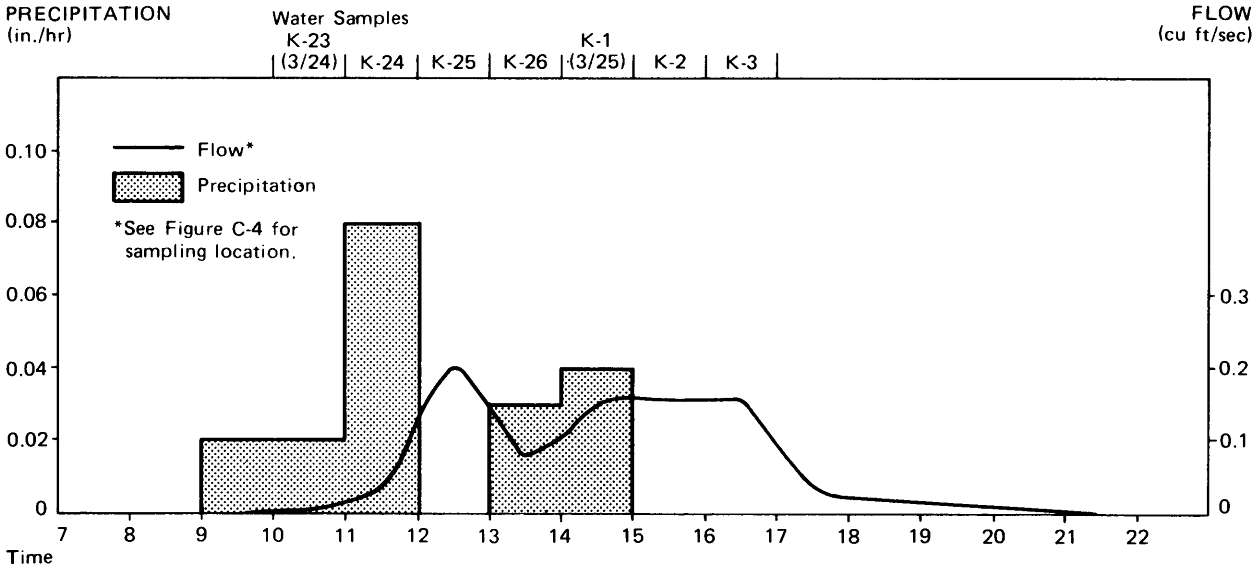


Figure F-3. Runoff from Keyes street study area during the rains of March 24, 1977.

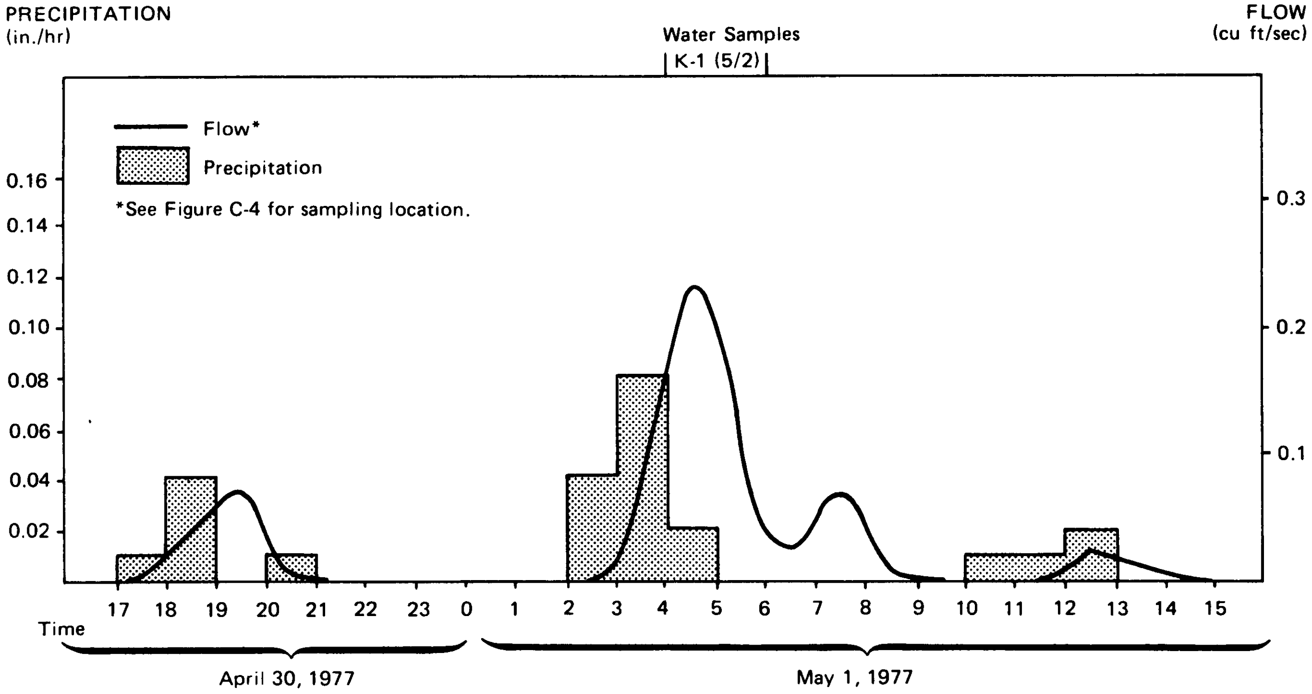


Figure F-4. Runoff from Keyes street study area during the rains of April 30 and May 1, 1977.

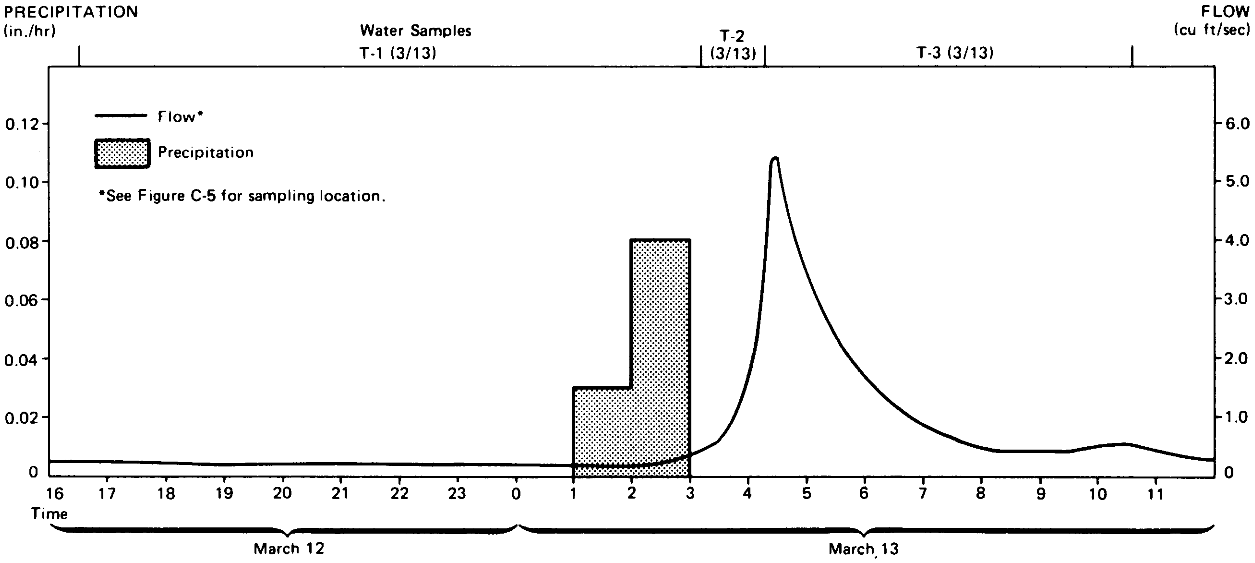


Figure F-5. Runoff from Tropicana study area during the rains of March 13, 1977.

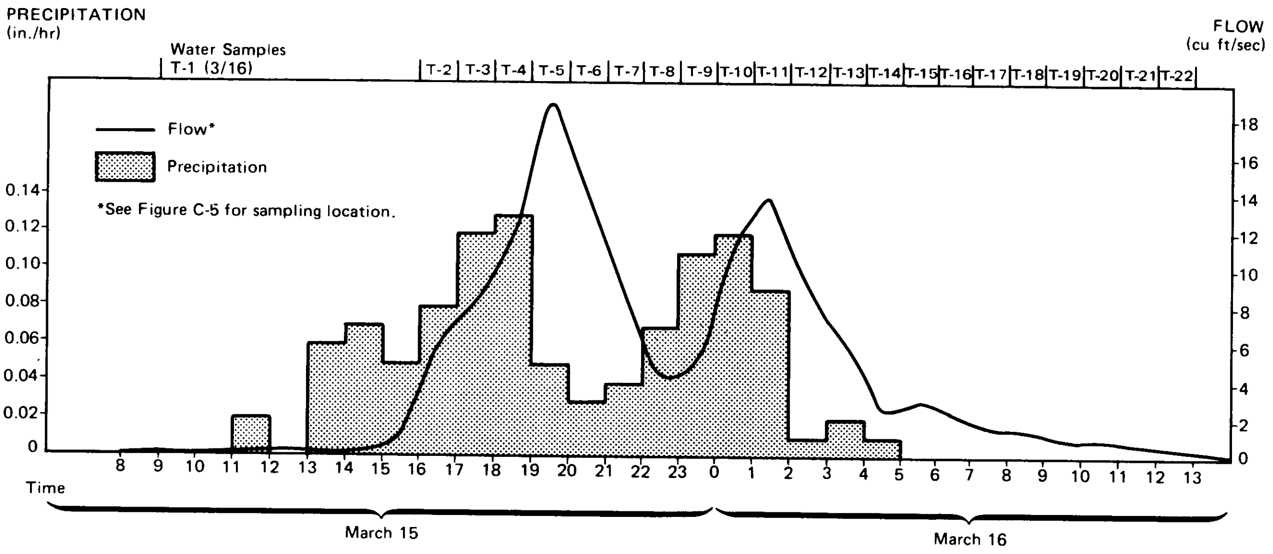


Figure F-6. Runoff from Tropicana study area during the rains of March 15 and 16, 1977.

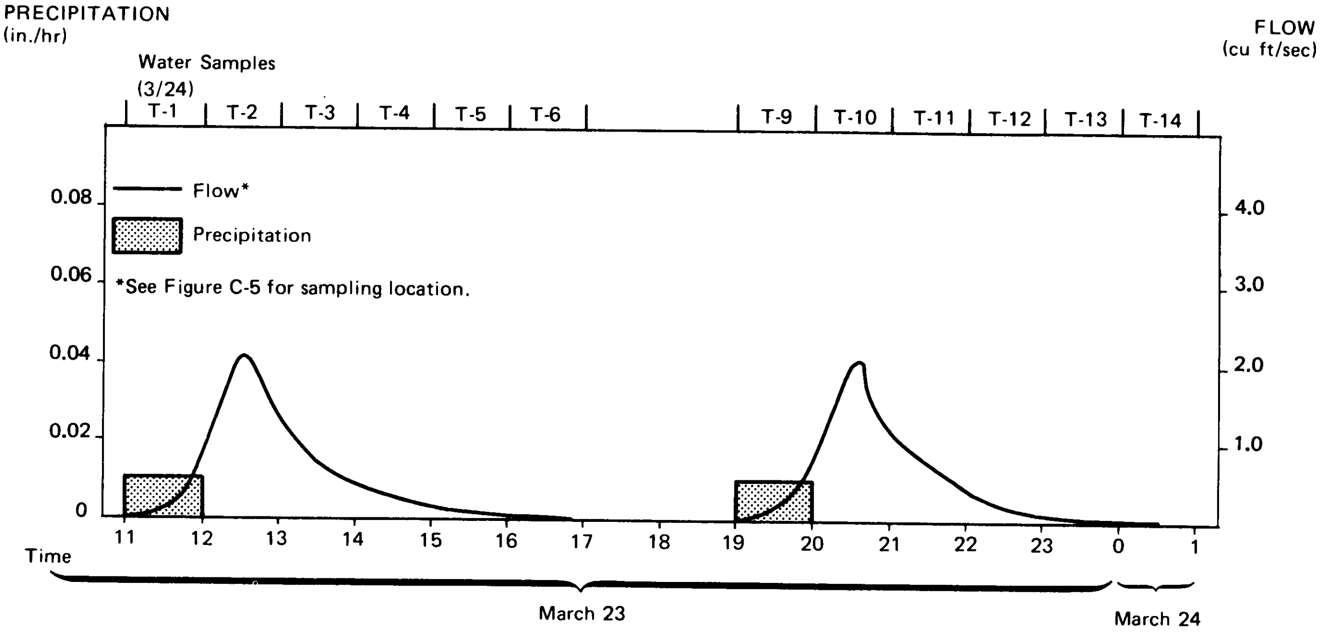


Figure F-7. Runoff from Tropicana study area during the rains of March 23, 1977.

