POLLUTIONAL CHARACTERISTICS OF STORMWATER RUNOFF

by

Edwin R. Bennett
K. Daniel Linstedt

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Edwin R. Bennett and K. Daniel Linstedt

Department of Civil, Environmental and Architectural Engineering
University of Colorado

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Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado 80523

Norman A. Evans, Director

ABSTRACT

The pollutional characteristics of stormwater runoff were evaluated by sampling stormsewer discharges at appropriate intervals throughout each runoff period for several storms at three locations. The study was made in Boulder, Colorado and the emphasis was placed on the characteristics of snowmelt runoff. The runoff from three types of land use areas was studied. The sampling locations included the stormsewer outfall on Boulder Creek for a urbanized residential area with a population density of twenty-five persons per acre (62 persons per hectare); the outfall of the stormsewer serving a suburban area with a density of twelve persons per acre (30 persons per hectare); and the runoff from an uninhabited, unsewered mountain watershed.

The results of the study showed that snowmelt pollution is released more slowly than rain runoff to a receiving stream and therefore the maximum concentrations were lower than those for rainfall. The total mass loadings were slightly lower for snowmelt compared to rain runoff on the same area for the major pollutants, COD, total and suspended solids. The mass loading were much lower in snowmelt for the nutrients, nitrogen and phosphorous.

Preliminary treatment evaluations of stormwater runoff were made using the process of plain sedimentation,coagulation-sedimentation using lime, alum, and ferric chloride and by sand filtration. Due to the colloidal nature of the organic

matter in the stormwater, coagulation-sedimentation and filtration were found to be effective treatment methods but plain sedimentation gave relatively poor results.

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SECTION 1

INTRODUCTION

The goal of improved water quality in the streams of Colorado and throughout the nation requires a comprehensive analysis of all sources of pollution. For many years, the emphasis has been placed on municipal and industrial point source discharges with the objective of reducing or eliminating pollutant discharges.

However, improved treatment plants do not always result in a proportionate improvement in overall water quality. While urban point waste sources are becoming less threatening, other non-point sources of water impairment typically go untreated and are becoming relatively more significant. This was demonstrated in a discussion concerning a Council on Environmental Quality study which indicated that in 80 percent of the urban areas studied, downstream quality was not controlled by point sources (Bowen, 1972).

Urban stormwater runoff is considered a non-point source of water pollution and is generated by precipitation which washes and cleanses an urban environment, and then transports collected residues to the nearest natural or man-made watercourse. Considering that precipitation cleanses a variety of objects in the urban environment, including homes, cars, streets, shopping centers, etc., it is not surprising that urban storm waters contain substantial amounts of pollutants. Many recent studies have identified organics, solids, nutrients, heavy metals, and micro-organisms as important components of urban stormwater runoff.

Urban surface waters are typically collected in storm sewers, combined sewers, or may appear as diffuse surface waters which flow into the nearest stream or artificial channel. Recent studies have found that the impact of this waste source on water quality management objectives is significant. As a result, many cities have initiated programs to cope with urban stormwater runoff problems.

This research was undertaken to evaluate the characteristics of stormwater runoff. Major emphasis was placed on characterizing the runoff from urban areas under rainfall and snowmelt conditions. Brief attempts were made at analyzing the impact from mountain watersheds and agricultural lands. The aim of the study was to provide a basis for developing a more complete picture of the need for stormwater pollution abatement in Colorado and the mountain states.

The urban runoff portion of the study was conducted in the City of Boulder, Colorado which is serviced by separate storm and sanitary sewer systems. Hence, the urban stormwater aspects of the study are limited to runoff collected by separate storm sewer systems and the characteristics of stormwater runoff refer to separate storm sewer discharges.

The specific objectives of the research were to characterize urban stormwater runoff under the conditions of rainfall and snowmelt for two different types of landuse areas and to evaluate the impact of mountain watershed runoff and agricultural runoff on a receiving stream in conjunction with urban runoff. A brief initial study was also made to judge the effectiveness of different types of potential treatment methods for the removal of pollutants from urban stormwater flows.

SECTION 2

BACKGROUND AND LITERATURE REVIEW

I. Historical Review of Sewer Systems

The people of ancient Rome constructed large storm drains to remove stormwater from the developed areas of their community. Later, stormwater systems were developed in Europe and North America. The early sewers were reserved for stormwater. Human pollutants and solid wastes were not permitted in the flow. When the industrial revolution occurred, people moved to city environments and the problem of human waste disposal became more significant. In 1815, the law was changed in London to allow for the disposal of sanitary wastes in storm sewers. This was the beginning of combined sewers. The trend continued in Boston in 1853 and in Paris in 1880 (Metcalf & Eddy, 1928). Not until the latter part of the nineteenth century was it recognized that the problem merely had been removed from land to the waters. Some cities initiated the practice of treating municipal sewage before discharge. This practice usually started with those cities located less favorably with respect to receiving waters.

Some interceptor sewer systems were then developed to bring the dry-weather flow to locations for treatment. But relief points had to be constructed to divide the large flows during storms. The combined sewers at that time might carry 5 to 50, or even more, times the dry-weather flow. A portion (up to 3 times the dry-weather flow) was intercepted and about half of it was treated (APWA, 1969).

For the past 40 years most cities and towns have required that all new buildings be provided with separate sewer systems, one for sanitary wastes and one for storm drainage. Nevertheless, quite a few of the older and larger cities in the nation still have combined sewers. Generally, it is the larger, older urban areas that have the greatest proportion of combined sewers. Combined sewer overflows constitute a serious pollutional load and many research studies have been made regarding methods to correct the problem.

The studies on combined sewer overflows are not directly applicable to the analysis of pollutional characteristics of separate storm sewers, but in an indirect way, they provide insights to the overall stormwater disposal problem.

II. Stormwater Pollution Studies

With the acceptance of the concept of separate sewers for stormwater and sanitary wastes, the general attitude was that stormwaters did not cause significant pollution of receiving streams. For this reason, most of the pollution control efforts were centered on sanitary sewage and industrial wastes. In the early 1960's, the significance of stormwater pollution was questioned (Sylvester, 1960; Weibel, Anderson and Woodward, 1964) and an in-depth U.S. Public Health Service study was published (EPA, 1974). The Water Quality Act of 1965 was the first legislative recognition of the problem. This was followed by the Clean Water Restoration Act of 1966 and the Federal Water Pollution Control Act Amendments (FWPCA) of 1972 which placed new and stronger emphasis on stormwater pollution. Since the early 1970's, numerous articles have been published dealing with different aspects of the problem.

III. Stormwater Pollution Literature (Separate Sewers)

The major significance of urban stormwater runoff pollution has been realized during the last ten years. A wide variety of contaminants have been evaluated at different locations and for various conditions of land use and traffic conditions. Some attempts have been made at establishing relationships between pollutional potential and the land use factors. Models have been developed for predicting the impact of stormwater pollution on a receiving stream. Most researchers have found that the pollutional characteristics of stormwaters are highly variable and this has been a problem in the utilization of the results obtained from predictive models.

The literature in the stormwater pollution field is becoming quite extensive and the articles discussed in this report were selected for their relationship to the experimental work of this study.

A. Concentration of Pollutants.

Many of the earlier studies have been summarized in EPA publications and the results are shown in the following tables (1 & 2). Three more recent studies have given results for a more extensive list of pollutants.

TABLE 1

Characteristics of Stormwater Runoff (APWA, 1969)

City	BOD (mg/ℓ)	Total Solids (mg/ℓ)	Suspended Solids (mg/ℓ)	Coliform (number/ℓ)	Chlorides (mg/ℓ)	COD (mg/ℓ)
1. East Bay Sanitary						
District: Oakland, California						
Minimum	3	726	16	4	300	
Maximum	7,700		4,400	70,000	10,260	
Average	87	1,401	613	11,800	5,100	
2. Cincinnati, Ohio (1962-64)						
Maximum Seasonal Means	12	260				110
Average	17		227			111
3. Los Angeles County						
Average 1962-63	161	2,909			199	
4. Washington, D.C.						
Catch-basin samples during storm						
Minimum	6		26		11	
Maximum	625		36,250		160	
Average	126		2,100		42	
5. Seattle, Washington (1959-60)	10			16,100		
6. Oxney, England (1954)	100[a]	2,045				
7. Moscow, U.S.S.R. (1936)	186-285	1,000-3,500[a]				
8. Leningrad, U.S.S.R. (1948-50)	36	14,541				
9. Stockholm, Sweden (1945-48)	17-80	30-8,000		40-200,000		18-3,100
10. Pretoria, South Africa (1961)						
Residential	30			240,000		29
Business	34			230,000		28
11. Detroit, Michigan (1949)	96-234	310-914	102-213[b]	930,000[a]		

[a]Maximum

[b]Mean

TABLE 2

Comparison of Quality of Storm Sewer Discharges for Various Cities

Type of Wastewater Location	BOD_5 mg/ℓ Ave.	BOD_5 mg/ℓ Range	COD mg/ℓ Ave.	COD mg/ℓ Range	D.O. Ave.	SS mg/ℓ Ave.	SS mg/ℓ Range	Total Coliforms MPN/100 ml Ave.	Total Coliforms MPN/100 ml Range	Total Nitrogen mg/ℓ as N Ave.	Total Phosphorus mg/ℓ as P Ave.
Typical untreated municipal	200	100-300	500	250-750	-	200	100-350	$5x10^7$	10^7-10^9	40	10
Typical treated municipal:											
Primary effluent	135	70-200	330	165-500	-	80	40-120	$2x10^7$	$5x10^6$-$5x10^8$	35	7.5
Secondary effluent	25	15-45	45	25-80	-	15	10-30	10^3	10^2-10^4	30	5.0
Storm sewer discharges:											
Ann Arbor, MI, 1965	28	11-62	-	-	-	2080	650-11,900	-	-	3.5	1.7
Castro Valley, CA, 1971	14	4-37	-	-	8.4	-	-	$2x10^4$	$4x10^3$-$4x10^4$	1.8	-
Des Moines, IA, 1969	36	12-100	-	-	-	505	95-1053	-	-	2.2	0.87
Durham, N.C., 1960	31	2-232	224	40-660	-	-	-	$3x10^5$	$3x10^3$-$2x10^6$	-	0.18
Los Angeles, CA, 1967	9.4	-	-	-	8.9	1013	-	-	$3x10^3$-$2x10^6$	-	-
Madison, WI, 1970	-	-	-	-	-	81	10-1000	-	-	4.8	2.2
New Orleans, LA, 1967	12	-	-	-	4.5	26	-	$2x10^6$	$7x10^3$-$7x10^8$	-	-
Roanoke, VA, 1969	7	-	-	-	-	30	-	-	-	-	-
Sacramento, CA, 1968	108	24-283	58	21-176	-	71	3-211	$6x10^5$	$2x10^4$-$1x10^7$	-	-
Tulsa, OK, 1968	22	1-39	85	12-85	-	247	84-2052	10^5	10^3-10^8	0.3-1.5	0.2-1.2
Washington, D.C., 1961	19	3-90	332	29-1514	-	1097	130-11,280	$6x10^5$	10^5-10^6	2.1	0.6

A study in Trondheim, Norway (Kalleberg and Malme, 1974) evaluated stormwater runoff from an area with separate storm sewers and compared it with an area with combined sewers. The former area is a part of a newly developed residential section with an area of approximately 20 ha (49 acres) and rolling topography. The results are given in the following table.