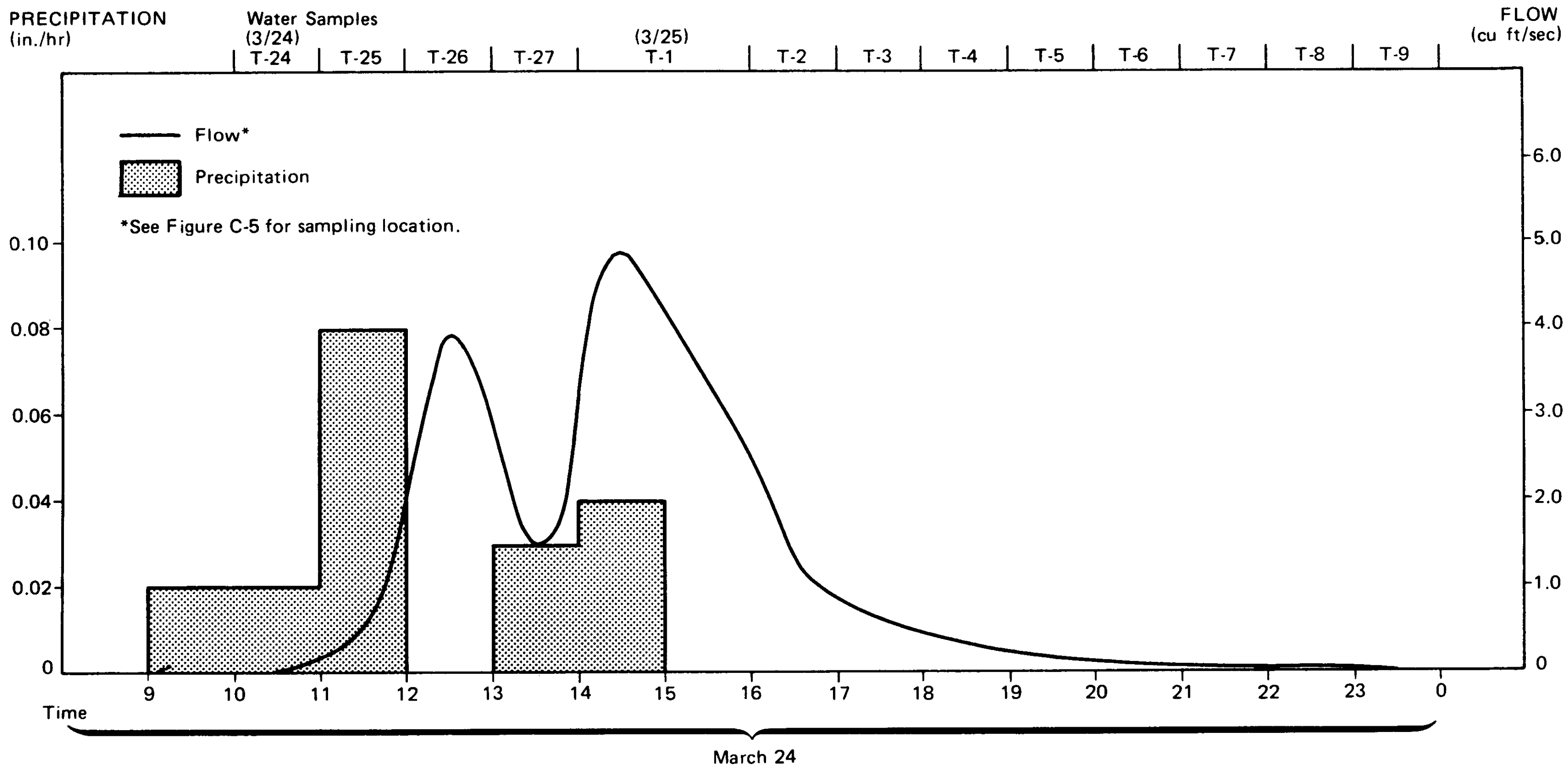


Figure F-8. Runoff from Tropicana study area during the rains of March 24, 1977.

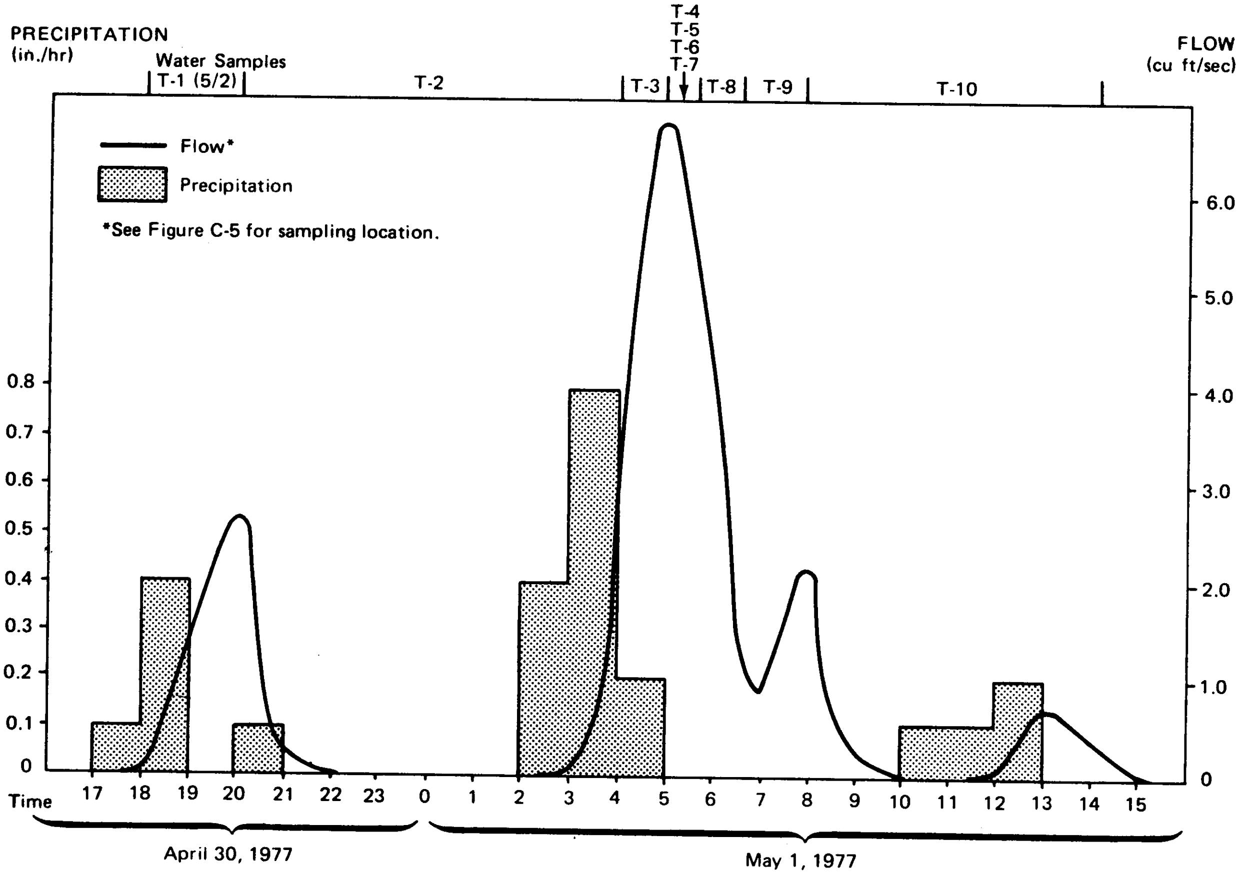


Figure F-9. Runoff from Tropicana study area during the rains of April 30 and May 1, 1977.

TABLE F-1. KEYES STUDY AREA WATER SAMPLE DATA FOR MARCH 15 AND 16, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/16 K-3	3/15	17 → 18	2.0*	7200*	6.6	140	60	77
K-4	3/15	18 → 19	2.8*	10,000*	6.8	---	40	78
K-5	3/15	19 → 20	4.5*	16,000*	6.8	---	40	81
K-6	3/15	20 → 21	3.3*	12,000*	6.8	---	35	75
K-7	3/15	21 → 22	1.7*	6100*	6.9	130	30	59
K-8	3/15	22 → 23	1.1*	4000*	7.0	---	30	53
K-9	3/15	23 → 0	1.2*	4300*	7.4	---	35	53
K-10	3/16	0 → 1	2.6*	9400*	7.2	---	33	36
K-11	3/16	1 → 2	3.3*	12,000*	7.3	130	28	28
K-12	3/16	2 → 3	2.1*	7600*	7.3	---	20	39
K-13	3/16	3 → 4	1.4*	5000*	7.2	---	20	27
K-14	3/16	4 → 5	0.8*	3000*	7.0	---	23	24
K-15	3/16	5 → 6	0.7*	2600*	7.1	140	30	22
K-16	3/16	6 → 7	0.5*	1900*	7.0	---	33	15
K-17	3/16	7 → 8	0.4*	1400*	7.0	---	38	13
K-18	3/16	8 → 9	0.3*	1200*	7.0	---	38	10

*Interpolated values.

TABLE F-2. KEYES STUDY AREA WATER SAMPLE DATA FOR MARCH 23, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/24 K-1	3/23	12 → 13	0.1*	360*	6.3	150	200	94

*Estimated.

TABLE F-3. KEYES STUDY AREA WATER SAMPLE DATA FOR MARCH 24, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/24 K-23	3/24	10 → 11	<0.01*	<36*	6.8	--	220	43
K-24	3/24	11 → 12	0.03*	110*	6.7	--	80	90
K-25	3/24	12 → 13	0.2*	720*	7.1	--	60	72
K-26	3/24	13 → 14	0.1*	260*	6.9	130	60	88
3/25 K-1	3/24	14 → 15	0.2	570	6.6	--	50	83
K-2	3/24	15 → 16	0.2	580	6.6	--	60	120
K-3	3/24	16 → 17	0.2	580	6.7	130	75	100

*Estimated.

TABLE F-4. TROPICANA STUDY AREA WATER SAMPLE DATA FOR MARCH 13, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/13 T-1	3/12→ 3/13	16 → 3	0.26	9400	7.5	130	590	17
T-2	3/13	3 → 4	5.4	19,000	7.1	130	160	69
T-3	3/13	4 → 11	0.77	19,000	6.8	130	175	51

TABLE F-5. TROPICANA STUDY AREA WATER SAMPLE DATA FOR MARCH 13 THROUGH 15, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/15 T-1	3/13	11 → 18	0.24	7000	6.7	140	125	12
T-2	3/13→ 3/14	19 → 16	0.18	15,000	7.2	130	220	5.8
T-3	3/14→ 3/15	17 → 8	0.19	11,000	7.5	120	260	5.1

TABLE F-6. TROPICANA STUDY AREA WATER SAMPLE DATA FOR MARCH 15 AND 16, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/16 T-1	3/15	9 → 16	0.3	7600	6.8	130	275	68
T-2	3/15	16 → 17	6.0	22,000	6.7	130	70	67
T-3	3/15	17 → 18	8.3	30,000	6.7	---	60	90
T-4	3/15	18 → 19	12	42,000	7.7	---	48	86
T-5	3/15	19 → 20	19	67,000	6.7	130	48	63
T-6	3/15	20 → 21	14	51,000	6.8	---	60	38
T-7	3/15	21 → 22	7.1	25,000	6.8	---	75	29
T-8	3/15	22 → 23	4.5	16,000	6.9	---	70	32
T-9	3/15	23 → 0	5.2	19,000	6.8	140	55	25
T-10	3/15	0 → 1	11	39,000	6.7	---	52	31
T-11	3/16	1 → 2	14	51,000	6.8	---	75	33
T-12	3/16	2 → 3	8.9	32,000	6.9	---	92	26
T-13	3/16	3 → 4	6.0	21,000	6.7	130	110	21
T-14	3/16	4 → 5	3.5	13,000	7.0	---	135	19
T-15	3/16	5 → 6	3.0	11,000	7.0	---	145	17
T-16	3/16	6 → 7	2.2	7900	7.0	---	140	13
T-17	3/16	7 → 8	1.6	5700	7.1	130	125	41
T-18	3/16	8 → 9	1.4	5100	7.0	---	128	61
T-19	3/16	9 → 10	0.9	3100	7.1	---	195	14
T-20	3/16	10 → 11	0.8	3000	7.2	---	210	14
T-21	3/16	11 → 12	0.6	2200	7.2	130	210	13
T-22	3/16	12 → 13	0.5	1800	7.3	---	215	12

TABLE F-7. TROPICANA STUDY AREA WATER SAMPLE DATA FOR MARCH 23, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/24 T-1	3/23	11 → 12	0.12	430	7.6	0	660	58
T-2	3/23	12 → 13	2.1	7400	6.7	--	175	30
T-3	3/23	13 → 14	0.7	2400	6.6	--	160	24
T-4	3/23	14 → 15	0.2	810	6.7	120	150	16
T-5	3/23	15 → 16	0.1	350	6.7	100	160	12
T-6	3/23	16 → 17	<0.1	<350	6.9	--	150	12
3/24 T-9	3/23	19 → 20	0.1*	360*	7.2	--	170	4.8
T-10	3/23	20 → 21	2.0*	7400*	7.0	--	210	6.2
T-11	3/23	21 → 22	0.7*	2400*	7.0	80	250	11
T-12	3/23	22 → 23	0.2*	810*	7.0	--	250	8.8
T-13	3/23	23 → 0	0.1*	350*	7.0	--	260	8.3
T-14	3/24	0 → 1	<0.1	<350*	7.1	120	260	6.2

* Estimated (flow meter fouled).

TABLE F-8. TROPICANA STUDY AREA WATER SAMPLE DATA FOR MARCH 24, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
3/24 T-24	3/24	10 → 11	<0.1	0	7.2	120	220	67
T-25	3/24	11 → 12	0.6	2000	7.0	---	70	65
T-26	3/24	12 → 13	3.9	14,000	7.0	---	50	38
T-27	3/24	13 → 14	1.5	5600	7.0	---	60	71
3/25 T-1	3/24	14 → 16	3.4	12,000	6.9	110	60	130
T-2	3/24	16 → 17	1.2	4500	6.9	---	60	67
T-3	3/24	17 → 18	0.7	2400	7.0	---	70	83
T-4	3/24	18 → 19	0.3	1100	7.0	---	80	47
T-5	3/24	19 → 20	0.2	590	7.2	130	90	47
T-6	3/24	20 → 21	0.1	360	7.1	---	90	37
T-7	3/24	21 → 22	<0.1	50	7.2	---	100	43
T-8	3/24	22 → 23	<0.1	0	7.4	---	100	32
T-9	3/24	23 → 0	<0.1	0	7.4	120	110	21

TABLE F-9. TROPICANA STUDY AREA WATER SAMPLE DATA FOR APRIL 30 AND MAY 1, 1977 RUNOFF

Water Sample Number	Date	Time of Day	Avg. Flow (cfs)	Flow during Sample Period (cu. ft.)	pH	ORP (mv)	Specific Conductance (μmhos/cm)	Turbidity (NTU)
5/2 T-1	4/30	18 → 20*	1.2*	8000	6.1	70	190	65
T-2	4/30 & 5/1	20 → 4*	0.35*	8000	6.6	40	260	68
T-3	5/1	4 → 5*	2.6*	8000	6.1	60	110	64
T-4	5/1	5 → 6*	6.8*	8000	6.0	60	85	49
T-5	5/1	5 → 6*	6.8*	8000	6.2	70	110	28
T-6	5/1	5 → 6*	6.8*	8000	6.3	80	145	31
T-7	5/1	5 → 6*	6.8*	8000	6.1	90	90	23
T-8	5/1	6 → 7	3.9*	8000	6.4	90	110	12
T-9	5/1	7 → 8	0.9*	8000	6.5	110	140	35
T-10	5/1	8 → 14*	0.5*	6000	6.3	110	90	33
5/2 K-1	5/1	4:20 → 5:50	0.18	1200	6.2	100	100	15

TABLE F-10. IN SITU DISSOLVED OXYGEN AND TEMPERATURE RUNOFF MEASUREMENTS

Keyes Street Study Area

Date:	3/15	3/16	3/16	3/23	3/24
Time:	1435	917	1115	1117	1515
DO* (mg/L):	9.4	--	6.5	7.4	9.9
Temp. (°C):	15	16	15	16	15

Tropicana Study Area

Date:	3/12	3/12	3/13	3/15	3/16	3/23	3/24
Time:	1120	1130	1045	1500	1214	1300	1515
DO* (mg/L):	12.8	5.4	6.9	7.5 →8.2	7.4	7.5	8.6
Temp. (°C):	16.5	--	15	15	14	16.5	15

*Dissolved Oxygen.

TABLE F-11. MAJOR IONS FOR MARCH 15 AND 16, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu. ft.)	Parameter Unit	Ca^{++}	K^{+}	Mg^{++}	Na^{+}	Cl^{-}	$SO_4^{=}$	HCO_3^{-}	$CO_3^{=}$	NO_3^{-}
				KEYES STREET STUDY AREA									
3,4,5,6,7, 8,9,10,11, 12,13,14, 15,16,17,18	17(3/15)→ 9(3/16)	16 hrs	103,800	mg/L	2.8	1.5	1.4	2.1	3.9	6.3	16	0.0006	0.5
				lb	18	9.7	9.1	14	25	41	100	0.007	3
				lb/hr	1.1	0.61	0.57	0.85	1.6	2.6	6.5	0.0004	0.2
				mg/kg*	20,000	11,000	10,000	15,000	27,000	43,000	110,000	41	3400
				TROPICANA STUDY AREA									
1,2,3,4,5, 6,7,8,9,10, 11,12,13, 14,15,16, 17,18,19, 20,21	9(3/15)→ 12(3/16)	27 hrs	474,000	mg/L	10.5	1.9	3.9	14.4	11.7	15.2	37	0.013	1.5
				lb	310	56	120	425	346	450	1,100	0.38	44
				lb/hr	11.5	2.1	4.3	15.7	12.8	16.6	40.5	0.01	1.6
				mg/kg*	38,000	6,900	14,000	52,000	43,000	55,000	135,000	47	5500

*Mg pollutant/kg total solids.

TABLE F-12. KEYES STUDY AREA MAJOR PARAMETERS FOR MARCH 15 AND 16, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu. ft.)	Parameter Unit	BOD_5	COD	KN	OPO_4	TS[a]	TDS[b]	SS[c]
3,4,5, 6,7,8 9,10	17(3/15)→ 1(3/16)	8 hrs	69,200	mg/L	35	162.6	9	4.6	182	40	142
				lb	151	701	38.9	19.8	785	172	612
				lb/hr	18.9	87.6	4.9	2.5	98.1	21.5	76.5
				mg/kg[d]	192,000	893,000	49,500	25,300	--	220,000	780,000
11,12 13,14 15,16, 17,18	1→9(3/16)	8 hrs	34,600	mg/L	19	73.2	6	0.6	73	22	51
				lb	41.0	158	12.9	1.29	157	47	110
				lb/hr	18.9	19.8	1.6	0.16	19.1	5.9	13.8
				mg/kg	260,000	1,000,000	82,200	8220	--	300,000	700,000
Flow - weighted average or total of above	17(3/15)→ 9(3/16)	16 hrs	103,800	mg/L	29.8	133	8	3.3	146	34	112
				lb	192	859	51.8	21.1	942	219	722
				lb/hr	12.0	53.7	3.2	1.3	59	14	45.1
				mg/kg[d]	204,000	911,000	54,800	22,600	--	230,000	770,000

[a] Total solids. [b] Total dissolved solids. [c] Suspended solids. [d] Mg pollutant/kg total solids.

TABLE F-13. TROPICANA STUDY AREA MAJOR PARAMETERS FOR MARCH 15 AND 16, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu. ft.)	Parameter Unit	BOD_5	COD	KN	OPO_4	TS[a]	TDS[b]	SS[c]
1,2,3, 4,5,6 7	9 → 22(3/15)	13 hrs	245,000	mg/L	28	96.8	3.7	3	376	110	266
				lb	427	1,480	56.5	45.8	5,740	1,680	4,060
				lb/hr	32.8	114	4.3	3.5	442	129	312
				mg/kg[d]	74,500	257,000	9840	7980	--	293,000	707,000
8,9,10, 11,12 13,14	22(3/15) → 5(3/16)	7 hrs	191,000	mg/L	22	52.6	2	1.4	164	110	54
				lb	262	626	23.8	16.7	1,950	1,310	643
				lb/hr	37.4	89.4	3.4	2.4	279	187	91.9
				mg/kg[d]	134,000	321,000	12,200	8540	--	671,000	329,000
15,16, 17,18, 19,20, 21	5 → 12(3/16)	7 hrs	37,700	mg/L	23	68.5	4.2	1.4	174	120	54
				lb	54.0	161	9.9	3.3	409	282	127
				lb/hr	7.7	23.0	1.4	0.47	58.4	40.3	18.1
				mg/kg[d]	132,000	394,000	24,100	80,540	--	690,000	310,000
Flow-weighted average or total of above	9(3/15) → 12(3/16)	27 hrs	474,000	mg/L	25.2	77.0	3.1	2.2	275	111	164
				lb	743	2,267	90.2	65.8	8,099	3,272	4,830
				lb/hr	27.5	84.0	3.4	2.4	300	121	179
				mg/kg[d]	91,600	280,000	11,300	8000	--	404,000	596,000

[a] Total solids. [b] Total dissolved solids. [c] Suspended solids. [d] Mg pollutant/kg total solids.

TABLE F-14. HEAVY METALS FOR MARCH 15 AND 16, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu. ft.)	Parameter Unit	Cd	Cr	Cu	Pb	Zn	Hg
				KEYES STREET STUDY AREA						
3,4,5,6,7,8 9,10,11,12 13,14,15, 16,17,18	17(3/15)→ 9(3/16)	16 hrs	103,800	mg/l	0.004	0.01	0.02	0.27	0.11	<0.0001
				lb	0.026	0.065	0.13	1.75	0.71	<0.0006
				lb/hr	0.002	0.004	0.008	0.11	0.044	<0.001
				mg/kg*	27	68	140	1800	750	<1
				TROPICANA STUDY AREA						
1,2,3,4,5, 6,7	9 → 22 (3/15)	13 hrs	245,000	mg/l	<0.002	0.02	0.02	0.32	0.13	<0.0001
				lb	<0.03	0.3	0.3	4.9	2.0	<0.002
				lb	<0.002	0.02	0.02	0.38	0.15	<0.0001
				mg/kg*	<5	50	50	850	350	<0.3
8,9,10,11, 12,13,14,	22(3/15) → 5(3/16)	7 hrs	191,000	mg/l	<0.002	0.01	0.01	0.10	0.06	<0.001
				lb	<0.02	0.1	0.1	1.2	0.71	<0.01
				lb/hr	<0.003	0.02	0.02	0.17	0.10	<0.002
				mg/kg*	<10	60	60	610	370	<6
15,16,17, 18,19,20, 21	5 → 12 (3/16)	7 hrs	37,700	mg/l	<0.002	0.01	0.02	0.18	0.09	<0.001
				lb	<0.005	0.02	0.05	0.42	0.21	<0.002
				lb/hr	<0.001	0.003	0.007	0.06	0.03	<0.001
				mg/kg*	<11	60	110	1000	520	<6
Flow - weighted average or total of above	9(3/15)→ 12(3/16)	27 hrs	474,000	mg/l	<0.002	0.01	0.02	0.22	0.1	<0.001
				lb	<0.055	0.4	0.45	6.5	2.9	<0.01
				lb/hr	<0.002	0.02	0.017	0.24	0.11	<0.001
				mg/kg*	<7	40	70	800	360	<4

*Mg pollutant/kg total solids.

TABLE F-15. TROPICANA STUDY AREA SOLIDS AS A FUNCTION OF TIME FOR MARCH 15 AND 16, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft.)	Parameter Unit	Total Solids	Total Dissolved Solids	Suspended Solids	Specific Conductance
1,2	9 → 17 (3/15)	8 hrs	29,290	Concentration^a	314	180	134	$\frac{275 + 70}{2} = 173$
				lb	573	328	245	--
				lb/hr	19.5	11.2	8.3	--
				mg/kg^b	--	573,000	427,000	--
				Spec. cond./TDS^c	--	0.96	--	--
3,4	17 → 19 (3/15)	2 hrs	72,040	Concentration^a	281	35	246	54
				lb	1260	157	1104	--
				lb/hr	630	79	552	--
				mg/kg^b	--	125,000	875,000	--
				Spec. cond./TDS^c	--	1.5	--	--
5,6	19 → 21 (3/15)	2 hrs	118,370	Concentration^a	172	60	112	54
				lb	1268	442	826	--
				lb/hr	634	221	413	--
				mg/kg^b	--	349,000	651,000	--
				Spec. cond./TDS^c	--	0.90	--	--
7,8	21 → 23 (3/15)	2 hrs	41,700	Concentration^a	117	80	37	73
				lb	304	208	96	--
				lb/hr	152	104	48	--
				mg/kg^b	--	684,000	316,000	--
				Spec. cond./TDS^c	--	0.91	--	--
9,10	24 → 0 (3/15) 0 → 1 (3/16)	2 hrs	57,620	Concentration^a	107	50	57	53
				lb	384	179	--	--
				lb/hr	192	89	103	--
				mg/kg^b	--	467,000	533,000	--
				Spec. cond./TDS^c	--	1.061	--	--
11,12	1 → 3 (3/16)	2 hrs	82,980	Concentration^a	126	90	36	84
				lb	651	465	186	--
				lb/hr	325	232	93	--
				mg/kg	--	714,000	286,000	--
				Spec. cond./TDS^c	--	0.93	--	--
13,14	3 → 5 (3/16)	2 hrs	34,140	Concentration^a	149	130	19	123
				lb	317	277	40	--
				lb/hr	159	139	20	--
				mg/kg^b	--	872,000	128,000	--
				Spec. cond/TDS^c	--	0.95	--	--
15,16	5 → 7 (3/16)	2 hrs	18,570	Concentration^a	177	160	17	143
				lb	205	185	20	--
				lb/hr	103	93	10	--
				mg/kg^b	--	904,000	96,000	--
				Spec. cond/ TDS^c	--	0.89	--	--
17,18	7 → 9 (3/16)	2 hrs	10,810	Concentration^a	222	120	102	127
				lb	150	81	69	--
				lb/hr	75	40	35	--
				mg/kg^b	--	541,000	459,000	--
				Spec. cond/TDS^c	--	1.06	--	--
19,20	9 → 11 (3/16)	2 hrs	6120	Concentration^a	245	230	15	203
				lb	93	88	5.7	--
				lb/hr	47	44	3	--
				mg/kg^b	--	939,000	61,000	--
				Spec. cond./TDS^c	--	0.88	--	--
Flow-weighted average of above	9(3/15) → 11(3/16)	26 hrs	471,640	Concentration^a	180	83	97	80
				lb	5210	2410	2800	--
				lb/hr	200	93	107	--
				mg/kg^b	--	460,000	540,000	--
				Spec. cond./TDS^c	--	0.86	--	

[a] Concentrations in mg/l or µmhos/cm.
[b] Mg pollutant/kg total solids.
[c] Special conductance/total dissolved solids.

TABLE F-16. MAJOR IONS FOR MARCH 23 AND 24, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft.)	Parameter Unit	Ca^{++}	K^{+}	Mg^{++}	Na^{+}	Cl^{-}	$SO_4^{=}$	HCO_3^{-}	$CO_3^{=}$	NO_3^{-}
KEYES STREET STUDY AREA													
1,23,24, 25,26, 1,2,3	12 → 13 (3/23) 10 → 17 (3/24)	8 hrs	3160	mg/l	19	3.0	3.9	9.2	11.7	17.5	153	0.055	0.9
				lb	3.7	0.59	0.77	1.8	2.3	3.4	30	0.01	0.18
				lb/hr	0.47	0.07	0.096	0.23	0.29	0.43	3.8	<0.01	0.022
				mg/kg*	28,000	4400	5800	14,000	17,000	26,000	230,000	81	1300
TROPICANA STUDY AREA													
1,2,3, 4,5,6, 9,10, 11,12, 13,14, 24,25, 26,27, 1,2,3, 4,5,6, 7,8,9	11 → 0 (3/23) 0 → 0 (3/24)	25 hrs	72,700	mg/l	15	3.4	6.2	26.8	15.7	26.4	62	0.022	0.5
				lb	68	15	28	120	71.1	120	280	0.10	2.3
				lb/hr	2.7	0.62	1.1	4.9	2.8	4.8	11	<0.01	0.09
				mg/kg*	54,000	12,000	22,000	95,700	56,000	94,300	220,000	79	1800

*Mg pollutant/kg total solids.