TABLE 3
Stormwater Pollutant Concentrations
Trondheim, Norway
(Kalleberg and Malme, 1974)

	Min (mg/ℓ)	Max (mg/ℓ)
COD	6	241
BOD	5	20
SS	39	3080
VSS	6	130
Top P	0.01	0.5
Lead	0.001	0.02
Oil & Grease		15.9

Recently, a second study was made in Durham, N.C. (Colston, 1974). The stormwater runoff system is composed of overland flow, street gutters, small pipes and culverts and no storm sewer system exists as such. The results of this study are shown in the Table 4.

A very complete analysis of the pollutional characteristics was made at seventeen sampling points in Dallas, Texas for a 48 mm (1.9 inch) storm that occurred on February 11, 1977 (Dallas Water Utility, 1977). The results, averaged for the seventeen sampling points, are shown in Table 5. It was stated in the report that

TABLE 4

Stormwater Pollutant Concentrations
Durham, N.C.
(Colston, 1974)

Pollutant	Mean mg/ℓ	Standard Deviation	Range (mg/ℓ) Low	Range (mg/ℓ) High
COD	170	135	20	1042
TOC	42	35	5.5	384
Total Solids	1440	1270	194	8620
Volatile Solids	205	124	33	1170
Total Suspended Solids	1223	1213	27	7340
Volatile Suspended Solids	122	100	5	970
Kjeldahl Nitrogen as "N"	.96	1.8	.1	11.6
Total Phosphorus "P"	.82	1.0	.2	16
Fecal Coliform (#/ml)	230	240	1	1000
Aluminum	16	8.15	6	35.7
Calcium	4.8	5.6	1.1	31
Cobalt	.16	.11	.04	.47
Chromium	.23	.10	.06	.47
Copper	.15	.09	.04	.50
Iron	12	9.1	1.3	58.7
Lead	.46	.38	0.1	2.86
Magnesium	10	4.0	3.6	24
Manganese	.67	.42	.12	3.2
Nickel	.15	.05	.09	.29
Zinc	.36	.37	.09	4.6
Alkalinity	56	30	24	124

TABLE 5

Concentration of Pollutants from Dallas Stormwater
(Dallas Water Utility, 1977)

	Min. 5 sites	Max.	Ave.	
DO	0	5+		mg/ℓ
BOD	0	21	6.2	mg/ℓ
COD	22	167	67.3	mg/ℓ
TS	48	1480	581	mg/ℓ
TSS	18	1368	349	mg/ℓ
N	0.28	10.48	2.28	mg/ℓ
P	0.13	5.40	0.87	mg/ℓ
Hg	0.06	16.25	1.15	μg/ℓ
Pb	0	1300	227	μg/ℓ
Zn	30	330	98	μg/ℓ
Sr	70	750	349	μg/ℓ
Fecal Coliform	251	26000	6530	coli/100 ml
Chlorphenoxy Herbicides	0.016	1.94	0.56	μg/ℓ
Chlorinated Hydrocarbons	0.006	0.105	0.021	μg/ℓ
Organic Phosporus Carbonates	0	0.018	.003	μg/ℓ

the stormwater contributed 99% of the suspended solids and 75% of the BOD in the stream on the day of the storm with the remaining 1% TSS and 25% BOD being contributed by the sewage treatment plant effluents. It was also estimated that the BOD contribution of the stormwater for the single storm was equivalent to 17 days of effluent discharge from a sewage treatment plant serving the same drainage area, discharging 10 mg/ℓ BOD, and the total suspended solids was equivalent to 361 day discharge of treated wastewater with a concentration of 10 mg/ℓ.

It can be concluded from these data that the pollutional contribution of the discharges from separate storm sewers may have a significant impact on a receiving stream since the concentrations of chemical oxygen demand and suspended solids are generally higher than would be permitted for sewage treatment plant effluents. It is also apparent that a high degree of variation in pollutional quality has resulted from different cities and that generalizing on the pollutional strength of stormwaters can only be done in broad terms.

The major reason for the highly variable pollutional strengths of stormwaters is the large number of factors relating to the storms producing the runoff and to the character of the catchment areas. Some of the relationships associated with these factors have been investigated and reported in the literature.

B. Rainfall and Snowmelt

Most of the previous work on stormwater quality has related to rainfall events. A few articles have been published on the effects of snowmelt runoff and the impact of deicing chemicals.

A study in Des Moines, Iowa involved storm sewer discharge sampling for a twelve month period (Lager and Smith, 1974). The study involved both combined sewer overflows and separate storm sewer discharges. The data for snow events was separated in the data and compared with rain events. The results are shown in the following table.

TABLE 6

Comparison of BOD_5 from Combined Overflows, and Separate Storm Discharges, and Snow Melt; Des Moines, Iowa (Lager and Smith, 1974)

Type of Discharge	Mean of the Test Areas, mg/ℓ	Range of the Test Area Means, mg/ℓ
Combined overflows (5 areas)	80	53-117
Storm sewer discharge (rain induced - 4 areas)	32	23-46
Storm sewer discharge (snow melt - 4 areas)	75	67-85

It is interesting to note the high concentrations associated with urban snowmelt. In this case, the mean values are more than twice as high for snowmelt as for rain.

In 1969, during the spring, a study was conducted in the southern part of Stockholm, Sweden (Soderlund, Lehtinen and Finberg, 1970), in a newly developed area with separate drainage systems. The area is mostly residential and commercial, but includes some industrial sites. European Highway No. 4 passes the area with an average of 55,000 vehicles every 24 hours. The stormwater is collected in a discharge tunnel 2.2 m (7.22 ft) in diameter which dewaters 1,000 hectares (2,470 acres) of the sampling area.

The sampling was started in February after a heavy snowfall. Since most of the snow was later removed and dumped into a lake, snow samples from different streets were collected about four

TABLE 7

Snow Samples Collected from Six Different Streets in Stockholm; February 1969 (Soderlund, Lehtinen and Finberg, 1970)

Analysis (mg/ℓ)	Arithmetic Mean	Standard Deviation	Reference Sample
Dry solids	3,600	1,900	43
Volatile DS	500	480	37
Suspended solids	2,700	1,800	48
Volatile SS	300	190	19
Oil	40	35	1
Lead	20	10	Traces
Cl^-	320	140	5

days after the snowfall. The results from this sampling are shown in Table 7. The reference sample, appearing in the third column, was one of untouched snow from a park in the area. After a cold period, the sampling of the melt-water from the area was continued in March. The first spring rain, in April, and the following rains were also collected. A strong correlation was found between the pollutional load and the air temperature. This was due to the increased melting of the polluted snow in a warmer atmosphere and also a washing of the street with the melt-water. From the figures presented in their report, the approximate concentration ranges presented in Table 8 can be found from the runoff in the tunnel of March 25-26th, 1969.

TABLE 8

Runoff in the Tunnel
Stockholm, March 1969
(Soderlund, Lehtinen and Finberg, 1970)

Parameter	Concentration Range (mg/ℓ)
BOD_5	5 - 90
Total Solids	450 - 1000
Total N	0.3 - 2.4
Total P	0.01- 0.07
Cl^-	25 - 450
pH	6.5 - 9.0
Oil	Trace - 12

Samples had also been collected from the highway, terrace houses, and residential blocks, and it was found that traffic routes gave a high degree of contamination as compared with the other test areas.

A study was conducted in Ottawa, Canada, on lead contamination of snow. It was found that snow from snowdumps and major highways had the largest concentrations of lead, ranging from 0.02 to 50.0 mg/ℓ for snowdumps, and 86.0 to 113.0 mg/ℓ for highways. The levels of lead in snow along city roads were found to be roughly proportional to traffic volumes. Up to 15 mg/ℓ of lead was reported for industrial streets, while commercial and residential streets were only slightly lower (LaBarre, Milne, and Oliver, 1973).

Further studies in Ottawa have indicated the existence of extremely high chloride concentrations in snowmelt runoff. Table 9 shows the distribution of chloride in snow and snowmelt as a

TABLE 9

The Distribution of Chloride in Snow and Snowmelt as a Function of Sampling Location (Oliver, Milne, and LaBarre, 1974)

Location	Range of Chloride Levels (mg/ℓ)	Mean Chloride Level (mg/ℓ)
Snow Dumps	40-2,500	464
Commercial Street	4-15,266	3,233
Industrial Street	143-2,448	1,703
Residential Street	154-8,151	2,283
Roof Samples	0-3	.6
Snow Dump Runoff	16-4,397	500
Storm Sewer Runoff	11-1,163	219
Raw Wastewater	84-332	162
Treated Wastewater	88-363	200
River	8-57	19

function of sampling location. The low chloride levels in the rooftop samples indicate that the chloride in the street and dump samples comes almost exclusively from road salting. The higher chloride levels in the street samples as compared to the dump samples were attributed to continuous salt buildup in the roadside locations (Oliver, Milne, and LaBarre, 1974).

Sodium chloride is the most widely used deicing chemical. Its non-biodegradable nature accounts for the fact that street runoff from the melting of ice and snow mixed with chloride salts eventually finds its way to nearby receiving waters (Field, Struzeski, Masters, and Tafuri, 1973), whether it be directly through storm sewers, or indirectly through combined sewers. Daily chloride loads were shown to be 50 percent higher for winter months as compared to summer months in municipal sewage at Milwaukee, Wisconsin (Schraufnagel, 1965). Recorded chloride loads during days of heavy snowmelt were more than 3 times the normal summertime loads.

Street runoff samples collected from a downtown Chicago expressway, during the winter of 1967, showed chloride levels from 1,900 to 4,500 mg/ℓ when highway salts were not being applied (APWA, 1969). But during snowfalls the chloride in highway runoff ranged from 11,000 to 25,000 mg/ℓ. The study further indicated that almost all the deicing salts subsequently left the area in the form of runoff. The APWA study in Chicago also concluded that "the salt content of highway drainage will depend upon many factors including ambient temperatures, amounts of precipitation, quantity of salt applied, traffic patterns, and the volume and rate of surface runoff."

In Wisconsin studies Schraufnagel (1965) reported that in the Chippewa Falls area, wintertime highway runoff was found to contain upwards of 10,000 mg/ℓ chlorides, whereas during the summer months street runoff ranged from 0-16 mg/ℓ chlorides.

In an investigation of water quality on Meadow Brook in Syracuse, New York (Hawkins, 1971), chloride concentrations were usually found to be between 200-1000 mg/ℓ in winter, but on a number of occasions chlorides rose to over 2,000 mg/ℓ, with one sample in December yielding 10,000 mg/ℓ chlorides. Hawkins believes that deicing chemicals may also "be stored in the street itself, including: the snow and ice cover; on the street surface; and directly within the street masonry concrete, cobbles and other street construction materials." Observations of "summer leakage of salt" upward onto the street surface, in areas which had been heavily salted the winter before, verified his beliefs. This resupply of salts continued through the summer rains and lasted well into the autumn, continually finding their way into street and storm sewers.