TABLE F-17. KEYES STREET STUDY AREA MAJOR PARAMETERS FOR MARCH 23 AND 24, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft)	Parameter Unit	BOD$_5$	COD	KN	OPO$_4$	TS[a]	TDS[b]	SS[c]	VSS[d]
1,23, 24,25	12 → 13 (3/23)	4 hrs	1,430	mg/l	35	474	4.4	0.2	345	107	238	52
				lb	3.1	42	0.39	0.02	31	9.5	21	4.6
	10 → 13 (3/24)			lb/hr	0.78	11	0.10	0.005	7.8	2.4	5.3	1.2
				mg/kg[e]	100,000	1.4×10^6	13,000	580	--	310,000	690,000	150,000
26,1, 2,3	13 → 17 (13/24)	4 hrs	1,730	mg/l	11	242	2.9	--	952	107	845	200
				lb	1.2	26	0.31	--	100	12	91	22
				lb/hr	0.30	6.5	0.078	--	26	2.9	23	5.4
				mg/kg[e]	12,000	250,000	3000	--	--	110,000	890,000	210,000
Flow-weighted average or total	12 → 13 (3/23)	8 hrs	3,160	mg/l	22	350	3.6	--	678	107	571	140
				lb	4.3	68	0.70	--	134	22	112	27
	10 → 17 (3/24)			lb/hr	0.54	8.5	0.088	--	16	2.7	14	3.3
				mg/kg[e]	32,000	520,000	5300	--	--	160,000	840,000	210,000

[a] Total solids.
[b] Total dissolved solids.
[c] Suspended solids.
[d] Volatile suspended solids.
[e] mg pollutant/kg total solids.

TABLE F-18. TROPICANA STUDY AREA MAJOR PARAMETERS FOR MARCH 23 AND 24, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu. ft.)	Parameter Unit	BOD_5	COD	KN	OPO_4	TS[a]	TDS[b]	SS[c]	VSS[d]
1,2,3, 4,5,6	11 → 17 (3/23)	6 hrs	11,400	mg/l	31	210	5.6	0.8	401	334	67	8
				lb	22	150	4.0	0.6	280	240	48	5.7
				lb/hr	3.7	25	0.66	0.1	47	40	7.9	1.0
				mg/kg[e]	77,000	520,000	14,000	2000	--	830,000	170,000	20,000
9,10, 11,12, 13,14	19 → 0 (3/23) 0 → 1 (3/24)	6 hrs	780	mg/l	17	182	3.7	0.8	386	371	15	5
				lb	0.83	8.8	0.18	0.04	19	18	0.73	0.24
				lb/hr	0.14	1.5	0.030	0.006	3.1	3.0	0.12	0.04
				mg/kg[e]	44,000	470,000	9600	2100	--	960,000	39,000	13,000
24,25, 26,27, 1,2,3, 4,5,6, 7,8,9	10 → 0 (3/24)	13 hrs	60,520	mg/l	14	154	3.4	0.4	254	118	136	29
				lb	53	580	13	1.5	960	440	510	110
				lb/hr	4.1	45	1.0	0.12	74	34	39	8.4
				mg/kg[e]	55,000	610,000	13,000	1600	--	460,000	540,000	110,000
Flow - weighted average or total of above	11 → 0 (3/23) 0 → 0 (3/24)	25 hrs	72,700	mg/l	17	160	3.8	0.5	280	160	120	27
				lb	76	740	17	2.1	1260	700	560	120
				lb/hr	3.0	30	0.69	0.086	50	28	22	4.6
				mg/kg[e]	61,000	570,000	14,000	1800	--	570,000	430,000	96,000

[a] Total solids. [b] Total dissolved solids. [c] Suspended solids. [d] Volatile suspended solids. [e] Mg pollutant/kg total solids.

TABLE F-19. HEAVY METALS FOR MARCH 23 AND 24, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft.)	Parameter Unit	Cd	Cr	Cu	Pb	Zn	Hg
				KEYES STREET STUDY AREA						
1,23 24,25, 26,1, 2,3	12 → 13 (3/23) 10 → 17 (3/24)	8 hrs	3160	mg/l	0.004	0.03	0.04	0.76	0.32	0.0001
				lb	0.0008	0.0059	0.0079	0.15	0.063	2×10^{-5}
				lb/hr	0.0001	0.0007	0.0010	0.018	0.008	2.5×10^{-6}
				mg/kg*	5.9	44	59	1100	470	0.15
				TROPICANA STUDY AREA						
1,2 3,4 5,6	11 → 17 (3/23)	6 hrs	11,400	mg/l	<0.002	0.005	0.03	0.24	0.11	<0.0001
				lb	<0.0014	0.0036	0.021	0.17	0.078	<0.0001
				lb/hr	<0.0002	0.0006	0.0035	0.028	0.013	<0.00002
				mg/kg*	<5	12	75	600	270	<0.25
9,10, 11,12, 13,14	19 → 0 (3/23) 0 → 1 (3/24)	6 hrs	780	mg/l	<0.002	0.005	0.02	0.15	0.08	<0.0001
				lb	<0.0001	0.0002	0.001	0.0073	0.0039	$<5 \times 10^{-6}$
				lb/hr	<0.00002	0.00003	0.00016	0.0012	0.00065	$<8 \times 10^{-7}$
				mg/kg*	<5.2	13	52	389	207	<0.26
24,25, 26,27, 1,2,3, 4,5,6 7,8,9	10 → 0 (3/24)	13 hrs	60,520	mg/l	<0.002	0.01	0.01	0.19	0.12	<0.0001
				lb	<0.008	0.038	0.038	0.72	0.45	$<4 \times 10^{-4}$
				lb/hr	<0.0006	0.0029	0.0029	0.055	0.035	$<3 \times 10^{-5}$
				mg/kg*	<7.9	39	39	748	472	0.39
Flow - weighted average or total of above	11 → 0 (3/23) 0 < 0 (3/24)	25 hrs	72,700	mg/l	<0.0021	0.009	0.013	0.199	0.118	<0.0001
				lb	<0.0095	0.042	0.060	0.897	0.532	<0.0005
				lb/hr	<0.0004	0.002	0.002	0.036	0.021	$<2 \times 10^{-5}$
				mg/kg*	<7.5	33	48	711	421	<0.36

*mg pollutant/kg total solids.

TABLE F-20. TROPICANA STUDY AREA SOLIDS AS A FUNCTION OF TIME FOR MARCH 23 AND 24, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft.)	Parameter Unit	Total Solids	Total Dissolved Solids	Suspended Solids	Volatile Suspended Solids	Specific Conduct-ance
1,2	11 → 13 (3/23)	2 hrs	7830	Concentration[a]	195	140	55	6	418
				lb	95	68	27	2.9	--
				lb/hr	48	34	14	1.5	--
				mg/kg[b]	--	720,000	280,000	43,000	--
				Spec. cond/TDS[c]	--	3.0	--	--	--
3,4	13 → 15 (3/23)	2 hrs	3220	Concentration[a]	200	180	20	15	155
				lb	40	36	4.0	3.0	--
				lb/hr	20	18	2.0	1.5	--
				mg/kg[b]	--	900,000	100,000	75,000	--
				Spec. cond./TDS[c]	--	0.86	--	--	--
5,6	15 → 17 (3/23)	2 hrs	350	Concentration[a]	282	257	25	7	155
				lb	6.1	5.6	0.55	0.15	--
				lb/hr	3.1	2.8	0.28	0.08	--
				mg/kg[b]	--	910,000	90,000	25,000	--
				Spec. cond/TDS[c]	--	0.60	--	--	--
9,10	19 → 21 (3/23)	2 hrs	0	Concentration[a]	338	303	35	7	190
				lb	0	0	0	0	--
				lb/hr	0	0	0	0	--
				mg/kg[b]	--	900,000	100,000	21,000	--
				Spec. cond./TDS[c]	--	0.63	--	--	--
11,12	21 → 23 (3/23)	2 hrs	590	Concentration [a]	448	183	265	50	250
				lb	16	6.7	9.7	1.8	--
				lb/hr	8	3.4	5.3	0.9	--
				mg/kg[b]	--	410,000	590,000	110,000	--
				Spec. cond./TDS[c]	--	1.37	--	--	--
13,14	23 → 1 (3/23 and 3/24)	2 hr	190	Concentration[a]	430	230	200	--	260
				lb	5.1	2.7	2.4	--	--
				lb/hr	2.5	1.4	1.2	--	--
				mg/kg [b]	--	530,000	470,000	--	--
				Spec. cond./TDS[c]	--	1.13	--	--	--

(Continued)

TABLE F-20. (CONCLUDED).

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft.)	Parameter Unit	Total Solids	Total Dissolved Solids	Suspended Solids	Specific Conductance
24,25	10 → 12 (3/24)	2 hr	2010	Centcentration[a]	331	231	100	$\frac{220 + 70}{2}$
				lb	41	29	13	--
				lb/hr	21	14	6.5	--
				mg/kg[b]	--	700,000	300,000	--
				Spec. cond./TDS[c]	--	0.63	--	--
26,27	12 → 14	2 hr	19,490	Concentration[a]	158	78	80	55
				lb	192	95	97	--
				lb/hr	96	48	48	--
				mg/kg	--	490,000	510,000	--
				Spec. cond./TDS[c]	--	0.71	--	--
1,2	15 → 17 (3/24)	2 hr	16,760	Concentration[a]	51	26	25	60
				lb	53	27	26	--
				lb/hr	27	14	13	--
				mg/kg	--	510,000	490,000	--
				Spec. cond./TDS[c]	--	2.31	--	--
3,4	17 → 19	2 hrs	3490	Concentration[a]	136	116	20	75
				lb	30	25	4.3	--
				lb/hr	15	13	2.2	--
				mg/kg	--	850,000	150,000	--
				Spec. cond./TDS[c]	--	0.65	--	--
Flow weighted average of above	11 → 0 (3/23) 0 → 19 (3/24)	25 hrs	71,700	Concentration[a]	107	66	41	123
				lb	476	292	184	--
				lb/hr	19	12	7.4	--
				mg/kg	--	630,000	390,000	--
				Spec. cond./TDS[c]	--	1.9	--	--

[a] Concentration expressed in mg/l except for specific conductance, which is measured in µ mhos/cm.

[b] Mg pollutant/kg total solids. [c] Specific conductance/total dissolved solids.

TABLE F-21. TROPICANA STUDY AREA MAJOR IONS FOR APRIL 30 AND MAY 1, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft.)	Parameter Unit	Ca^{++}	K^+	Mg^{++}	Na^+	Cl^-	$SO_4^=$	HCO_3^-	$CO_3^=$	NO_3^-
1,2,	18(4/30) →	20 hrs	78,000	mg/l	15.5	3.5	4.8	22.6	17.6	27	0	0	0.3
3,4,	10(5/1)			lb	75	17	23	110	86	131	--	--	1.46
5,6,				lb/hr	3.8	0.85	1.15	5.5	4.3	6.6	--	--	0.07
7,8,				mg/kg*	40,800	9200	13,000	59,500	46,300	71,000	--	--	800
9,10													

*Mg pollutant/kg total solids.

TABLE F-22. MAJOR PARAMETERS FOR APRIL 30 AND MAY 1, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elapsed Time (cu.ft.)	Parameter Unit	BOD$_5$	COD	KN	OPO$_4$	TS[a]	TDS[b]	SS[c]
				KEYES STREET STUDY AREA							
1	4 → 6 (approx) (5/1)	1.5 hrs	1200; not complete storm (total >2480)	mg/l	--	--	--	1.7	155	80	75
				lb	--	--	--	0.13	11.6	6.0	5.6
				lb/hr	--	--	--	0.08	7.7	4.0	3.7
				mg/kg[d]	--	--	--	11,000	--	520,000	480,00
				TROPICANA STUDY AREA							
1,2,3	18(4/30)→ 14(5/1)	10 hrs	24,000	mg/l	56	520	25	17.6	870	330	540
				lb	84	780	37	26.3	1300	490	810
				lb/hr	8.4	78	3.7	2.6	130	49	8.1
				mg/kg[d]	64,000	600,000	29,000	20,000	--	380,000	620,000
4,5,6	4 → 5 (5/1)	1 hr	24,000	mg/l	22	157	12	1.0	158	80	78
				lb	33	235	18	1.5	236	120	120
				lb/hr	33	235	18	1.5	236	120	120
				mg/kg[d]	140,000	990,000	76,000	6300	--	510,000	490,000
7,8,9,10	5 → 14 (5/1)	9 hrs	30,000	mg/l	11	127	9	0.8	168	100	68
				lb	21	237	17	1.5	314	190	130
				lb/hr	2.3	26	1.9	0.2	35	21	14
				mg/kg[d]	65,000	760,000	54,000	4800	--	600,000	400,000
Flow-weighted average or total of above	18(4/30)→ 14(5/1)	20 hrs	78,000	mg/l	28	260	15	6.0	380	160	
				lb	138	1,250	72	29	1850	800	1100
				lb/hr	6.9	63	3.6	1.5	93	40	53
				mg/kg[d]	74,000	680,000	39,000	16,000	--	420,000	580,000

[a] Total solids. [b] Total dissolved solids [c] Suspended solids. [d] Mg pollutant/kg total solids.

TABLE F-23. TROPICANA STUDY AREA HEAVY METALS FOR APRIL 30 AND MAY 1, 1977 RUNOFF

Sample Numbers	Time of Samples	Elapsed Time	Flow in Elasped Time (cu. ft.)	Parameter Unit	Cd	Cr	Cu	Pb	Zn	Hg
1,2,3	18(4/30) → 4(5/1)	10 hrs	24,000	mg/l	0.006	0.04	0.09	1.5	0.55	0.0006
				lb	0.009	0.06	0.14	2.2	0.82	0.0009
				lb/hr	0.001	0.006	0.013	0.22	0.082	0.0001
				mg/kg*	7	50	100	1700	630	0.7
4,5,6	4 → 5(5/1)	1 hr	24,000	mg/l	<0.002	0.01	0.03	0.35	0.17	0.0001
				lb	<0.003	0.015	0.045	0.52	0.25	0.00015
				lb/hr	<0.003	0.015	0.045	0.52	0.25	0.00015
				mg/kg*	10	60	200	2200	1100	0.6
7,8,9, 10	5 → 14(5/1)	9 hrs	30,000	mg/l	<0.002	0.01	0.02	0.26	0.11	<0.0001
				lb	<0.004	0.02	0.04	0.49	0.21	<0.0002
				lb/hr	<0.0004	0.002	0.004	0.054	0.023	<0.0001
				mg/kg*	<10	60	100	1500	650	<0.6
Flow-weighted average or total of above	18(4/30) → 14(5/1)	20 hrs	78,000	mg/l	0.002	0.02	0.05	0.66	0.27	0.0002
				lb	0.009	0.1	0.23	3.2	1.3	0.001
				lb/hr	0.0005	0.005	0.012	0.16	0.065	0.0001
				mg/kg*	5	50	100	1700	710	0.5

*Mg pollutant/kg total solids

APPENDIX G

ALTERNATIVE URBAN RUNOFF CONTROL MEASURES AND THE USE OF DECISION ANALYSIS

The first phase in designing an urban runoff control program is to identify which pollutants need to be controlled. This must be determined by monitoring the receiving water, sediments and beneficial uses directly. This monitoring can be supplemented with computer modelling by using locally calibrated runoff and receiving water models. Few, if any, models are available that can predict actual biological beneficial use impairments. Therefore, if biological uses of the receiving water are important, actual biological conditions must be studied. Hydrology, along with sediment and water column chemical analyses would be necessary to estimate cause and effect relationships. Control areas having acceptable biological conditions must also be analyzed to help define goal conditions. Those parameters that exceed these goal conditions for various sections of the receiving water can then be identified. Seasonal variations of removal goals needed to obtain acceptable discharge limits should also be determined, as beneficial uses and receiving water assimilative capacities change with season.