Several storm drainage areas in the Des Moines, Iowa study were evaluated for chlorides by Henningson, Durham, and Richardson, Inc. (1973). The winter of 1968-69 which they examined was relatively severe, with large quantities of road deicing materials used. "Total deicers used, from December through March, were 8900 kg (9800 tons) with a chloride equivalent of 5300 kg (5830 tons)." A look at the results of one of the many storm drainage areas in the city shows the results of this heavy salting. A total of over 13,600 kg (15,000 lbs) of chlorides were carried off between January 15 and March 2, in the runoff of a storm drain serving an area of 127 hectares (315 acres). Similar results were seen in the other storm drainage areas throughout the city. The HDR study also reported that "samples of water from the Des Moines and Raccoon Rivers were significantly higher in the winter months than in the summer. Winter chloride values upstream of the city were in the 30-50 mg/ℓ range and downstream of Des Moines in the 50-80 mg/ℓ range; this was in contrast to the spring and summer chloride levels which were below 20 mg/ℓ at both sampling points."

Other studies on chloride levels of major rivers have shown similar results. Hutchinson (1967) analyzed seven major rivers in Maine for sodium and chloride levels over the period 1965-67. These ions were generally "1-2 mg/ℓ at the headwaters and increased to as high as 15-18 mg/ℓ at the mouths of the respective rivers." Highest levels of sodium and chloride were shown in the southern section of the state where highway miles were greatest.

Special additives present within much of the highway salts sold today may create pollutional problems even more severe than caused by chloride salts. Ferric ferrocyanide and sodium ferrocyanide are commonly used to minimize the caking of salt stocks. This sodium form is quite soluble in water, and will generate cyanide in the presence of sunlight (Hanes, et al., 1970). Tests showed that "15.5 mg/ℓ of the sodium salt can produce 3.8 mg/ℓ cyanide after 30 minutes." The maximum levels of cyanide allowed in public water supplies range from 0.2 to 0.1 mg/ℓ (USPHS, 1962).

Other special additives to highway salts have been chromate and nutritious phosphate, used to inhibit corrosion (Hanes, et al., 1970). As with cyanide, chromate is highly toxic, and limits permitted in drinking and other water are in the same low range. A study in the St. Paul-Minneapolis area during the winter of 1965-66 showed maximum levels of 24 mg/ℓ sodium chromate, 1.7 mg/ℓ hexavalent chromium, and 3.9 mg/ℓ total chromium in the snowmelt sampled (Cargill, Inc., 1967).

In addition to toxicity some deicing compounds may pose a more subtle threat to the receiving waters. Schraufnagel (1965) in discussing substitute deicing compounds, describing the glycols and alcohols in particular, as "having extremely high biochemical oxygen demand (BOD), ranging from 70 to 133 percent of the product weight". This is in contrast to urea which has a BOD_5: weight ratio of only 9 percent and sewage with a 0.02 percent ratio. Schraufnagel concluded that certain deicers, such as ethylene glycol, if released into a nearby stream can exert tremendous demand on existing dissolved oxygen. The report gave an example which indicated that "one pound of deicing compound with a BOD:weight ratio of 1.0, if discharged into a waterway having 7 mg/ℓ dissolved oxygen, will utilize all the oxygen available in about 17,000 gallons of streamflow."

Another major concern in snowmelt discharges relates to the lead concentration. Dramatic increases in the lead content of the world's atmosphere have been demonstrated from analysis of the Greenland ice cap (Chow and Earl, 1970). Concentrations have risen from 0.08 μg/kg in 1940 to 0.21 μg/kg in 1965. Large quantities of lead are present in the atmosphere of urban centers as shown by Colucci, et al. (1969). Values as high as 18.4 $\mu g/m^3$ have been found at sites near heavy traffic. Lead is a primary contaminant of automobile emissions and tends to be deposited within a short distance of the roadbed as well as escaping into the atmosphere. The lead accumulates on the surface of streets during dry periods and then is transported to surface streams during periods of runoff (EPA, 1972, 1973). Quite naturally then, the levels of lead in snow along city roads are roughly proportional to the traffic volume. Lead bromide chloride has been shown to be the major lead containing product in automobile exhaust, with $PbCO_3$ and PbO also forming on contact of the exhaust fumes with snow.

The lead appears to be adsorbed on the particulate present in the snow, as confirmed by adsorption studies. LaBarre, Milne and Oliver (1973) conducted a study of the concentration of lead in snow in an urban center, in order to assess the effects of snow disposal practices on water quality. They showed the level of lead in snow along city roads to be roughly proportional to the traffic volume. Also in sampling of lead concentrations of snow in 11 city snow dumps the average value was found to be 4.8 ppm. Snow collected from city roofs 325 and 40 ft in height, contained 0.02 and 0.25 ppm lead, respectively. By comparison, snow along roads and in snow dumps is severely contaminated with lead from automobile exhausts, as seen in the following table.

Newton, et al. (1974) presented observations of lead concentrations in street runoff. Data from automotive emissions and knowledge of daily vehicle travel in the Oklahoma City drainage basin studied provided them with a theoretical value of 0.23 mg/ℓ based upon uniformity of precipitation over the drainage basin.

Table 10

The Distribution of Lead in Snow and in Snow Melt
As A Function of Sampling Locations
(LaBarre, Milne and Oliver, 1973)

Location	Number of samples	Mean lead level (ppm) μg g^{-1} Filtrate	Sediment	Total sample	Range of lead levels (ppm) for total sample
Snow dumps	149	0.052	555	4.8	0.02 50
Major highway	3	0.060	3287	102	86 113
Commercial street	41	0.042	822	3.7	0.02 11.3
Industrial street	6	0.048	935	4.7	0.06 14.3
Residential street	9	0.014	1228	2.0	0.12 10.2
Roof samples	5	0.041	--	0.12	0.02 0.25
Snow dump run-off	39	0.009	1322	0.11	0.004 0.51
Storm sewer run-off	50	0.007	1791	0.13	0.002 1.19
Raw sewage	5	0.026	479	0.09	0.05 0.16
Treated sewage	13	0.027	448	0.06	0.003 0.14
River	8	0.006	69*	0.03†	0.004 0.046

* Value for river bed sediments (22 samples).

† Calculated using levels in transported sediment (av. 494 ppm) as opposed to river bed sediments.

This was compared with observations of the lead content in snow, water, and ice sampled on road surfaces and adjacent areas. Concentrations of lead from road edges averaged 5.5 mg/ℓ, ranging from 3.6 to 8.5 mg/ℓ. Again, concentrations of lead in samples taken at points away from the roadbed decreased with increasing distance from the roadbed. A value of 0.09 mg/ℓ was reported for lead concentrations in a sample obtained from an "open field surrounded on three sides by heavily traveled streets". Observations were compared with the theoretical value and a number of factors were suggested to explain the differences.

Bryan (1970) in his original Durham, N.C. study on urban runoff, noticed erratic BOD results. Exploratory work indicated "evidence of toxicity to the reaction (BOD) detected in some samples which upon further exploration revealed presence of lead at concentration levels in the order of 1.0 mg/ℓ." A subsequent study on the same drainage area revealed lead concentrations in the storm water runoff to range from 0.10 mg/ℓ to a maximum value of 12.6 mg/ℓ. The yield of lead from the predominantly residential area within the drainage basin was one-half of that from the more commercially developed area, and was almost exactly in proportion to the percentage of paved surfaces (Bryan, 1972). In addition, the yield of lead presumed to originate from "internal combustion engines operating on and near the basin was determined to be 0.0006 lb/day/acre (0.00067 kg/hectare/day)."

C. Effects of Storm Pattern

Several researchers have investigated the relationship of duration and intensity of a storm with the resulting runoff pollutional characteristics. Higher runoff concentrations have been predicted (EPA, 1974) under the following conditions: 1) the early stages of a storm, including first-flush effects, 2) in response to intense rainfall periods, 3) after prolonged dry periods, 4) in areas of construction activities, and 4) in densely settled, highly paved or industrial areas.

The early portion of a storm tends to dissolve and suspend the pollutional materials that have collected on roofs, lawns, and streets. For this reason, a concentration peak for some pollutant arrives at the storm sewer outlet ahead of the flow peak produced by a rainstorm. This has been termed the first-flush effect. It is usually more dominant in combined sewers than with separate storm sewers due to the scouring of solids in the combined sewer system (Lager and Smith, 1974).

Weibel, Anderson and Woodward (1964) in a study in Cincinnati, Ohio reported average concentrations of various pollutants for different time intervals of runoff. These data have been summarized in Table 11, and include data obtained for all flow conditions and seasonal variations. The first-flush effect is shown clearly for its impact on constituent concentrations.

Burn, Kranczyle, and Harlow (1968) also reported average annual discharge concentrations at various time increments for storm sewer discharges and the "first-flush" effect was evident, especially in the case of the different solids parameters.

TABLE 11

Average Concentrations of Various Pollutants for Various Time Intervals of Runoff, Cincinnati, Ohio (Weibel, Anderson and Woodward, 1964)

Parameter	0-15 Min.	15-30 Min.	30-60 Min.	60-120 Min.	120+
COD, mg/ℓ	170	130	110	97	72
BOD, mg/ℓ	28	26	23	20	12
SS, mg/ℓ	390	280	190	200	160
VSS, mg/ℓ	98	69	47	58	33
Total N, mg/ℓ	3.6	3.4	3.1	2.7	2.3
PO_4, mg/ℓ	0.99	0.86	0.92	0.63	0.63

McElroy and Bell (1974) reported that a "first-flush" of suspended solids and BOD was exhibited at the urban sampling station; however, no first flush of BOD was apparent at the semi-urban/rural station, and only a very small first flush of suspended solids was observed. It was also reported that although first flushing was evident, several subsequent flushes of suspended solids also occurred after the initial flush when the flow increased dramatically. However, upon reaching maximum flow, solids concentrations decreased and remained constant regardless of the flow pattern. This implies that a minimum flow is required to completely flush the solids from the basin.

De Fillipi and Shih (1971) studied the time and flow dependency of storm sewer flows in Washington, D.C. They also found the "first-flush" to be evident in most cases. Storms with various durations and intensities, as well as consecutive storms, were investigated with regard to (1) concentration versus time, and (2) waste load versus time.

The first flush observance is a concentration of pollutants effect. Both articles (McElroy and Bell, 1974 and DeFillipi and Shih, 1971) presented plots of instantaneous mass loading (the product of flow and concentration in lb/day) of pollutants. The maximum mass of pollutants per unit of time occurred at the flow peak and not at the time of the first flush concentration. This is shown in Figure 1.

Studies in San Francisco (Friedland, Shead and Ludwig, 1970) and in England (Davidson and Gameson, 1967) have shown the pollutional profile during the total runoff period of storms and have identified the factors that cause variations in pollutional strength as: the rainfall intensity, antecedent dry period and the sewerage system configuration.

A few investigators have attempted to correlate the relationship between the concentration of some parameters with the amount of flow at sampling sites. No relation has been found between parameters like BOD, Total N, Total P, and flow. However, for suspended solids a correlation was found in a study in Stockholm, Sweden (Soderlund and Lehtinen, 1972). Figure 2 shows a straight line relationship with a correlation coefficient of 0.92. One interesting observation they made was that the amount of pollutants was linearly related to the rainfall intensity and independent of the interval from the beginning of the downpour.

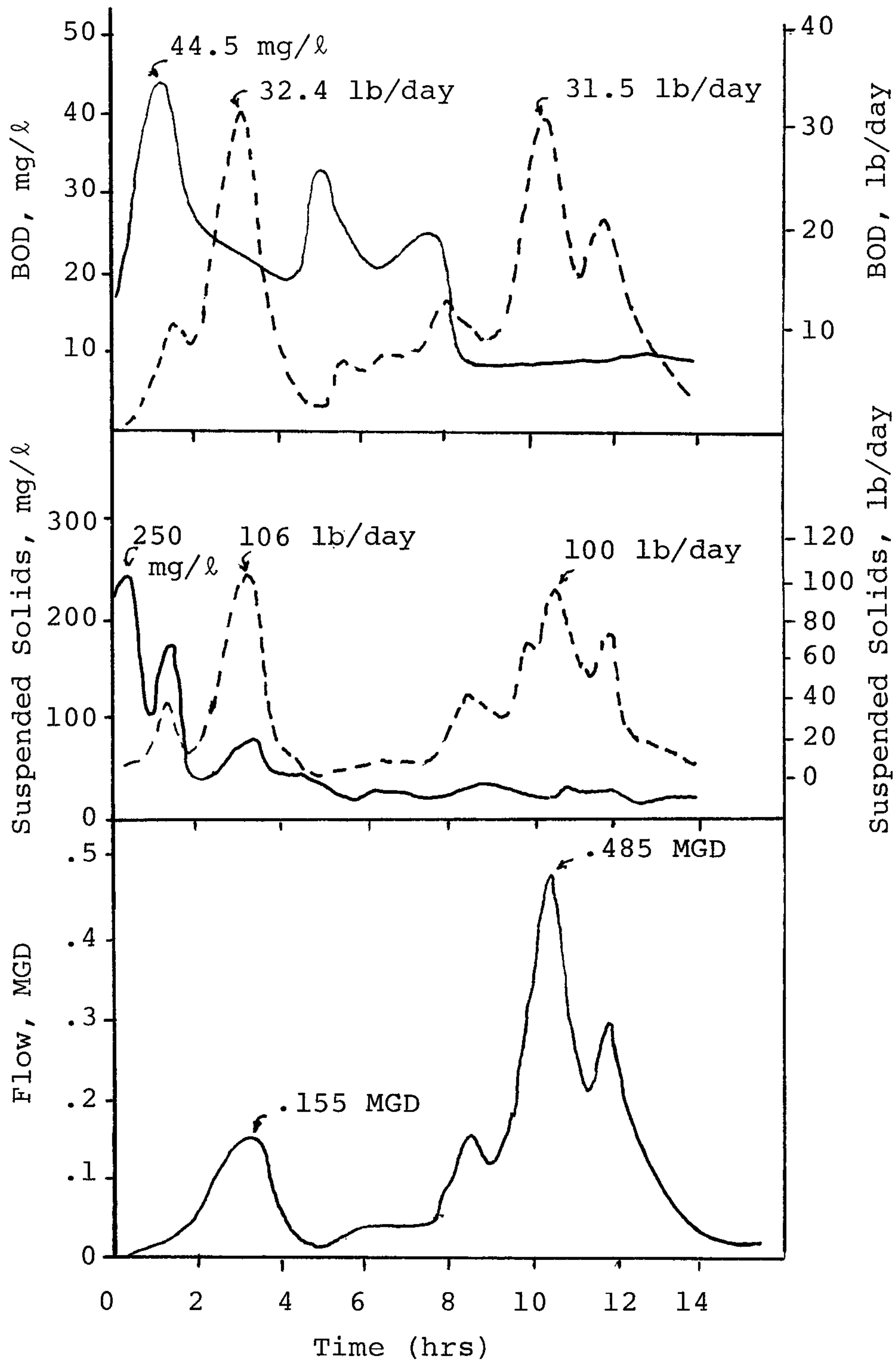


Figure 1. Variation of Flow, BOD, and Suspended Solids during the Storm of November 13, 1972 at the Urban Sampling Station (McElroy and Bell, 1974).

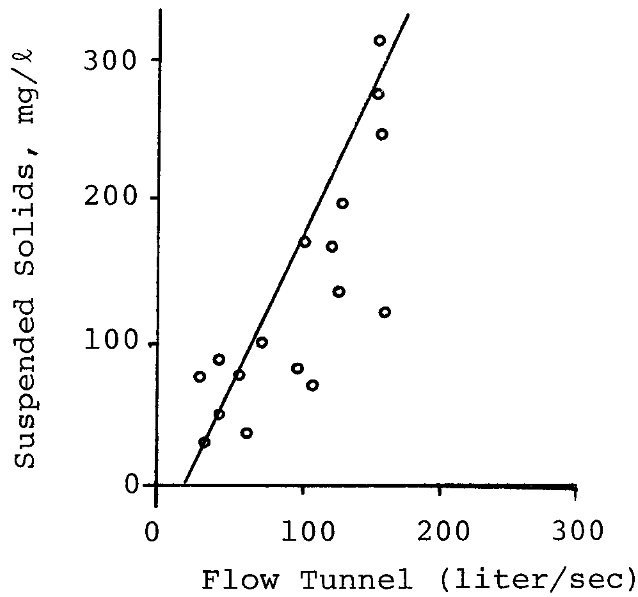


Figure 2. Concentration of SS vs. Flow in the Storm-Water Sewer (Soderlund and Lehtinen, 1972)

other parameters, especially the heavy metals did not display this extremely high correlation. The significance of this result is that no "washing-out" effect occurred. This is important if stormwater runoff has to be collected and treated. At Sacramento, California (EPA, 1971a) the same relationship has been shown to exist between river flow and the suspended solids concentration. However, an inverse relation was found to exist between fecal coliforms and flow. The concentrations of BOD and Total-N seemed to decrease with increasing flow, according to the British study at Northampton (Davidson and Gameson, 1967).

The effect of antecedent dry period has been investigated by Sartor and Boyd (1972) and their results are presented in the curve shown in Figure 3.

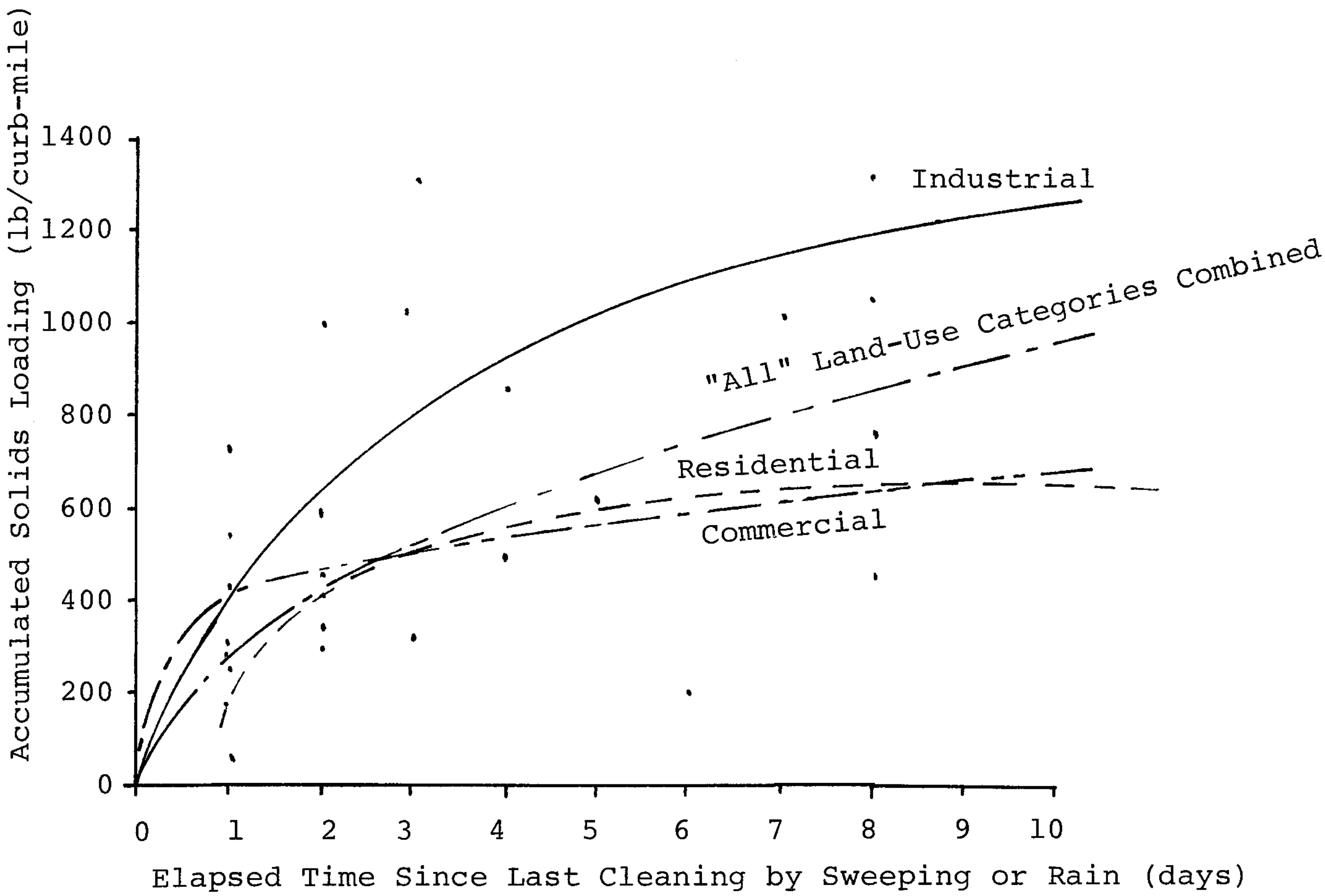


Figure 3. Accumulated Solids Loading _vs_ Time Since Last Cleaning (Sartor and Boyd, 1972).

It can be noted that after one or two days after street sweeping or a storm, the accumulated solids become nearly constant on street surfaces in residential or commercial areas. Apparently wind and auto movement resuspend deposited material after it reaches a certain depth and a constant level of accumulated solids results.

The configuration of the sewer system has been considered in a few studies. Contaminants may be introduced into storm sewers through openings in the system. When violations of local ordinances occur, additional contaminants find their way into the system. Various wastes that are difficult to dispose of, such as motor oil, transmission fluid, etc., often enter storm sewers via street inlets. In separate storm sewers, these wastes will be discharged untreated, or will collect until the next storm washes them out (Lager and Smith, 1974).