The next phase in an urban runoff control program is to determine the sources of the problem pollutants in the watershed. Table G-1 summarizes potential significant sources of various pollutant groups of an urban watershed. Again, these sources must be verified and quantified through actual field monitoring for the identified problem pollutants. Runoff samples, along with necessary dry samples from these and other appropriate source areas, should be analyzed. Source strengths should be estimated by season for the problem pollutants. The source areas associated with each problem pollutant can be identified and assigned priorities.

The third phase in developing an urban runoff control program is to determine what control measures can be used in the identified "problem" source areas. Table G-2 summarizes those control measures that are most suitable for controlling pollutants from various source areas. These control measures have been examined in many 208 studies. The effectiveness of the various control measures in the different source areas must also be determined by local studies. Some literature information, including the street cleaning results presented in this report, can be used to make a preliminary control design that can be modified with local experience. The following discussion summarizes available literature information pertaining to various erosion control and runoff treatment methods. Many of the other potential control measures listed on Table G-2 are regulatory in nature and would be 100 percent effective if complete compliance was possible.

Table G-3 shows the suitability of various control measures for controlling common urban runoff pollutants. It combines the information presented on Tables

TABLE G-1. POTENTIAL SIGNIFICANT URBAN RUNOFF POLLUTANT SOURCES

	POTENTIAL SIGNIFICANT POLLUTANT SOURCES									
Common Urban Runoff Pollutants	Rain	Roof Tops	Street Surfaces	Parking Lots	Litter (Including Animal Feces)	Landscaped Areas	Vacant Land	Construction Sites	Road Ice Control	Other (Industrial and Solid Waste Runoff)
Sediment			X				X	X	X	
Oxygen Demanding Matter					X	X				
Nutrients	X				X	X	X			
Salts									X	
Bacteria					X		X			
Heavy Metals			X	X						
Pesticides/Herbicides						X				
Oils and Greases		X	X	X	X			X		
Floating Matter					X	X				
Other Toxic Materials		X	X						X	X

TABLE G-2. CONTROL MEASURES MOST SUITABLE FOR CONTROLLING POLLUTANTS FROM VARIOUS SOURCE AREAS

	POTENTIAL POLLUTANT SOURCE AREAS									
Control Measures	Rain	Roof Tops	Street Surfaces	Parking Lots	Litter	Land-scaped Areas	Vacant Land	Con-struction Sites	Road Ice Control	Other (Industrial and Solid Waste Runoff)
Street Cleaning			X	X	X				X	
Leaf Removal				X	X	X				
Alternate De-Icing Methods									X	
Control Grass Types						X	X			
Repair Streets			X	X						
Control Fertilizer, Pesticide, etc.						X	X			
Control Use of Vacant Land							X			X
Control Litter					X		X			
Control Dog Litter					X	X	X			
Control Direct Discharge of Pollutants to Storm Drains	X	X			X					X
Eliminate Cross Connections with Sanitary Sewers										X
Clean Catchbasins			X					X		
Clean Storm Sewers and Drainage Channels			X					X		
Prevent Roof Drainage from Entering Storm Sewer Directly	X	X								
Direct Runoff Away from Contaminated Areas								X		X
Retain Runoff from Contaminated Areas								X		X
Regrade Disturbed Areas							X	X		X
Control Erosion at Construction Sites								X		
Store and Treat Runoff	X	X	X	X	X	X	X	X	X	X

TABLE G-3. SUITABILITY OF CONTROL MEASURES FOR CONTROLLING COMMON URBAN RUNOFF POLLUTANTS

	Common Urban Runoff Pollutants								
Control Measures:	Sediment	Oxygen Demanding Matter	Nutrients	Salts	Bacteria	Heavy Metals	Pesticides/ Herbicides	Oils and Grease	Floating Matter
Street Cleaning (with streets in good repair)	M*	L*	L	M	L/M*	H*		M	M
Leaf Removal (seasonal use)		L/M	L/M		L	L	L	L	H
Alternate De-icing Methods (seasonal use)	L			H					
Control Grass Types	L	L	L				L/M		L/M
Repair Streets	L/M					L		L	
Control Fertilizer, Pesticides, etc.			H				H		L
Control Use of Vacant Land	L/M		L/M		L/M				
Control Litter	L	L	L		L/M			L/M	M
Control Dog Litter		L	L		M/H*				L
Eliminate Cross Connections with Sanitary Sewers		L/M	L/M		M/H				
Clean Catchbasins	L					L/M		L	
Clean Storm Sewer and Drainage Channels	L/M					L/M		L	
Prevent Roof Drainage From Entering Storm Sewer Directly			L					L	
Direct Runoff Away from Contaminated Areas	M								
Retain Runoff From Contaminated Areas	M								
Regrade Disturbed Areas	M/H		L						
Control Erosion and Construction Sites	H							L/M	
Store and Treat Runoff	H	M/H	M	L	H	L/M	L	M	H

*L = Low suitability
L/M = Low-medium suitability
M = Medium suitability
M/H = Medium-high suitability
H = High suitability

G-1 and G-2, and also considers relative source strengths and approximate control measure effectivenesses. Any one of the control measures shown is highly suitable for only a few of the pollutant groups, while many of the control measures can be partially suitable for many of the pollutants. Even if a potential problem is confined to a single pollutant, a combination of control measures will most likely be needed.

The most appropriate control measure combination can be selected knowing potential removals and unit costs for each control measure. As an example, consider the hypothetical situation presented in Table G-4 for the Tropicana Study Area. This table presents a selection of possible control measures and estimated potential total solids removals (ton/year) and associated unit costs. Not considering the other objectives or partial control of the other pollutants, one would simply start with the least costly control measure until the desired removal is obtained. If less than 1 ton is all that must be removed, the least expensive erosion control option would be sufficient. However, if greater quantities must be removed, then a combination of control measures is needed, as illustrated in Table G-5. The selected mixture of control measures could vary, depending upon the parameter of concern and the total control needed .

TABLE G-4. ESTIMATED CONTROL MEASURE COSTS AND USE POTENTIALS FOR TROPICANA STUDY AREA

Control Measure	Potential Total Solids Removal (ton/year)	Unit Cost ($/lb)
Minimal (2 times/month) street cleaning*	3	0.14
Minimal (2 times/month) street cleaning with parking controls*	5	0.14**
Increased (4 times/week) street cleaning with parking controls*	15	0.25**
Erosion control	1	0.03***
Runoff control	25	1.00

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*These three levels of street cleaning use are alternatives; only one can be selected.

**But with increased service area complaints due to parking inconveniences.

***Usually paid by developer and passed along to property buyer--not a public cost.

TABLE G-5. CANDIDATE CONTROL MEASURE PRIORITY LISTING FOR TROPICANA STUDY AREA

Control Measure	Potential Total Solids Removal (tons/year)	Unit Cost ($/lb)	Total Annual Cost ($/year)
Erosion Control	1	0.03	60
Minimal street cleaning (2 times/month) with parking control	5	0.14	1400
Alternate street cleaning program: increased street cleaning (4 times/week) with parking controls	15	0.25	7,500
Runoff Control	25	1.00	50,000

More sophisticated procedures can be used to select the appropriate mix of control measures that consider a variety of parameters, control objectives and partial fulfillment of the objectives. The following paragraphs present very brief descriptions of other potential control measures. One type of decision analysis procedure is also briefly described in the following discussion.

EROSION CONTROL ALTERNATIVES

Effective erosion control practices applied within an urban area can decrease the particulate and pollutant loadings in urban stormwater runoff. Possible areas for erosion control include vacant lots, construction sites, and other denuded soil areas. Bare soils erode during rains and the runoff carries solids and particulates into the receiving waters. Vegetative and structural controls are the two types of controls generally used.

When rain energy is transferred to the soil, it brings about soil particle detachment. These particles are then transported by surface runoff. Vegetation protects soil from the initial impact of falling raindrops and further runoff. Vegetation also retards wind erosion.

If seasonal or other short-term adverse soil conditions exist, soil erosion may be reduced through the use of temporary soil binders. Certain mulches, generally applied at time of seeding, may provide temporary soil stabilization until the vegetation can become established. Wood chips and chemical soil binders are generally preferred because they are readily available and easily applied. Grasses and sod may also provide sufficient protection for denuded soils.

Wood chips, made from the processing of scrap wood in wood-chipping machines, seem to be the most favorable product for short-term erosion control because of their low cost and availability. They are long lasting and (because of their heavy weight) require little or no tacking to stay in place. Approximately 100 yd^3/acre may be necessary.

The application of chemical soil binders can also temporarily reduce erosion. These products are designed to be sprayed and are available from a number of manufacturers in either liquid or powder form. The chemical spray penetrates the soil and binds it at or near the surface, protecting it from wind and water erosion. These chemical binders do not necessarily preclude the growth of vegetation. The stabilizer usually becomes effective from 2 to 8 hours after application; drying time is affected by temperature, humidity, type of soil, and the specific product. Application requirements range from 2000 to 5000 gal/acre, depending on the dilution ratios required for the specific soil. This type of erosion control is increasing in demand and decreasing in cost.

Vegetation provides permanent soil stabilization. In addition to climate, soil type, and nutrient availabiity, the choice of vegetation depends on the erodibility of the soils, the steepness of the slopes, and the desired aesthetics for the area. Unless young trees or partly mature plants are used, various planting aids such as mulches, mulching stocks, and fertilizers may be required.

The erosion control benefits of vegetation are caused by the dense root mats that stabilize the soil. Foliage can also filter sediment in overland flow. In addition, vegetation increases infiltration of precipitation, reducing runoff volumes. Hardy strains of grasses and plants have also been developed for areas containing adverse soil conditions. Robust strains of grasses that germinate quickly and form thick undermats and uniform surface covers are available. Growth begins 5 to 7 days after planting, and the soil may be stabilized within 21 days after planting. Depending on the type of seed, 60 to 300 lb/acre are required.

Mulches are placed during or after seeding of an area to ensure seed protection from wind and rain. A mulch is either an organic or an inorganic material that conserves moisture in the ground, serves as an insulator, dissipates energy from falling rain drops, and reduces erosion caused by overland sheet flow. Wood chips, hay (or straw), and wood fiber (paper) are the main organic mulches. Mulching requirements are: 60 to 100 yd^3/acre for wood chips; 1 to 2 ton/acre for hay; and 1000 to 1500 lb/acre for wood fiber.

Organic mulches, except wood chips, generally need to be tacked down. When applied in a spray, added chemicals can tack down the mulch, but they can then cure more slowly. Crimping and netting are two other methods of tacking. Crimping, used on straw and hay mulches, requires punching the mulch into the soil. Netting is used on steep slopes, where crimping is not possible. Jute, plastic, fiberglass, and paper are used as netting materials. Jute and paper have a short life span, are biodegradable, and are therefore preferred when promoting the growth of fast-germinating grasses and plants. Where fiber mulches are not sufficient, mulch blankets are available for use on swales, ditches, and steep slopes.

Hydroseeding is a process that combines the application of all the previously described materials. The sprayed slurry consists of mulch, soil stabilizers, seed, fertilizer, and water. Costs vary with choice of seed and mulch.

Erosion control, temporary or permanent, may be accomplished through vegetative growth and soil stabilizers. Table G-6 summarizes the alternative procedures and illustrates the comparative costs for the kinds of material designed to protect the ground surface from erosion. The costs vary widely, depending upon the area to be covered, the choice of specialized products, and the distance from the manufacturer. Hydroseeding can range from $850/acre for 1 acre to $400/acre for 30 acres (Thronson 1973). The least expensive combination appears to be the one that includes chemical soil stabilizers. Wood chips or the combination of hay or straw with tacking are reasonable alternatives for many applications. Straw and hay usually require tacking; the low cost for straw or hay without tacking is not considered justifiable.

Other combinations of materials are possible. The effectiveness of the erosion control practice should approach 100 percent if materials are properly chosen and applied. It is extremely important that specific needs and conditions are considered when choosing the best erosion control method.

It was estimated, using a modified universal soil loss equation and appropriate South San Francisco Bay Area factors, that the erosion yield to urban runoff associated with new construction in the San Jose area is about 10 ton/acre/year*. This is low when compared with normal construction site losses in other parts of the United States (ranging from about 40 to 200 ton/acre/year). Table G-7 presents the amounts of pollutants that can be controlled by using various erosion control practices and the unit costs. Some of the least costly erosion control practices may not be applicable to certain situations, requiring the more costly alternatives. Most of these costs could be the responsibility of the builders and not the public.

RUNOFF TREATMENT ALTERNATIVES

The runoff treatment methods discussed here are only a few of the available technologies for treating combined sewer overflows or stormwater runoff. The treatment procedures described have been or are in the process of being tested for applicability and feasibility. The treatment systems descriptions, which are very brief, are only intended to introduce these systems to the reader and to define the systems as summarized in the tables accompanying this section. Excellent descriptions of these runoff treatment alternatives can be found in Lager and Smith (1974) and other literature listed in the bibliography.