Catch basins, which were originally installed to prevent sewer clogging and to provide water seals to entrap odors from sewers, have been found to be a significant source of pollutants (APWA, 1969). A study in Chicago indicated that the liquid remaining in the catch basin between runoff events tended to become septic, and that the solids trapped in the basin took on characteristics of anaerobic sludge. The BOD content of catch basin liquid was found to be 60 ppm (50 to 85 ppm range) in a residential area. It was also found that even for minor storms, the BOD of the liquid was 7½ times that of the runoff which had been in contact with street surface contaminants. Since the

Chicago study, other researchers have investigated the characteristics of catch basins, and in each case it was found that, unless they are cleaned between storms, catch basins are surely a significant source of pollution during storm events (Lager and Smith, 1974)

D. Catchment Area Land Use Effects

In recent years, several investigators have conducted studies to assess the variations of stormwater runoff quality with variations in land use. In 1972, McElroy and Bell conducted a field study of stormwater runoff from a small urban watershed and a larger semi-urban/rural watershed. The urban watershed was a 29 acre (12 ha) fully-developed residential area having 33 percent impervious area and containing 72 single-family dwellings with a total population of 252 persons (8.7 persons/acre). Sampling of stormwater drainage from this area was conducted in a concrete pit receiving runoff from the storm sewer system. The semi-urban/rural watershed had an area of 292 acres (118 ha) and included 178 acres (72 ha) of partially developed residential land (3.4 persons/acre)(8.4 persons/ha), and 292 acres (118 ha) of farm land. Sampling of this area was performed in a drainage ditch.

It was found in the study that the concentrations of pollutants resulting from the runoff from one acre of urban watershed were much greater than those from the larger semi-urban/rural watershed. The ranges of the peak concentrations are shown in Table 12. Both minimum and maximum peak values

TABLE 12

Comparisons of Peak Pollutant Concentrations in Stormwater Runoff from an Urban Watershed and a Semi-Urban/Rural Watershed (McElroy and Bell, 1974)

Parameter Measured	Range of Peak Pollutant Concentrations	
	Semi-Urban/Rural Watershed	Urban Watershed
BOD, mg/ℓ	3 to 7	11 to 44
Suspended Solids, mg/ℓ	6 to 170	62 to 250
Total Coliform Counts (organisms/ml)	930 to 46,000	930 to 240,000
Fecal Coliform Counts (organisms/ml)	930 to 9,300	430 to 98,000

were much higher for the urban watershed as compared to the semi-urban/rural watershed for all of the parameters that were studied.

Turner and Burton (1975) carried out studies on the effects of land use on hydrology and nutrient and suspended solids exports from three north Florida watersheds. The three watersheds represented a wide variation in land use as indicated in Table 13, which summarizes their characteristics. Sampling and flow measurements were taken in a stream that drained each individual area. Each stream had a low flow of less than 0.02 cubic meters per second (0.7 cfs), and each occasionally became dry.

TABLE 13

Comparison of Land Use of the Three North Florida Watersheds (Turner and Burton, 1975)

Land Use	Ox Bottom Creek (Forested-Agricultural)	Meginniss Arm Tributary (Urban)	Ford's Arm Tributary (Suburban)
Forest	327 ha* (52%)	85 ha (12%)	290 ha (84%)
Agricultural	306 ha (48%)	63 ha (9%)	24 ha (7%)
Residential	0	482 ha (67%)	7 ha (2%)
Commercial	0	91 ha (13%)	0
Interstate Highway	0	0	24 ha (7%)
Total	633 ha	721 ha	345 ha

*1 hectare (ha) = 2.47 acres

The mean concentrations of streamwater constituents in the discharges from the three watersheds are presented under low flow and high flow conditions in Table 14. The primary differences between the three watersheds were seen to be in the concentrations of suspended solids, dissolved solids, dissolved silicon, and in the dissolved inorganic nitrogen species (NO_3-N, NO_2-N, NH_3-N). Suspended solids were found to be an important factor in many of

Table 14

Comparison of Mean Concentrations (mg/ℓ) for Stream Water Constituents in the Three Watersheds under Stormflow and Baseflow (Low Flow) Conditions (Turner and Burton, 1975).

Constituent	Forested	Suburban	Urban
	Stormflow		
SS*	34±25	176±324	299±378
TDS*	58±25	115±118	161±181
Silicon	3.57±0.48	2.56±0.49	1.72±0.74
NO_3-N	0.06±0.03	0.30±0.15	0.12±0.10
NO_2-N	0.002±0.002	0.04±0.05	0.014±0.02
NH_3-N	0.06±0.02	0.08±0.05	0.16±0.23
PO_4-P	0.10±0.06	0.05±0.04	0.12±0.13
	Baseflow		
SS*	12±4	7±3	10±17
TDS*	43±8	53±9	86±30
Silicon	4.17±0.54	2.96±0.13	2.15±0.74
NO_3-N	0.05±0.03	0.18±0.05	0.10±0.06
NO_2-N	0.009±0.022	0.021±0.045	0.007±0.011
NH_3-N	0.04±0.01	0.05±0.02	0.06±0.12
PO_4-P	0.13±0.06	0.04±0.02	0.06±0.03

* SS = suspended solids.

* TDS = total dissolved solids.

the mechanisms controlling constituent concentrations. The greater overland flow, higher peak discharge, and shorter residence time of water in soils in the urban system were identified as the primary factors contributing to the observed differences between the watersheds.

The quality and quantity of storm runoff from a regional shopping mall in Tallahassee was also examined (Turner and Burton, 1975). The mall covered approximately 75 acres (30 ha), with reported traffic volumes of approximately 8.6 million vehicles annually. Table 15 summarizes the concentrations of selected constituents of the runoff from the one storm that was sampled. Some of the notable features of these data include (1) the very large variability in concentrations of nearly all the constituents, (2) the relatively high dissolved solids concentrations, (3) the high proportions of volatile solids, dissolved organic carbon, and particulate organic carbon in the runoff, and (4) the high concentrations of phosphorus in the runoff considering the lack of a sanitary sewage source. The reasons for the high phosphorus concentrations were not determined.

A recent study concerning the effects of land use on urban runoff quality was carried out by Rimer, Reynolds and Nissen (1976). Their study utilized the Third Fork Creek drainage area in Durham, N.C., and was part of a 208 study for the Triangle J. Council of Governments. The study involved the inventory and analysis of point and non-point pollution (Pollution Source Analysis). Instead of monitoring the drainage basin as a whole

Table 15

Summary Statistics for Concentrations of Storm Runoff Constituents, Tallahassee Mall, November 11, 1974 (Rainfall = 6.35 mm; Runoff = 3.24 mm; Antecedent Dry Period - 25 days) (Turner and Burton, 1975)

Constituent[1]		Standard Deviation	Range	Number of Samples
Turbidity (JTUs)	34	41	10-205	23
Conductance (μmhos/cm)	225	340	67-1530	23
SS	57	63	6-195	23
VSS	32	32	4-98	23
TDS	202	339	41-1613	23
VDS	67	143	4-708	23
Cl	10.2	16.6	2.1-75	23
Si	2.71	5.51	0.18-17	23
NO -N	0.184	0.083	0.051-0.352	23
NO -N	0.014	0.017	0.003-0.088	23
NH -N	0.076	0.044	0.035-0.214	23
Ortho P	1.47	3.09	0.028-12.0	23
Diss. P	1.62	3.23	0.086-12.5	23
Tot. P	2.69	4.50	0.281-15.1	23
DOC	131	197	12-648	10
POC	294	726	4-2220	9

[1]Concentrations in mg/l or as indicated.

as Bryan and Colston did, sub-basins, consisting of different land use patterns, were identified and monitored. The results of the study are summarized in Table 16 using data from all of the storms sampled. It was found that:

TABLE 16

Average Peak Concentrations of Pollutants for All Storms Sampled by Rimer, Reynolds and Nissen, Durham, North Carolina
(Rimer, Reynolds and Nissen, 1976)

Land Cover Type	Percent Impervious Area	Average Peak Concentrations (mg/ℓ)			
		COD	SS	TP	Pb
Low Activity Rural	2.7	41	284	1.40	< 0.1
High Activity Rural	5.1	58	416	0.76	< 0.1
Low Activity Commercial	12	87	575	0.83	0.2
Low Activity Residential	16	166	664	0.84	0.6
High Activity Residential	32	194	1199	1.03	2.1
High Activity Commercial	35	320	1082	1.08	1.7
Central Business District	80	336	528	0.66	0.9

(1) COD levels in stormwater runoff were generally a function of the amount of development and impervious surface within the catchment being drained. Increasing values of COD concentrations can be expected from land cover types which have an increasing percentage of impervious surfaces.

(2) Suspended solids concentrations were also found to increase as the percentage of impervious surfaces increases. Rural areas were found to have the lowest suspended solids concentration of any of the land uses investigated. The relatively low peak suspended solids concentration in the central

business district was attributed to the fact that there was very little land disturbing activity in a downtown area and the solids buildup rates were reduced by street sweeping practices.

(3) Phosphorus levels were closely associated with the suspended solids concentration, and generally increased with increasing levels of suspended solids. One exception, the low activity rural land, exhibited the lowest peak suspended solids concentration but the highest peak phosphorus concentration, probably due to increased use of fertilizers.

(4) The peak lead concentrations increased with increasing impervious area and vehicular traffic and appeared closely correlated to the suspended solids level in the runoff.

As a part of their study, Sartor and Boyd (1972) measured the difference in total solids loadings as a function of land use type. Their results are shown in Table 17.

E. Total Pollutant Loads

Several investigators have reported results in terms of pollutant yields (lbs/in/acre) and total pollutant contributions (lbs/acre/year). Expressing results in this manner is useful in determining the relative long term influence of urban stormwater runoff on water quality in relation to other pollutant sources.

Weibel, Anderson, and Woodward (1964) computed loadings on a pound/acre/year basis for several of the constituents that were found in the stormwater runoff from their test site in

TABLE 17

Land Use Effects on Total Solids Concentration (Sartor and Boyd, 1972)

Land Use	Total Solids Loading Numerical Mean (lb/curb mi)	Total Solids Loading Weighted Mean (lb/curb mi)
Residential		1,200
low/old/single	850	
low/old/multi	890	
med/new/single	430	
med/old/single	1,200	
med/old/multi	1,400	
Industrial		2,800
light	2,600	
medium	890	
heavy	3,500	
Commercial		290
central		
business district	290	
shopping center	290	
Overall		1,400
1 lb/curb mile = 0.28 kg/curb km		

Ohio. These values are shown in Table 18. The comparison is with raw sewage, however, and a comparison with secondary treated sewage would result in higher percentages. For example, a comparison with secondary sewage treatment plant effluent would reveal annual stormwater runoff BOD loads averaging 60 percent of the treatment plant effluent BOD.

In Durham, N.C., Bryan (1972) found that during the 1972 calendar year the pollutant loadings were as shown in Table 19. When compared to domestic waste, the urban stormwater contributed approximately 48 percent of the total COD, 41 percent of the total BOD and 95 percent of the total suspended solids on a lbs/acre/year basis. Bryan also estimated the overall pollutant

Table 18

Comparison of Stormwater Runoff Loads and Sanitary Sewage Loads (lbs/yr/acre)*
(Weibel, Anderson, and Woodward, 1964)

Constituent	Stormwater Runoff	Sanitary Sewage (raw)	% Storm Sanitary
SS	730	540	140
VSS	160	360	44
COD	240	960	25
BOD	33	540	6
PO_4	2.5	27	9
Total-N	8.9	81	11

* Multiply by 1.12 to obtain kg/yr/ha.