In general, the physical units are the simplest to operate. Biological facilities are vulnerable to variable flow rates and the physical-chemical systems, although highly effective, are costly.

The following paragraphs describe some of the treatment systems that have been shown to be effective in removing pollutants found in urban runoff. The operating principles are briefly described. All the system designs are sub-

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*See Metric Conversion Table 0-1.

TABLE G-6. COST ESTIMATES FOR EROSION CONTROL PROCEDURES

Protection Ground Surface	Includes	Material Cost $/ac	Labor Cost $/ac	Equipment Cost $/ac	Total Cost $/ac
Excelsior Mat	1,2,3,4 5,6,7,10	2200	9700	360	12,000
Jute Mesh	1,2,3,4,5, 6,7,8,9,10	2500	4800	360	7700
Straw or Hay w/o tacking	3,5,6,7,8	250	340	580	1200
Straw or Hay w/tacking	3,5,6,7, 8,9	2100	3000	580	5700
Wood Chips 3 in. cover	3,5,7,8	2000	3700	2200	8000
Wood Chips 0.75 in. cover	1,2,3,4,5, 6,7,8,10	600	1400	1100	3100
4 in. Square Plugs of Sod	2,3,7,8, 11,12	850	5000	5500	11,000
Hybrid Bermuda Grass Blanket Sodding	2,3,7,8, 11,12	6600	2500	5700	15,000
Chemical Soil Stabilizer	1,2,7,8	1000	130	140	1300

Source: From Thronson, July 1973

(1) Seed
(2) Fertilizer
(3) Labor
(4) Fiber mulch
(5) Equipment
(6) Transportation
(7) Move-in and move-out
(8) Labor supervision
(9) Staples
(10) Hydroseeder
(11) Soil Preparation
(12) Watering

TABLE G-7. ESTIMATED CONSTRUCTION SITE EROSION CONTROL UNIT BENEFITS (lb controlled/acre/year) AND COSTS ($/lb controlled)

Control Measure Total cost, $/acre(1) % Control(2)	Excelsior Mat $12,000 60%	Jute Mesh $7700 60%	Straw or Hay (w/o tacking) $1200 85%	Straw or Hay (with tacking) $5700 85%	3 in. cover of wood chips $8000 94%	Sod Plugs $11,000 60%	Blanket Sod $15,000 99%	Chemical Soil Stabilizer $1300 50%	Median Value $6900 75%
10 tons/acre loss potential									
Total Solids	12,000 lb $1.00	12,000 lb $0.67	17,000 lb $0.07	17,000 lb $0.34	19,000 lb $0.43	12,000 lb $0.94	19,800 lb $0.76	10,000 lb $0.13	15,000 lb $0.55
Suspended Solids	6000 2.00	6000 1.30	8500 0.14	8500 0.68	9400 0.86	6000 1.90	9900 1.50	5000 0.26	7500 1.10
BOD_5	240 50	240 34	340 3.50	340 17	380 22	240 47	400 38	200 6.50	290 28
Nitrogen	12 1000	12 670	17 70	17 340	19 430	12 940	20 760	10 130	15 550
Phosphorous	18 670	18 450	26 47	26 230	28 290	18 630	30 570	15 87	22 360
40 tons/acre loss potential									
Total Solids	48,000 lb $0.25	48,000 lb $0.17	68,000 lb $0.02	68,000 lb $0.09	76,000 lb $0.11	48,000 lb $0.24	79,200 lb $0.19	40,000 lb $0.03	60,000 lb $0.14
Suspended Solids	24,000 0.50	24,000 0.33	34,000 0.04	34,000 0.17	38,000 0.22	24,000 0.48	39,600 0.38	20,000 0.07	30,000 0.28
BOD_5	960 13	960 8.50	1400 0.88	1400 4.30	1500 5.50	960 12	1600 9.50	800 1.60	1200 7.00
Nitrogen	48 250	48 170	68 18	68 85	76 110	48 240	80 190	40 33	60 140
Phosphorous	72 170	72 113	100 12	100 58	110 73	72 160	120 140	60 22	88 90
200 tons/acre loss potential									
Total Solids	240,000 lb $0.05	240,000 lb $0.03	340,000 lb $0.01	340,000 lb $0.02	380,000 lb $0.02	240,000 lb $0.05	396,000 lb $0.04	200,000 lb $0.01	300,000 lb $0.03
Suspended Solids	120,000 0.10	120,000 0.07	170,000 0.01	170,000 0.03	190,000 0.04	120,000 0.10	200,000 0.08	100,000 0.01	150,000 0.06
BOD_5	4800 2.50	4800 1.70	1400 0.18	1400 0.85	1500 1.10	4800 2.40	8000 1.90	4000 0.33	5800 1.40
Nitrogen	240 50	240 34	68 3.50	68 17	76 22	240 47	400 38	200 6.50	300 28
Phosphorous	360 34	360 23	100 2.40	100 12	110 15	360	600	300	440

(1) See Table G-6 for cost breakdown.

(2) Estimated first year control effectivenesses are shown; the following years should have 99% control.

ject to the individual natures of the pollutant loads. The waste loads must be assessed during the design of a system. Pilot plant studies are recommended.

Swirl Concentration

The swirl concentration process uses a relatively new regulating and concentrating device that operates within the sewerage system. The device uses rotational fluid flow motions to split the storm flow into a low-volume concentrate and a high-volume, relatively clean stream. A channel attached to the bottom of the unit carries the concentrated settleable solids to an interceptor during wet-weather flows.

The main advantage of this process is that there are no moving parts, and and it can be used for the dual purpose of flow regulation and solids concentrations. Therefore, maintenance and adjustment requirements are minimal. A separate chamber, with a gate on the channel to the interceptor, provides fine-tuning control.

This process promises to give more cost-effective treatment (on a cost-per unit weight removed basis) than that provided by conventional primary treatment because the detention time is decreased by 90 percent, even though it is less effective. The process shows a good potential for control of stormwater runoff in combined sewerage systems.

Sedimentation

Sedimentation, the simplest system, is a physical process that removes settleable solids by gravity. Removals are good. When combined with slant tube settlers or separators, the detention times can be decreased while the solids removal can be increased.

The advantages of sedimentation include these factors:

- The process is familiar to design engineers and operators.
- Facilities can operate automatically.
- Sludge collection equipment, when added to storage facilities, requires a minimal incremental cost.
- The process provides for storage for at least part of the overflow.
- Disinfection can be administered concurrently in the same tank.

The disadvantages of sedimentation include these factors:

- The land requirements are high.
- The cost for this process alone is high.
- The wastewater receives only primary treatment.
- Periodic cleaning of the sedimentation basins is required to remove the settled material.

Dissolved Air Flotation

Dissolved air flotation, another physical process, operates by introducing super-saturated dissolved air into wastewater. As air bubbles are formed and rise, they attach to suspended solids and cause the solids to float to the surface, where they are subsequently skimmed. There are two procedures for introducing the air into the wastewater: (1) dissolved air under pressure is added, and the pressure is then relieved to allow bubbles to form and rise; or (2) the waste is saturated with air and a vacuum is applied at the surface, causing bubbles to form and rise.

Facilities include saturation tanks in which air is dissolved into part of the flow; a small mixing chamber that recombines the pressurized flow with nonpressurized flow; and flotation tanks or cells housing scrapers, with or without screens, for removing the floating solids.

Advantages of the dissolved air flotation process include these factors:

- Suspended solids (SS) and BOD removals are moderately good.
- The separation rate can be controlled by the rate of air influx.
- The inflow loading rate is higher than for sedimentation.
- The process is well suited for the high SS concentrations found in combined sewer overflows.
- The system can be automated.
- The process aids in oil and grease and floatables removal.

Disadvantages of this process include these factors:

- A common disadvantage for all primary sedimentation devices is that removal of dissolved solids requires chemicals and therefore higher operating costs than for solids removal alone.
- Operating costs are high relative to other physcial processes.
- Greater operator skill is required.
- Provisions must be made to ensure protection of float from wind and rain.

Microscreening

Microscreening is a physical process that uses finely woven stainless-steel fabric screens to remove fine suspended materials. The microscreen is the only screen that can serve as a main treatment device in treating combined sewer overflow. The microscreen may be used instead of sedimentation tanks in conjunction with disinfection, or as a polisher for treatment-plant effluent. Removal efficiencies are affected by the size of the screen opening and by the mat formed on the screen by particles unable to pass. The screen must be backwashed almost continuously by washwater jets. Commercial sodium hypocholoride is used for washing oil and grease off the units.

The advantages of microscreening are:

- Head losses are relatively small.
- Maintenance costs are low.

- Screens can have a life of 7 to 10 years.
- Low installation land requirements as compared to many other systems.

The disadvantages of microscreening are:

- Washwater will not remove oil and grease without the aid of detergents.
- Prechlorination or ozonation tends to corrode steel screens, which reduces screen life.

Filtration

Filtration, a more refined screening process, removes suspended solids by straining, impingement, settling, and adhesion. A dual-media material commonly used to remove a wide range of particle sizes consists of anthracite and sand. Fiberglass media may also be used. The filter must periodically be backwashed to remove clogging materials.

Advantages of filtration are:

- Removals of SS and BOD are relatively good.
- Non-compressible, discrete particles in stormwater will not clog filters as much as the compressible solids usually found in sanitary wastewater; therefore, loading rates are higher.
- Operation is easily automated.
- Land requirements are small.
- The process is versatile enough to act as an effluent polisher.

Disadvantages of filtration are:

- Costs are high.
- Dissolved materials may not be adequately removed unless polyelectrolytes are added; this requires the filter to be backwashed more frequently than when not using polyelectrolytes.
- Storage of backwash water is necessary.

Contact Stabilization

The equipment required for contact stabilization is a contact basin with return flow and aeration capabilities. The flow is first mixed with returned activated sludge for about twenty minutes, the sludge than settles in a clarifier, and is finally aerated for several hours in a stabilization tank where organisms use the organic material for growth. Part of the sludge then returns to the contact chamber where it mixes with new flow.

For biological treatment in general, the biomass used to assimilate organic material must be kept alive during dry-weather flow or be allowed to develop for each storm. One solution is to operate the contact-stabilization plant in conjunction with a dry-weather plant and treat sanitary sewage during dry periods.

Advantages of the contact-stabilization process are:

- A high degree of treatment is obtained.
- Location of maintenance personnel and equipment is centralized.
- Loadings on dry-weather plants are reduced by the dual use of facilities.

The disadvantages of the process are:

- Initial costs are high.
- Facilities should be located near a dry-weather plant.
- Varying loads may shock the system. Storage can control the flow volumes (with added costs and increased land requirements), but it is difficult to equalize the BOD_5 and SS inputs.

Trickling Filters

The trickling-filter process operates biologically rather than physically. Flow is applied intermittently or continuously over crushed rock, plastic, or other suitable material. A biological slime, allowed to build up on the media, metabolizes soluble organic material and adsorbs colloidal organic material. An upward movement of air, created by a temperature gradient, maintains aerobic conditions. The filter design is based on both hydraulic and organic loading conditions. Peak hydraulic loadings may wash established biomass off the media. A varying organic load may also decrease optimum removals because the utilization rate of microorganisms is limited.

The trickling filter has three flow classifications: low rate, high rate, and ultrahigh rate (for plastic media). Each design determines the hydraulic and organic loading. High-rate facilities are operated in series with recirculation. This allows greater removals because of increased contact time. During wet-weather conditions, filters can work in parallel to relieve the extra load. Large flow variations will still achieve significant removals of SS and BOD_5.

The advantages of trickling filters are:

- Filters are simple to operate.
- Filters will recover rapidly from high flows.

The disadvantages of the process are:

- A continuous base flow is required to keep the biomass alive, requiring combined use with a sanitary wastewater treatment facility.
- The percentage removal will decrease when high SS and BOD_5 loads are applied.
- Problems may occur with a diluted flow.

Rotating Biological Contactors

The rotating biological contactor is a cross between a trickling filter and an activated sludge process. A biomass builds up on rotating discs that are supported on a rotating shaft. The shaft rotates the partly submerged discs to maintain an aerobic environment. Organic matter is adsorbed by the growth. Excess biomass may shear off the rotating discs, so secondary clarification should follow to remove discharged flocs. Because biomass has a limited utilization rate, the organic loading is limited. Reserve biomass, however, reduces the importance of maintaining a uniform organic loading. Contact time, effluent settling, and the number of units in series affect removals.

The advantages of rotating biological contactors are:

- Power requirements are low.
- A moderate degree of flow variation will not shock the system.
- There are no fly or odor problems.

The disadvantages of this process are:

- A base flow is required to keep the biomass alive.
- The biological process is not controllable.
- In cold climates the facilities must be enclosed.
- More study is needed to define the system's capabilities for treating stormwater.
- Storage and equalization of the inflow is usually required.

Oxidation Ponds

Oxidation ponds, also referred to as stabilization ponds or lagoons, are designed to promote the symbiotic relationship between algae and bacteria. Photosynthetic processes of algae provide the oxygen that bacteria use to assimilate wastes. Removal also depends on the principle of sedimentation. These shallow earthen basins are generally used in series for greater SS and BOD_5 removals.

A number of factors will afffect removal efficiencies: oxygen must be in sufficient supply; organisms and algae must be removed from the effluent; the effect of temperature on biological activities must be considered; and sufficient sludge storage is needed to maximize detention times and reduce carryover of sludge into the effluent.

The advantages of oxidation ponds are:

- Little maintenance is required.
- Detention times are relatively short for stormwater treatment.
- Operation and maintenance costs are low.
- Ponds have the capability of acting as storage units.
- Ponds can act as a polishing lagoon during dry-weather flows.

The disadvantages of this process are:

- Land requirements are high.
- Discharge facilities must include a unit for removing algae from the effluent.
- The degree of treatment is difficult to predict.
- There are potential nuisance problems.
- Sludge deposits will reduce treatment capability.

Aerated Lagoons

The aerated lagoon operates on the same principle as the oxidation pond, except that mechanical equipment rather than an algae population ensures an adequate air supply. The system may be designed for either complete mixing or partial mixing (when enough oxygen is supplied for biological activity). The ponds are usually set in a series with alternate parallel operation making it possible to treat large flows. System performance is affected by DO concentration, adequate mixing, control of biological solids carry-over, short-circuiting, and temperature. A detention time of 2 to 4 days should provide good settling. Although sludge buildup is not generally a problem, additional units for removing biosolids may be included to ensure good removal for SS and BOD_5.