TABLE 19

Urban Runoff Pollutant Yield during 1972 in Durham, N.C.
(Bryan, 1972)

Parameter*	Pounds/Acre/Year	Kg/Ha/Year
COD	938	1208
TOC	187	212
TS	7700	8740
TVS	1458	1655
SS	6691	7594
VSS	797	905
TKN	6.1	6.9
Total-P	4.7	5.3
Pb	2.9	3.3

removal efficiency for COD at 48 percent, BOD at 46 percent, and suspended solids at 4 percent. These efficiency estimations are based on the fact that the total pollutant load from a municipality will include the stormwater runoff pollutant load as well as the pollutant load introduced by the sewage treatment plant. It is implied then that even though pollutant removal efficiencies for secondary sewage treatment plants are high, the overall pollutant removal efficiencies are low when stormwater runoff is also considered as a pollutant source.

A study in Tulsa, Oklahoma (EPA, 1974) has estimated the annual load of pollutants entering the area receiving streams. This is seen in Table 20, where the annual storm sewer discharges are compared with the annual load from treatment plant effluents. Although the storm sewer discharges contributed only 20 percent of the annual BOD_5 to the area receiving streams, this source contributed 85 percent to the annual SS. One should note that the COD contribution was higher; 31 percent compared to only 20 percent for BOD_5. This gives an indication that the material in the storm sewer discharges would therefore be more slowly oxidized than that in the treatment plant effluent.

Several investigators have reported waste loadings. However, they seem to differ somewhat in ways of reporting their results. DeFillipi and Shih (1971) have calculated waste loading, both for combined wastewater and storm runoff, in terms of pounds per minute. Assuming that combined wastewater and storm runoff makes up the total amount discharged to the nearest stream, the per-

Table 20

Estimated Annual Load of Pollutants
Entering the Area Receiving Streams
Tulsa, Oklahoma
(EPA, 1974)

Pollutant	Average annual storm sewer discharge pollution load, lb	Contribution of storm sewer discharges to total load, %	1968 Average annual load from treatment plant effluents[a] lb
BOD_5	1,620,000	20	7,060,000
COD	11,200,000	31	24,400,000
SS	39,000,000	85	6,710,000
Organic (Kjeldahl) nitrogen	130,000	31	278,000
Soluble orthophosphate	171,000	4	4,180,000

a. One primary (21 mgd) and three secondary (19 mgd, total) plants.

Note: lb x 0.454 = kg

mgd x 0.0438 = cu m/sec.

centages of COD, BOD, TS and SS from the storm runoff are 10.8, 5.7, 44.2, and 47.6 respectively. Thus, compared to the combined wastewater, the storm runoffs were most significant in terms of solids loading.

Studies in Stockholm, Sweden (Soderlund and Lehtinen, 1972) have compared discharges from biological and chemically treated sewage water with that from stormwater runoff. The loadings were in kg/ha/yr and were reported for 35 persons/hectare (P/ha) (14 P/acre) and 100 P/ha (40 P/acre). The SS loading of stormwater was about twice as high as that of treated wastewater for 35 P/ha, and over twice that of the treated wastewater for 100 P/ha. BOD and the nutrients, however, were only a small percentage of that reported for treated wastewater and bacteria in stormwater were a magnitude or so less.

In Atlanta, Georgia a study (EPA, 1971) compared the pollutant load from storm sewers with that of combined sewers. It was estimated that the average annual BOD from storm sewer areas amounted to 55 percent of that from combined sewers. A one-year storm of two-hour duration yielded 7.744 and 3.940 pounds BOD/acre/hour of rainfall, respectively, for combined and storm sewer areas. By contrast, a two-week storm of 5-hour duration yielded only 0.694 and 0.334 pounds BOD/acre/hr of rainfall (1 pound/acre/hr = 1.22 kg/ha/hr).

In the Detroit-Ann Arbor study (Burn, Kranczyle and Harlow, 1968) an estimate was made of total tonnage and pounds/acre discharged from combined and separate systems. Table 21 shows the

Table 21

Estimated Tonnage Discharged
from Combined and Separate Systems
June, July, August 1965

Analyses	Detroit-Conners Creek Combined Sewer Overflow		Ann Arbor Allen Creek Storm Sewer	
	Total Tonnage	lb/acre	Total Tonnage	lb/acre
Phenols	0.46	0.042	0.003	0.002
BOD	990	90	58	31
NH_3-N	68	6.2	1.4	0.7
Organic N	18	1.6	0.7	0.4
SS	2,210	200	1,910	1,010
VSS	1,020	93	3.0	185
Sett. Solids	2,010	183	1,480	780
Vol. Sett. Solids	910	83	260	137
Soluble PO_4	62	5.6	1.8	0.9
Total PO_4	121	11.0	5.3	2.8
NO_3-N	1.7	0.15	1.5	0.8

Note: Tons x 0.91 = metric tons; lb/acre x 1.12 = kg/ha.

analyses and estimation of loads. Comparing the two, one can readily see that the solids parameters are larger for the separate storm sewer in terms of pounds/acre.

The study made in Trondheim, Norway (Kalleberg and Malme, 1974) has also considered mass loadings, and besides reporting their own findings in area yield rates (kg/ha/yr), they have also tabulated values from other studies for both combined and separate sewer systems.

Loehr (1974) has published a listing of concentration and mass loadings based on reported studies and made an analysis of the impact of many of the non-point sources.

F. Pollution from Combined Sewers

Many of the older, larger cities in the U.S. have areas where combined sanitary storm sewers are used. The systems are designed so that total flow during dry weather will receive wastewater treatment. During large storms, the extra flow of water goes to the receiving stream without treatment. The untreated portion of the flow is termed stormwater overflows.

The impact of stormwater overflows has been researched more extensively than that of separate storm sewers. Although the emphasis of this study was with separate systems, a brief review of overflow quality is included for comparative purposes.

An EPA (1974) review of data from several investigations and comparisons of the quality of combined sewage for various cities has been made. Table 22 is a comparison of results for

TABLE 22

Comparison of Quality of Combined Sewage for Various Cities

Type of Wastewater Location	BOD_5 mg/ℓ		COD mg/ℓ		D.O.	SS mg/ℓ		Total Coliforms MPN/100 ml		Total Nitrogen mg/ℓ as N	Total Phosphorus mg/ℓ as P
	Ave.	Range	Ave.	Range	Ave.	Ave.	Range	Ave.	Range	Ave.	Ave.
Typical untreated municipal	200	100-300	500	250-750	-	200	100-350	$5x10^7$	10^7-10^9	40	10
Typical treated municipal:											
Primary effluent	135	70-200	330	165-500	-	80	40-120	$2x10^7$	$5x10^6$-$5x10^8$	35	7.5
Secondary effluent	25	15-45	45	25-80	-	15	10-30	10^3	10^2-10^4	30	5.0
Storm sewer discharges:											
Atlanta, GA, 1969	100	48-540	-	-	8.5	-	-	10	-	-	2.2
Berkeley, CA, 1968	60	18-300	200	20-600	-	100	40-150	-	-	-	-
Brooklyn, N.Y., 1972	180	86-428	-	-	-	1051	132-8759	-	-	-	1.2
Bucyrus, OH, 1968	120	11-560	400	13-920	-	470	20-2440	10^7	$2x10^5$-$5x10^7$	13	3.3
Cincinnati, OH, 1970	200	80-380	250	190-410	-	1100	500-1800	-	-	-	-
Des Moines, IA, 1968	115	29-158	-	-	-	295	155-1166	-	-	12.7	11.6
Detroit, MI, 1965	153	74-685	115	-	-	274	120-804	-	-	16.3	4.9
Kenosha, WI, 1970	129	-	464	-	-	458	-	$2x10^6$	-	10.4	5.9
Milwaukee, WI, 1969	55	26-182	127	118-765	-	244	133-848	-	$2x10^5$-$3x10^7$	3.24	0.8
Northampton, U.K., 1960	150	80-350	-	-	-	400	200-800	-	-	10	-
Racine, WI, 1971	119	-	-	-	-	439	-	-	-	-	-
Roanoke, WI, 1969	115	-	-	-	-	78	-	$7x10^7$	-	-	-
Sacramento, CA, 1968	165	70-328	230	50-513	-	125	56-502	$5x10^6$	$7x10^5$-$9x10^7$	-	-
San Francisco, CA, 1969	49	1.5-202	133	17-626	-	68	4-426	$3x10^6$	$2x10^4$-$2x10^7$	-	-
Washington, D.C., 1965	71	10-470	382	80-1760	-	622	35-2000	$3x10^6$	$4x10^5$-$6x10^6$	3.6	1.0

concentrations of typical untreated and treated municipal sewage (primary and secondary effluent). Different sampling techniques, variation in number of samples taken, and other procedures were used that probably could explain some of the greater differences in values reported by some investigators. However, the tabulated values are mean overflow--"flow-weighted means"--unless otherwise noted.

In another study by EPA (1973), Field reported the characteristics of the combined sewer overflows, in terms of parameter ranges, to be as shown in Table 23.

It can be noted that the pollutional strength of combined sewer overflows is somewhat greater than that for separate storm sewers due to the sanitary sewage in the mixture and the scouring of putrescible solids that have accumulated in the system during dry weather.

G. Stormwater System Modeling

Several different computer models for stormwater flows and pollutional strength prediction are available. The best known of the models is the USEPA SWMM and it has been described with applications by DiGiano, et al. (EPA, 1977). Bedrosyan and Ganczarczyk (1977) have added to this procedure in their STORM-RAFFI program. Models have also been developed at the Norwegian Institute of Water Research (Lindholm, 1976) that are capable of developing hydrographs and pollutographs for a given area and storm. A textbook on the background and fundamentals of stormwater modeling is available (Overton and Meadows, 1976).

Table 23

Characteristics of Combined Sewer Overflows
(selected data)
(EPA 1973)

BOD_5	30	to	600	MG/L
COD	50	to	1,800	MG/L*
TSS	20	to	1,700	MG/L
Tot. Sol.	150	to	2,300	MG/L
Vol. Tot. Sol.	15	to	820	MG/L
pH	4.9	to	8.7	MG/L
Settl. Sol.	2	to	1,550	MG/L
Org. N	1.5	to	33.1	MG/L
NH_3N	0.1	to	12.5	MG/L
Sol. PO_4	0.1	to	6.2	MG/L
Tot. Coli	20,000	to	$90 \times 10^6/100$	ML
Fec. Coli.	20,000	to	$17 \times 10^6/100$	ML
Fec. Strep.	20,000	to	$2 \times 10^6/100$	ML

* Added to table; as it appears from previous table.

The effective use of models requires that they are calibrated for the conditions of the area for application. The need for further field studies in this regard has been stressed (Whipple and Hunter, 1977).

IV. Sources of Stormwater Runoff Pollutants

The various contaminants found in urban stormwater runoff are derived from a number of different sources. Major sources of pollutants include the atmosphere during rain and snowfall events, the washing of pollutants from city streets and other impervious areas, and the washing of pollutants from the stormwater collection system itself. The contribution of pollutants from each of these sources must be evaluated before effective stormwater management alternatives can be developed and implemented.

A. Contaminants from the Air

Potential stormwater pollutants from the air can either be adsorbed or absorbed from the air as rain and snowfall over a city. Because of their uncontrollable nature and potential damaging effects, pollutants that are washed out of the atmosphere have received increasing attention in the past few years.

Industry and motor vehicles are the primary sources of air pollutants. The most significant pollutants from industry are the oxides of sulfur ($SO_2^{=}$) and nitrogen (NO_x) and particulate matter. Motor vehicles are also responsible for some of the oxides of nitrogen, and in addition, carbon monoxide and volatile hydrocarbons. As these and other pollutants are emitted into the air, the prevailing atmospheric conditions will redistribute them. Constituents placed in the atmosphere at one location will return to the earth at other locations. Because of this, pollutants introduced into a receiving water from precipitation are virtually uncontrollable.

Perhaps the most important result of air pollution washout has been the increase in the acidity of rainfall in many areas. The minimum pH value expected for pure water in equilibrium with ambient concentrations of atmospheric carbon dioxide is 5.6. When certain climatic conditions exist, oxides of sulfur and nitrogen combine with particulate matter and vapors (water) to eventually form droplets of sulfuric and nitric acid. The presence of these acids will result in a lowering of the pH value below 5.6, and values as low as 2.7 have been reported (Likens, 1976).

The consequences of this phenomenon have yet to be fully evaluated, but acid precipitation clearly seems to have had a far-reaching environmental impact. It has been linked to sharp declines in the number of fish in many lakes and streams. Evidence also suggests that acid rain, snow and aerosol particles may be damaging to trees and other plants as well as human health (Likens, 1976).

In Norway (Ottar, 1974), acid precipitation has caused detrimental effects on streams and lakes. pH values of the rain as low as 2.7 have been measured, and snowmelt in the spring has shown pH as low as 3.0. Some streams in the southern part of Norway supported good sport fisheries 50 years ago, but today they are nearly devoid of trout and other fish.

A study in Cincinnati and Coshoton, Ohio by Weibel, Weidner, Cohen and Christianson (1966) provided some indication of different constituents in rain water. The data from this study are presented in the following table.

TABLE 24

Analyses Reported on Rainfall Samples
Concentrations, mg/ℓ
(Weibel, Weidner, Cohen, Christianson, 1966)

Parameter	Cincinnati Average	Cincinnati Range	Coshoton
SS	13 mg/ℓ	0.50-58.00	11.70
COD	16	4.60-59.00	9.00
Hydrolizable PO_4	00.24	0.00-00.90	0.08
pH	4.80	3.90- 6.10	-
VSS	0.38	0.50-12.00	-
Inorganic Nitrogen	0.69	0.12- 2.30	-

The nutrient content of precipitation has also been studied extensively. A recent EPA review examined over 40 studies concerning the presence of nitrogen and phosphorus in precipitation (Uttormark, Chapin, and Green, 1974). The presence of nutrients was found to be highly variable, depending upon such factors as geographical location, agricultural land use, season, and the form of precipitation.

Schuman and Burwell (1974) monitored the nitrogen content in the precipitation falling on two adjacent watersheds near Treynor, Iowa. Precipitation nitrogen was found to range between 0.5 kg/ha and 18 kg/ha (0.4-14.8 lb/acre). No correlation between the precipitation nitrogen and the amount of precipitation (or any other factor) could be found.

In their review of the various sources of nutrient loadings, Uttormark, Chapin and Green used the literature data to develop a chart showing the average nitrogen loadings from precipitation. This chart is presented in Figure 4. Using this map, estimations of the average concentrations of inorganic nitrogen in precipitation can be made.

The phosphorus content of precipitation has been studied less extensively than nitrogen because, for both agriculture and lake management, other sources of phosphorus are likely to be more important (Uttormark, Chapin and Green, 1974). In 1974, McComas, Cooke, and Kennedy sampled and tested snow and rainfall for phosphorus in Portage County, Ohio. Total phosphorus concentrations ranged from .011 to .04 mg/ℓ. It was found that snowmelt contributed phosphorus mainly to the open water by direct fall. The contribution from snowmelt showed that less nutrient comes off the watershed following the event than was contributed to the watershed. Phosphorus from rainfall, however, contributed an instantaneous slug to the receiving water during peak flow of the event, and frequently more phosphorus came off the watershed than the rain contributed. This was attributed to

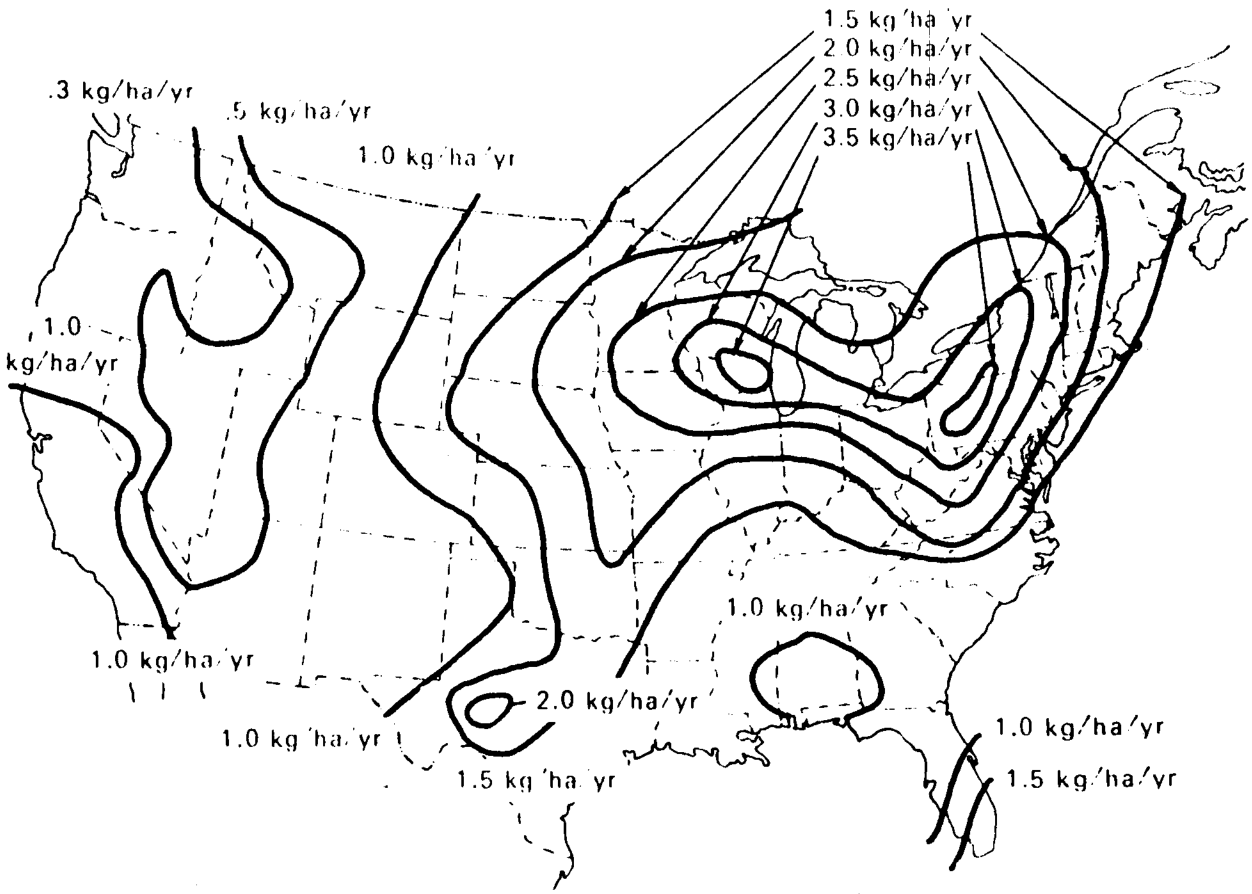


Figure 4. Nitrogen (NH_4-N and NO_3-N) in Precipitation (Uttormark, Chapin and Green, 1974). 1 kg/ha/yr = 0.82 lb/acre/yr

the fine sediment washload derived from the land surface of the watershed.

Contributions of phsophorus in rain and snowfall that have been reported from other areas are shown in Table 25. Areal loadings have also been reported by some investigators, and usually range from .02 to .85 kg/ha/year (0.016-0.7 lb/acre/yr) (Uttormark, Chapin and Green, 1974).

Other pollutants that may occur in precipitation have been studied very little. Table 26 shows reported data as compiled by Loehr. COD and major ions have only been reported by a few investigators.

B. Materials Deposited on City Streets

City and suburban streets and highways act as very effective collectors of dust, dirt, and other residues from many activities within an urban area. These materials, which are washed from roads and other impervious surfaces during stormwater runoff events, include:

- materials from the road pavement itself,
- depositions due to motor vehicles,
- chemicals from ice control and plant fertilizers,
- organic materials from the surrounding vegetation,
- debris, dirt, and dust from animal and human activities.

In 1972, Sartor and Boyd conducted extensive research into determining the amounts and characteristics of these street surface contaminants. It was found that the major components

TABLE 25

Some Total Phosphorus Concentrations in Snow and Rain in Eastern North America (McComas, Cooke and Kennedy, 1976)

Lake/State	Total Phosphorus (mg/ℓ) Snow		Rain	
Six Lakes/Ontario, Canada	.002	.021		
Western/New York	.007	.034		
Cayuga/New York	.017	.025	.011	.166
Houghton/Michigan	.002	.003	.020	.092
Michigan/Illinois-Indiana	.021	.054		.034
Twin Lakes/Ohio	.010	.449	.011	.040

TABLE 26

Precipitation Characteristics (Loehr, 1974)

Constituent	Concentration under Given Conditions* (mg/l) 1963-64 Urban	1963-64 Rural	Cooper	Northern Europe	1963-69 Forest	Feth	4 yr Ohio	Joyner
Nitrogen								
NH_4-N	—	—	—	0.06	0.16	0.17–1.5	1.1	—
NO_3-N	—	—	0.14	0.31	0.30	0.56	1.15	—
Inorganic N†	0.7	0.9	—	—	—	—	—	—
Total N	1.27	1.17	—	—	—	—	—	0.73
Phosphorus								
Total PO_4-P	—	—	—	—	0.008	—	0.02	0.04
Hydrolyzable PO_4-P	0.24	0.08	—	—	—	—	—	—
Suspended solids	13	11.7	—	—	—	—	—	—
COD	16	9	—	—	—	—	—	—
Major ions								
Ca	—	—	0.65	—	0.21	—	—	—
Cl	—	—	0.57	—	0.42	—	—	—
Na	—	—	0.56	—	0.12	—	—	—
K	—	—	0.11	—	0.19	—	—	—
Mg	—	—	0.11	—	0.16	—	—	—
SO_4	—	—	2.18	—	3.1	—		—
HCO_3					0			

of street surface contaminants were inorganic, mineral-like matter similar to common sand and silt. Organic matter was found to be a small fraction of the total on a mass basis. It has been indicated, however, that the organic fraction tends to accumulate at a faster rate than the inorganic fraction. The quantity and character of the contaminants found in the study are summarized in Table 27.