Physical-Chemical Systems

Physical-chemical systems are generally used for tertiary treatment of wastewaters. These systems typically include separation, filtration, carbon adsorption, and disinfection. The result is a high-quality effluent.

Chemicals provide for the majority of pollutant removal. The use of lime, iron, aluminum salt (alum), polyelectrolytes, or combinations of these will result in flocculation or coagulation of chemical materials in the water.

The principle of filtration has been discussed previously. Its place in the physical-chemical scheme depends on the type of adsorption unit.

The carbon adsorption unit removes soluble organic matter by either a downflow packed-bed or an upflow expanded-bed design. Either granular or powdered carbon can be used for carbon adsorption.

The feasibility of multiprocess physical-chemical systems will depend mostly on desired treatment standards and the use of the facilities during dry-weather conditions.

The advantages of the physical-chemical system are:

- Adaptability for automatic operation, including instantaneous startup and shutdown.
- Excellent resistance to shock loads.
- Low susceptibility to biological upsets or toxicity.
- Ability to consistently produce a high quality effluent.

The disadvantages of the system are:

- Costs are high.
- Skilled operators are required.

Summary

Table G-8 compares the treatment techniques discussed. The information is normalized for a 12 million-gal/day (MGD) wet-weather flow treatment plant

TABLE G-8. COST OF REMOVALS FOR VARIOUS WET-WEATHER FLOW TREATMENT SYSTEMS

Process[a]	Location	Annual Capital Cost[b] (30-year life at 6% interest)	Annual Operation[a] and Maintenance Cost for 12 MGD (100,000 pop., 20-in. rain/yr)	Total Yearly Cost for City of 100,000	Removal Percent				
					SS	BOD_L	COD	N	PO_4
Swirl	Syracuse, NY	5000	5000	10,000	40[d]	-[e]	-	-	-
Sedimentation	Cambridge, MA	73,000	15,000	88,000	45	erratic	-	-	-
Dissolved Air Flotation[f]	Racine, WI	34,000	150,000	184,000	75	50	44	18	81
Microstraining	Philadelphia, PA	11,000	10,000	21,000	70	10-50	-	-	-
Filtration[g]	Cleveland, OH	70,000	40,000	110,000	90	40	40-72	-	-
Contact Stabilization	Kenosha, WI	68,000	210,000	278,000	92	83	-	50	50
Trickling Filters[h]	New Providence, NJ	70,000	270,000	340,000	65	65	-	small	small
Rotating Biological Contactors	Milwaukee, WI	26,000	190,000	216,000	60-95	50-95	20-70+	40	50
Oxidation Lagoons	Springfield, IL	5700	45,000	50,700	erratic	erratic	-	-	-
Aerated Lagoons	Mount Clemens, MI	14,000	200,000	214,000	75-95	75-95	-	-	-
Physical-Chemical Systems	South Lake Tahoe, CA	365,000	526,000	891,000	100	97	75	98	98

Source: From Lager and Smith (1974).

[a] Does not include disinfection

[b] Excludes real estate costs, ENR cost index = 2000

[c] Excludes sludge disposal

[d] Preliminary evaluation data

[e] Information not available

[f] Includes fine screens as pretreatment and chemical addition

[g] Includes chemical addition

[h] Sanitary System with excessive infiltration

receiving sanitary wastes and urban runoff, which would serve a town with a population of 100,000 in an area with an annual rainfall of 20 in. No costs for separation or storage are included. Determinations were made for capital cost on an annual basis, for annual operation and maintenance costs, and for percent removals for each technique. The annual cost is based on a 30-year life at 6 percent interest.

Table G-9 presents estimated unit costs for treating urban runoff characterized by the measurements shown in Section 4 of this report by various runoff treatment operations and processes. Costs for the optimum (least cost) storage/ treatment combination are also shown. These costs were determined by calculating the appropriate storage and treatment costs for various capacity storage and treatment combinations necessary (instantaneous treatment with no storage to continuous treatment with 12-months storage). When flow equalization (storage) and collection facility costs are excluded, the unit costs are all significantly less than the unit costs for street cleaning operations. However when flow equalization costs are included, the unit costs for removal of a pound of the various pollutants are all much larger than similar costs for street cleaning operations. If collection facilities are also necessary (such as collection trunklines), these unit costs would be much greater. The costs utilized in these calculations include the annual operation and maintenance costs, depreciation costs, and interest costs over the expected life of the project. Estimated average cost and labor effectiveness values are also shown in this table. The operation and maintenance labor unit effectiveness for these runoff control processes are all about one-half to one-hundredth of the unit labor requirements for street cleaning operations.

The most effective treatment system appears to be the physical-chemical system. Choice of the optimum unit must be made on an individual basis. The choice depends on the specific trade-off between required removal rates and cost. Procedures for selecting the most appropriate treatment system are discussed in the following decision analysis section of this report.

Tables G-10 and G-11 present operational and cost information for the San Jose-Santa Clara Water Pollution Control Plant. Unit costs and unit labor requirements are also shown. It is assumed that these costs and labor requirements would remain approximately the same if the facility began treating combined urban runoff and sanitary wastewater. These costs are, for the most part, less than the unit costs for the special treatment facilities without flow equalization and collection processes. Unfortunately, there are no adequate data to compare the unit removal costs and labor effectiveness for treating heavy metals in the runoff systems. It is expected that these unit requirements for the important heavy metals (Pb, Zn, Cu) would be much greater than requirements for street cleaning programs.

DECISION ANALYSIS APPROACH TO THE SELECTION OF AN URBAN RUNOFF CONTROL PROGRAM

Decision analysis (Keeney and Raiffa 1976) may be used as an important guide in selecting an urban runoff control program. Decision analysis is a systematic procedure that enables one to study the trade-offs among multiple and usually conflicting program objectives. An alternative procedure is to

TABLE G-9. ESTIMATED UNIT COSTS FOR TREATING URBAN RUNOFF.

Process	Unit Costs, Excluding Flow Equalization and Collection ($/lb)					Unit Costs, Including Flow Equalization, Excluding Collection ($/lb)				
	Suspended Solids	BOD_5	COD	N	PO_4	Suspended Solids	BOD_5	COD	N	PO_4
Swirl Concentrator	0.003	--	--	--	--	No flow equalization needed				
Sedimentation	0.036	--	--	--	--	2.00	--	--	--	--
Dissolved Air Flotation	0.032	0.42	0.06	4.00	2.00	1.00	14	2.00	130	70
Microstraining	0.004	0.08	--	--	--	1.00	23	--	--	--
Filtration	0.026	0.31	0.03	--	--	0.90	17	1.50	--	--
Contact Stabilization	0.04	0.38	--	2.00	5.00	0.90	9	--	48	110
Trickling Filters	0.07	0.59	--	--	--	1.30	11	--	--	--
Rotating Biological Contactors	0.04	0.33	0.06	2.00	4.00	1.10	9	1.70	60	110
Aerated Lagoons	0.03	0.29	--	--	--	1.00	8	--	--	--
Physical-Chemical	0.12	1.00	0.17	3.50	8.00	0.90	8	1.30	27	65
Average Cost ($/lb removed)	0.04	0.40	0.08	2.90	5.00	1.10	12	1.60	66	90
Estimated labor (hr/lb removed)	0.007	0.70	0.01	0.30	0.50	0.007	0.70	0.01	0.30	0.50

TABLE G-10. SAN JOSE-SANTA CLARA WATER POLLUTION CONTROL PLANT EFFLUENT CONDITIONS

Parameter	Influent Concentration (mg/l, except as noted)	Effluent Concentration (mg/l, except as noted)	Percentage Removal	Tons/Year Removed	Tons/Year Effluent	$/lb Removed	Man-Hours/lb Removed
Flow	89×10^6 gal/day*	--	--	--	--	--	--
Total solids	--	1040	--	--	141,000	--	--
Suspended solids	610	26*	93.8*	53,300	3520	0.01	0.003
Settleable solids	24	0.05	99.8	3390	6.8	0.65	0.04
Total dissolved solids	--	1010	--	--	137,000	--	--
Specific conductance	--	1850 µmhos/cm	--	--	--	--	--
Turbidity	--	20 JTU	--	--	--	--	--
pH	--	7.6 pH units	--	--	--	--	--
Alkalinity (as HCO_3)	312	233	25	10,500	31,500	0.21	0.014
Hardness (as $CaCO_3$)	--	289	--	--	39,100	--	--
BOD_5	395	21*	94.2*	46,100	2840	0.05	0.003
TOC	--	30	--	--	4060	--	--
Oil and grease	73.0	3.1*	96	10,100	419	0.22	0.015
Total phosphate (PO_4)	42.6	19.2*	55	3180	2600	0.69	0.047
Organic nitrogen	26.8	5.1*	81	2940	690	0.75	0.051
Ammonia (NH_3)	28.0	18.8*	33	1250	2540	1.76	0.12
Kjeldahl nitrogen	54.8	23.9*	56	4110	3230	0.52	0.037
Nitrates (NO_3)	1.5	4.9*	--	--	663	--	--
Nitrites (NO_2)	1.3	1.4*	--	--	189	--	--
Total coliform bacteria	--	108 organisms 100 ml	--	--	--	--	--
Fecal coliform bacteria	--	8 organisms/ 100 ml	--	--	--	--	--
Sulfates (SO_4)	105	148	--	--	20,000	--	--
Chlorides (Cl)	--	330	--	--	44,600	--	--
Silica (SiO_2)	36	31	14	680	4190	3.22	0.22
Sodium (Na)	215	218	--	--	29,500	--	--
Potassium (K)	18.4	23.8	--	--	3220	--	--
Calcium (Ca)	59	65	--	--	8790	--	--
Magnesium (Mg)	37	35	6	300	4690	7.34	0.50
Phenols	195	2.9	99	38,600	390	0.06	0.004
Cyanide (CN)	0.06	0.06	--	--	8.1	--	--
Fluoride (F)	2.0	1.3	35	95	176	23	1.6
Boron (B)	--	0.9	--	--	122	--	--
Arsenic (As)	--	0.0004*	--	--	0.05	--	--
Cadmium (Cd)	--	0.002*	--	--	0.27	--	--
Chromium (Cr)	--	0.016*	--	--	2.2	--	--
Copper (Cu)	--	0.081*	--	--	11.0	--	--
Lead (Pb)	--	0.0098*	--	--	1.3	--	--
Mercury (Hg)	--	0.0019*	--	--	0.26	--	--
Nickel (Ni)	--	0.038*	--	--	5.1	--	--
Silver (Ag)	--	0.002*	--	--	0.27	--	--
Zinc (Zn)	--	0.087*	--	--	11.8	--	--

*These values are from routine analyses (several grab samples per month). The remaining values are from only a few data points (1 to 4) collected during the spring of 1977.

TABLE G-11. SAN JOSE-SANTA CLARA WATER POLLUTION CONTROL PLANT SUPPORT REQUIREMENTS (1975-76 data)

Parameter	Unit	Units/10^6 gal Treated	Units/32.5×10^9 gal (annual requirement)
Total cost	$	135	4.4×10^6
Labor cost	$	55	1.8×10^6
Electricity	kwh	120	3.9×10^6
Natural gas	therms	69	2.2×10^6
Domestic water	gal	3700	120×10^6
Labor	man-hrs	9.3	0.3×10^6

separately determine the programs necessary to meet each objective and to use the least costly program that satisfies all the identified objectives. This is an acceptable procedure most of the time, but it may not result in the most cost-effective program. Decision analysis considers the partial fulfillment of all the objectives. It translates these into their relative worths to the decision-maker or other interested parties. Although this discussion will not enable a novice to apply decision analysis procedures, it will introduce the technique and advantages of the system.

To illustrate the basic elements of decision analysis as it may be used to select a street cleaning program, consider a community of 100,000 people. The objectives of such a program might include maximizing air, water, and aesthetic quality and minimizing the noise and cost of cleaning operations. Unfortunately, some objectives (such as cost and environmental quality) tend to conflict with each other. The community must choose the system that makes the best tradeoffs among the competing objectives. To aid in the selection process, the techniques of decision analysis are employed.

The first step consists of defining the alternatives and quantitative measures (attributes) for the objectives. How well each alternative achieves its objective is measured. In this example, five attributes were chosen to reflect major considerations in deciding which street cleaning system to select. These attributes, their units of measurement, and the associated ranges are shown in Table G-12. To get a better feel for these measures, descriptions of certain attribute quantities are provided below:

- Aesthetics: <300 pounds total solids/curb-mile; not very noticeable.

  >300 pounds total solids/curb-mile; may be objectionable.

Table G-12. DECISION ANALYSIS ATTRIBUTES, MEASURES, AND RANGES

Attribute Description		Units of Measurements	Range of Values Best	Range of Values Worst
1.	Aesthetics (residual loading)	lb/curb-mile	68	525
2.	Annual cost	\$/curb-mile/year	350	3600
3.	Air quality (particulates)	$\mu g/m^3$	100	200
4.	Water quality (total dissolved solids)	mg/l	200	1500
5.	Noise Level	dB_A	65	82

- Cost: $14/curb-mile/cleaned
- Air Quality: Federal primary air quality standard (to protect public health) for suspended particulates: 260 $\mu g/m^3$

  Federal secondary air quality standard (to protect public welfare) for suspended particulates: 150 $\mu g/m^3$.
- Water quality: U.S. Public Health Service recommended drinking water limit: 500 mg/l for total dissolved solids (TDS).

  Irrigation and stock watering criteria 5000 mg/l TDS.
- Noise: 68-78 dB_A normally "acceptable."

  78-90 dB_A normally "unacceptable."

The second step consists in decribing each alternative in terms of the attributes defined in step one. The value of each attribute for each of the alternatives must be determined. The attribute levels may be described either in terms of probabilistic forecasts, where uncertainties are quantified, or by point estimates representing the level expected for each attribute. In this example, five alternative street cleaning techniques are considered. They consist of combinations of equipment types and their frequencies of use. The alternatives are defined in Table G-13. Point estimates for illustrative purposes are used

TABLE G-13. DEFINITION OF ALTERNATIVES

Alternative	Description
1	Conventional mechanical cleaner, one pass every week
2	Conventional mechanical cleaner, one pass every weekday
3	Vacuumized cleaner, one pass every week
4	Flusher, one pass every week
5	Conventional mechanical cleaner followed by a flusher, one pass every week

TABLE G-14. ESTIMATED ATTRIBUTE LEVELS FOR EACH ALTERNATIVE*

	Attributes				
Alternatives	Aesthetics (lb total solids/ curb-mile)	Annual Cost ($/curb-mile/ year)	Air Quality (μg suspended particulates/m^3)	Water Quality (mg TDS/1)	Noise Level (dB$_A$/ pass)
1	340	700	200	1000	65
2	68	3600	120	200	65
3	470	700	150	1400	70
4	525	350	200	1500	80
5	150	1000	150	400	82

for this example and summarized in Table G-14. Considering the estimates for alternatives one and two, it shows that all attributes except cost are better than equal for alternative two.

The third step consists of quantifying the preference and tradeoffs for the various attribute levels. The concepts of utility theory provide a consistent scale to quantify how much one gives up when choosing one attribute over another. First, utility curves are assessed for the individual attributes. These curves quantify the preferences that exist for the total range of each attribute. They also quantify attitudes toward risk. This is important when alternatives yield uncertain consequences. The curves are defined from a series of questions that determine points on each of the utility curves. The most preferred point is defined as having a utility value of 1.00 and the least preferred a utility value of 0.00. The utility assessments establish where the intermediate points fall on the utility scale. An example of an assessed utility function for a water quality attribute is shown in Figure G-1. Each of the other attributes can be assessed on a similar curve.

The questions used to define the individual attribute utility curves consist of asking the decision maker to choose one of two possible situations. One situation is uncertain and describes a 50-50 chance for a successful outcome of one of the two possible levels of the attribute; the second situation occurs with certainty and consists of achieving a specified level of the attribute. The level of the attribute in the second situation is somewhere between the two equally possible levels of the first situation. The utility assessment for each point on the curve is determined by the attribute level in the second situation, where the decision maker is indifferent to the choice of the two situations. Since, at the point of indifference, each choice is equally acceptable, the expected utility values of the two situations must be equal, and a point of the utility curve can be established.

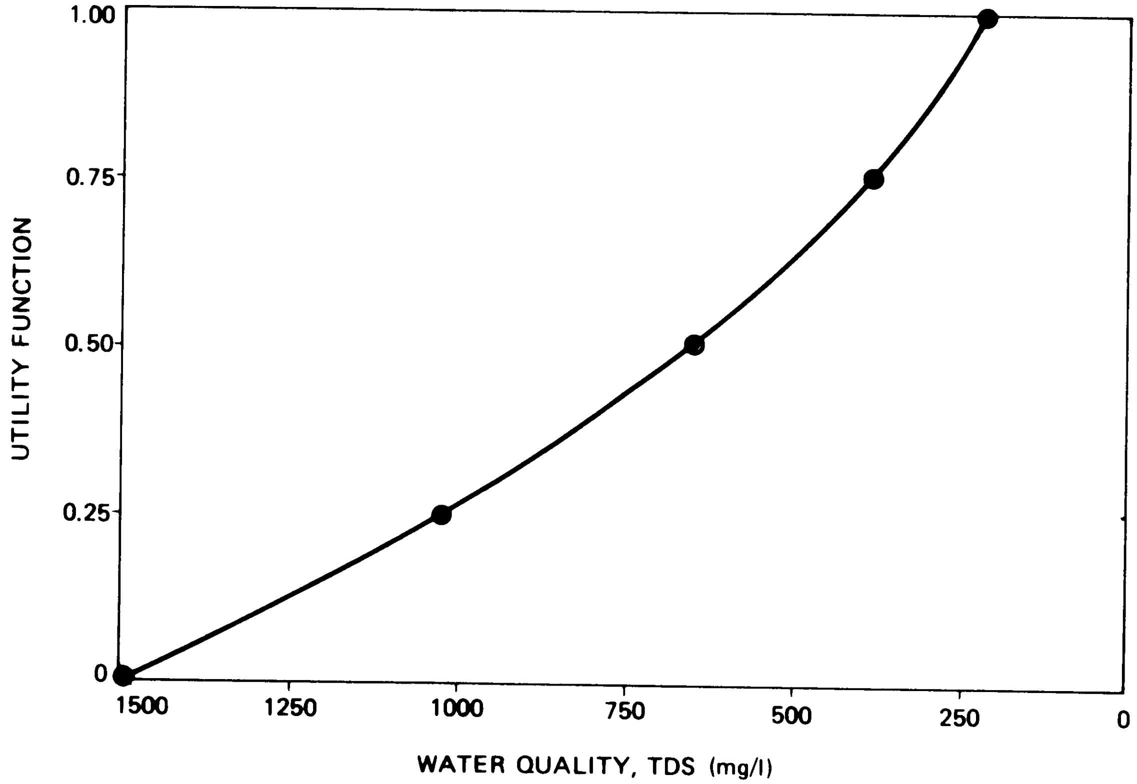

Figure G-1. Example utility function for a water quality attribute.

Considering, for example, a situation with a 50-50 chance of achieving water quality at either 1500 or 200 mg TDS/l, what level of water quality (if known with certainty) would be equally preferable to the uncertain situation above? After a series of trial choices, it was determined that a water quality level of 650 mg TDS/l would be indifferent to the uncertain situation. Thus the utility of a water quality level of 650 mg/l must equal the expected utility of the uncertain situation with a 50-50 chance of achieving either 1500 or 200 mg/l. Since the utility values of 1500 and 200 mg/l are known to be 0.00 and 1.00 respectively, the expected utility of the first situation can be calculated to be 0.5 (0) + 0.5 (1.00) = 0.5. Therefore, the utility value of 650 mg/l must equal 0.5. This point is plotted on Figure G-1. Similar questions were asked to define the other points shown on Figure G-1.

The trade-offs that exist among the attributes are established next. This is accomplished by first ranking the attributes in order of importance. The rank order is established by answering the following type of question: "Given that all attributes are at their worst levels, which attribute would one first move to its best level?" The question is repeated to determine which attribute would next be moved to its best level. This process is continued until the complete rank order of the attributes is established. In this example, the following rank order of the attributes was established:

- Water Quality
- Annual Cost
- Air Quality
- Aesthetics
- Noise Level

The trade-offs among attributes are addressed next. This is accomplished by considering the choice between two possible situations for a pair of attributes. Both situations are certain but consist of different levels for the pair of attributes. The levels for the pair of attributes are in the form of "worst, best" compared with "?,worst". The unknown attribute level is established after repeated trials until the decision maker is indifferent to the two situations. Considering the water quality/annual cost attribute pair, the two situations would be "1500 mg/l, \$350" and "?, \$3600". In this example, it is established that if the water quality were 650 mg/l, the second situation would be indifferent to the first situation. Similar questions were asked for other pairs of attributes. These results are summarized below, using the notation (≃) to indicate indifference.

- (Water quality, annual cost) = (1500 mg/l, \$350) ≃ (650 mg/l, \$3600)
- (Annual cost, noise level) = (\$3600, 65 db_A/pass) ≃ (\$3000, 82 dB_A/pass)
- (Annual cost, aesthetics) = (\$3600, 68 lb/mile) ≃ (\$3000, 525 lb/mile)
- (Annual cost, air quality) = (\$3600, 100 $\mu g/m^3$) ≃ (\$1500, 200 $\mu g/m^3$)

The above information concerning the preferences for achieving levels for the attributes can be used to establish a multiattribute utility function. A multiattribute utility function is a mathematical expression that summarizes attribute utility functions and the trade-offs between attributes. The mathematical form of the multiattribute utility function is established by verifying several reasonable assumptions regarding preferences. To illustrate, an additive multiattribute utility function is used. It is represented as:

$$u(x_1,x_2,x_3,x_4,x_5,) = \sum_{i=1}^{5} k_i \; v_i \; (x_i) \qquad (1)$$

where:

x_i = the level of the i^{th} (i-1,5) attributes

$u_i(x_i)$= the utility of the i^{th} individual attribute

u = the multiattribute utility

k_i = tradeoff constant for i^{th} attribute

and

$$\sum_{i=1}^{5} K_i = 1$$

The trade-off constants in equation (1), k_i, are calculated based on the individual attribute utility functions and indifference points for pairs of attributes. Although the utility functions actually assessed would normally be used to illustrate this example, it is assumed that each of the individual attribute utility functions is linear.

The multiattribute utility values for assessed points of indifference between pairs of attributes must be equal because they are equally preferable. Holding all attributes not considered in the pair trade-offs at their worst level so that their utility value is zero, the k_i values (where the subscript i for each attribute is in accordance with Table G-12) in equation (1) can be calculated. The ratio between the trade-off constants for any two attributes (such as k_2/k_4, the ratio of the cost and water quality trade-off constants) is therefore equal to the utility value of the attributes that is the denominator for this worst-case comparison.

As an example, the water quality attribute value of 650 mg/l relates to the worst case cost attribute value of $3600. The corresponding utility value for this water quality attribute value is 0.65, the ratio between the cost and water quality trade-off constant (k_2/k_4). The following relationships show the ratios of the other trade-off values:

$$\frac{k_2}{k_4} = u_4 \text{ (650 mg/l)} = 0.65 \qquad (2)$$

$$\frac{k_5}{k_2} = u_2\ (\$3000) = 0.23 \qquad (3)$$

$$\frac{k_1}{k_2} = u_2\ (\$3000) = 0.23 \qquad (4)$$

$$\frac{k_3}{k_2} = u_2\ (\$1500) = 0.46 \qquad (5)$$

Using equation (2): $\sum_{i=1}^{5} k_i = (0.23 + 1.00 + 0.46 + 1.54 + 0.23)\ k_2 = 1.00$ (6)

$$k_2 = 0.29 \qquad (7)$$

Therefore:

$$k_1 = 0.07 \qquad (8)$$

$$k_3 = 0.13 \qquad (9)$$

$$k_4 = 0.42 \qquad (10)$$

$$k_5 = 0.07 \qquad (11)$$

The above trade-off constant values, the individual attribute utility functions, and the original equation completely define the multiattribute utility function.

The fourth step consists in synthesizing the information. The multiattribute preferences, when combined with the attribute levels associated with each alternative, allow a ranking of the five alternative street cleaning systems. The estimated attribute levels for each alternative shown in Table G-14 and the individual attribute utility functions are used to determine u_i (x_i) for each alternative. The individual attribute utility values associated with each alternative are summarized in Table G-15.

The information given in Table G-15 is then substituted into equation (1) to define the multiattribute utility associated with each alternative. These utility values provide the basis for determining the rank order of the alternatives and the degree to which one alternative is preferred over another. The utility values associated with each alternative are shown in Table G-16.

The most preferred alternative is that with the highest utility value. For this example, examination of Table G-16 reveals that alternative five (conventional mechanical cleaner followed by a flusher, every five days) is the best alternative. This is followed closely by alternative two (conventional mechanical cleaner, one pass every day). The least desirable was alternative four (flusher, one pass every five days).

TABLE G-15. INDIVIDUAL ATTRIBUTE UTILITY VALUES FOR EACH ALTERNATIVE

	Attributes				
Alternatives	Aesthetics	Annual Cost	Air Quality	Water Quality	Noise Level
1	0.40	0.90	0	0.38	1.00
2	1.00	0	0.80	1.00	1.00
3	0.12	0.90	0.50	0.08	0.71
4	0	1.00	0	0	0.12
5	0.82	0.80	0.50	0.85	0

TABLE G-16. UTILITY OF EACH ALTERNATIVE

Alternative	Utility
1	0.52
2	0.66
3	0.42
4	0.30
5	0.72

It should be noted that changes in preferences for the attributes or estimated attribute levels associated with each alternative may alter the order of preference for the alternatives. The decision analysis methodology summarized here would allow such changes to be rapidly investigated by a sensitivity analysis of the rank order of alternatives. For example, if the trade-off between annual cost and water quality were changed so that the annual cost is somewhat more important than in the previous tradeoff, alternatives one and two can become equally preferred, but alternative five is still the most preferred. New attributes may be added to the analysis if so desired and the alternatives ranked again.

The decision analysis approach has the flexibility of allowing for variable levels of analytical depth, depending on the problem requirements. The preliminary level of defining the problem explicitly in terms of attributes often serves to make the most preferred alternative clear. The next level might consist of a first-cut assessment and ranking as described in this example. Utility functions were assumed to be linear and an additive model was employed. Hand calculations with such a model are easily performed. The deepest level can utilize all the analytical information one collects, such as probablistic forecasts for each of the alternatives and the preferences of experts over the range of individual attributes.

In summary, decision analysis has several important advantages. It is very explicit in specifying trade-offs, objectives, alternatives, and sensitivity of changes to the results. It is theoretically sound in its treatment of trade-offs and uncertainty. Other methods ignore uncertainty and often rank attributes in importance without regard to their ranges in the problem. It can be implemented flexibly with varying degrees of analytical depth, depending on the requirements of the problem.

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(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

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16. ABSTRACT

A presentation of the results and conclusions from the EPA-sponsored demonstration study of nonpoint pollution abatement through improved street cleaning practices. An important aspect was the development of sampling procedures to test street cleaning equipment performance in real-world conditions. Other areas explored in this study include: (1) accumulation rate characteristics of the various pollutants associated with street dirt; (2) runoff flow characteristics, concentrations and total mass yields of monitored pollutants in runoff, and street dirt removal capabilities and effects on deposition in the sewerage for various kinds of storms; (3) costs and labor effectiveness of street cleaning, runoff treatment, and combined runoff and wastewater treatment; and (4) results of a special study of airborne dust losses from street surfaces.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air pollution, Dust control, Municipal engineering, Public works, Streets, Storm sewers, Water Pollution, Pavements, Waste treatment, Surface water runoff, Cost analysis, Cost effectiveness	Non-point sources, Non-point source control, Street cleaning	13B

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