TABLE 27

Pollutant Loading Intensities
(Sartor and Boyd, 1972)

Measured Constituents	Weighted Means for All Samples (lb/curb mile)
Total Solids	1400
Oxygen Demand	
BOD_5	13.5
COD	95
Volatile Solids	100
Algal Nutrients	
Phosphates	1.1
Nitrates	.094
Kjeldahl Nitrogen	2.2
Bacteriological	
Total Coliforms (org/curb mile)	99×10^9
Fecal Coliforms (org/curb mile)	5.6×10^9
Heavy Metals	
Zinc	.65
Copper	.20
Lead	.57
Nickel	.05
Mercury	.073
Chromium	.11
Pesticides	
p,p-DDD	67×10^{-6}
p,p-DDT	61×10^{-6}
Dieldrin	24×10^{-6}
Polychlorinated Biphenyls	1100×10^{-6}

Perhaps one of the most important findings of the study was that a great portion of the overall pollutional potential was associated with the fine solids fraction of the street surface contaminants, although these fines accounted for only a minor portion of the total loading on street surfaces. Table 28 from the study shows the fraction of the total constituents associated with each particle size range. It can be seen that the very fine silt-like material (43 microns) accounted for only 5.9 percent of the total solids, but about one-fourth of the oxygen demand and about one-third to one-half of the heavy metals and nearly three-fourths of the total pesticides.

TABLE 28

Fraction of Total Constituent Associated
With Each Particle Size Range (% by Weight)
(Sartor and Boyd, 1972)

<table>
<tr><th></th><th>< 43μ</th><th>43μ-246μ</th><th>< 246μ</th></tr>
<tr><td>Total Solids</td><td>5.9</td><td>37.5</td><td>56.5</td></tr>
<tr><td>BOD_5</td><td>24.3</td><td>32.5</td><td>43.2</td></tr>
<tr><td>COD</td><td>22.7</td><td>57.4</td><td>19.9</td></tr>
<tr><td>Volatile Solids</td><td>25.6</td><td>34.0</td><td>40.4</td></tr>
<tr><td>Phosphates</td><td>56.2</td><td>36.0</td><td>7.8</td></tr>
<tr><td>Nitrates</td><td>31.9</td><td>45.1</td><td>23.0</td></tr>
<tr><td>Kjeldahl Nitrogen</td><td>18.7</td><td>39.8</td><td>41.5</td></tr>
<tr><td>Heavy Metals (all)</td><td colspan="2">51.2</td><td>48.7</td></tr>
<tr><td>Pesticides (all)</td><td colspan="2">73</td><td>27</td></tr>
<tr><td>Polychlorinated Biphenyls</td><td colspan="2">34</td><td>66</td></tr>
</table>

It was also determined in the study that street surface contaminants were not distributed uniformly across the street surface. The solids intensity across a typical street is shown in Table 29. Seventy-eight percent of the material was found within 6 inches (0.15 m) of the curb, and over 95 percent within the first 40 inches (1.0 m). This indicates that the majority of the solids, and hence the street surface contaminants, are within the gutter region of the street where water accumulates and drains during runoff periods at relatively high velocities.

TABLE 29

Solids Intensity Across a Typical Street
(Sartor and Boyd, 1972)

Street Location (Distance from Curb)	Solids Loading Intensity (% of Total)
0 - 6 in. (0-0.15 m)	78
6 - 12 in. (0.15-0.3 m)	10
12 - 40 in. (0.3-1.0 m)	9
40 - 96 in. (1.0-2.44 m)	1
96 to center line (2.44 m to ℄)	2

In a follow-up of the study by Sartor and Boyd, Pitt and Amy (1973) conducted research on the toxic materials associated with street surface contaminants. Of the 74 elements that were investigated, they concluded that lead, zinc, copper, nickel, chromium, strontium, titanium, and zirconium were the most important from a water pollution standpoint. Land use was an important factor in determining the metals loading in an area, with industrial areas typically having the greatest loading factors (lbs/curb mile). Grease and oil were also found to be a major constituent of street surface contamiants. The smaller size ranges of particles appeared to contain a greater percentage of grease and oil than the larger size ranges, possibly due to the greater surface area per unit weight.

1. Traffic Related Deposits

Traffic related activity within an urban area contributes a broad range of street surface contaminants in a number of different ways. Although the contributions are difficult to quantify, they can be listed by general category (Sartor and Boyd, 1972):

- leakage of fuel, lubricants, hydraulic fluids, and coolants,
- fine particles worn off of tires and clutch and break linings,
- particulate exhaust emissions,
- dirt, rust, and decomposing coatings which drop off of fender linings and undercarriages,
- vehicle components broken by vibration or impact.

One of the attempts at the quantification of traffic related deposits was done by Shaheen (1975) at various locations in the Washington, D.C. metropolitan area. The pollutant deposition rates which he measured are shown in Table 30. All materials deposited at the rates given in the table were attributable to

TABLE 30

Deposition Rates and Composition of Traffic-Related Roadway Deposits
(Washington, D.C. Metropolitan Area)

Parameter	Dust and Dirt Deposition Rates (Units -- Unless Otherwise Stated): lbs/axle-mile	Dust and Dirt Deposition Rates (Units -- Unless Otherwise Stated): g/axle-km	Composition (% by Weight Unless Otherwise Stated)
Dry Weight	2.38×10^{-3}	6.71×10^{-1}	-
Volume	6.33×10^{-4} (quarts/axle-mile)	4.33 (l/axle-km)	-
Volatile Solids	1.21×10^{-4}	3.41×10^{-2}	5.1
BOD	5.43×10^{-6}	1.53×10^{-3}	0.23
COD	1.28×10^{-4}	3.61×10^{-2}	5.4
Grease	1.52×10^{-5}	4.29×10^{-3}	0.64
Total Phosphate-P	1.44×10^{-6}	4.06×10^{-4}	0.061
Nitrate-N	1.89×10^{-7}	5.33×10^{-5}	0.0079
Nitrite-N	2.26×10^{-8}	6.37×10^{-6}	0.00095
Kjeldahl-N	3.72×10^{-7}	1.05×10^{-4}	0.016
Chloride	2.20×10^{-6}	6.20×10^{-4}	0.092
Petroleum	8.52×10^{-6}	2.40×10^{-3}	0.36
n-Paraffins	5.99×10^{-6}	1.69×10^{-3}	0.25
Asbestos	$3.86 \times 10^{+5}$ (fibers/axle-mile)	$2.40 \times 10^{+5}$ (fibers/axle-km)	3.6×10^{5} (fibers/gram)
Rubber	1.24×10^{-5}	3.50×10^{-3}	0.52
Lead	2.79×10^{-5}	7.87×10^{-3}	1.2
Chromium	1.85×10^{-7}	5.22×10^{-5}	0.008
Copper	2.84×10^{-7}	8.01×10^{-5}	0.012
Nickel	4.40×10^{-7}	1.24×10^{-4}	0.019
Zinc	3.50×10^{-6}	9.87×10^{-4}	0.15
Magnetic Fraction	1.26×10^{-4}	3.55×10^{-2}	5.3

traffic, and would not be present were it not for the passage of motor vehicles. It was concluded that many of the traffic related street surface contaminants were representative of local geology and, to a lesser extent, products abraded from the roadway surfaces.

An analysis of "pure" materials was undertaken to aid in establishing the origin of pollutants found in roadway deposits. The results of this analysis are shown in Table 31. It was found that most of the traffic related BOD, COD, magnetic fraction, chloride, nitrogen, volatile solids, and phosphorus arose from sources other than the motor vehicle itself. "Phosphorus and chloride are most likely derived from area soils and roadway abrasion. The low levels of traffic related nitrogen found were contributed by soils and plant materials carried onto the roadway by motor vehicles."

It was found that less than 5 percent (by weight) of the traffic related deposits originated directly from motor vehicles; however, these pollutants were among the most important by virtue of their potential toxicity. Other findings of the study were that (Shaheen, 1975):

- much of the grease and all of the petroleum and n-paraffins resulted from spills or leaks of motor vehicle lubricants, antifreeze, and hydraulic fluids,
- traffic related lead was deposited principally through the use of leaded fuels; however, some resulted from the wear of tires in which lead oxide is used as a filler material,

TABLE 31

Analysis of "Pure" Materials (Shaheen, 1975)

Material	Tot. Vol. Solids (mg/g)	BOD (mg/g)	COD (mg/g)	Grease (mg/g)	Petroleum (mg/g)	n-Paraffins (mg/g)
Gasoline	999.5	154.0	682.1	1.3	1.3	1.3
Lubricating Grease	973.9	143.3		753.1	665.8	566.3
Motor Oil	996.9	143.8	220.8	989.2	937.7	850.0
Transmission Fluid	999.8	102.6	198.3	985.6	941.7	875.4
Antifreeze	987.8	37.6	1102.4	143.8	69.6	6.1
Undercoating	998.7	89.8	309.5	958.1	182.8	120.7
Asphalt Pavement	64.2	1.2	85.5	21.4	15.0	9.0
Concrete	70.7	1.4	63.6	2.7	1.3	1.0
Rubber	986.3	26.8	2097.4	191.6	97.8	56.0
Diesel Fuel	999.9	80.2	399.0	385.3	307.8	209.7
Brake Linings	285.3	16.9	416.5	30.5	8.3	7.6
Brake Fluid	999.8	25.8	2420.8	883.0	33.1	18.6
Cigarettes	862.2	85.4	776.8	30.0	21.2	2.7
Salt	74.7	-	-	0.0	0.0	0.0
Cinders	0.0	-	59.3	1.3	1.2	1.2
Area Soil	-	-	-	-	-	-

TABLE 31 (Continued)

Analysis of "Pure" Materials (Shaheen, 1975)

Material	Metals Content (μg/g)					
	Lead	Mercury	Chromium	Copper	Nickel	Zinc
Gasoline	663	0	15	4	10	10
Lubricating Grease	0	0	0	0	0	164
Motor Oil	9	0	0	3	17	1060
Transmission Fluid	8	0	0	0	21	244
Antifreeze	6	0	0	76	16	14
Undercoating	116	0	0	0	476	108
Asphalt Pavement	102	0	357	51	1170	164
Concrete	450	0	93	99	264	417
Rubber	1110	0	182	247	174	617
Diesel Fuel	12	0	15	8	8	12
Brake Linings	1050	0	2200	30600	7454	124
Brake Fluid	7	0	19	5	31	15
Cigarettes	492	0	71	716	193	560
Salt	2	0	2	2	9	1
Cinders	0	0	0	3	4	7
Area Soil	0	0	36	23	25	27
Detection Limit	2	0.05	2	1	1	0.01

- zinc is also used as a filler in tires and at high concentrations in motor oil as a stabilizing additive,
- copper, nickel, and chromium are wear metals from metal plating, bearings, bushings, and other moving parts within the engine. Considerable amounts of copper were deposited as a result of wear of brake linings which had copper added to increase mechanical strength and promote more rapid dissipation of heat,
- asbestos arose from wear of clutch and break linings and tire wear was the source of traffic related rubber found in roadway deposits.

Shaheen also conducted investigations into the variables affecting deposition of street surface contaminants. One important observation was the effect of curb height upon the amount of material collected on the roadway. Figure 5 shows the average loadings per axle dry weight for litter (particles larger than 3.35 mm) and dust and dirt (particles smaller than 3.35 mm) collected at the roadway sites as a function of height of the curb or barrier along which the samples were collected. Accumulation of litter particles was not markedly affected. However, dust and dirt loadings increased with curb height up to about 15 to 20 inches.

Other factors that were found to influence the deposition of street surface contaminants from traffic related sources were land use activities and season. No apparent effect on depositions of street surface contaminants was discernible due to speed,

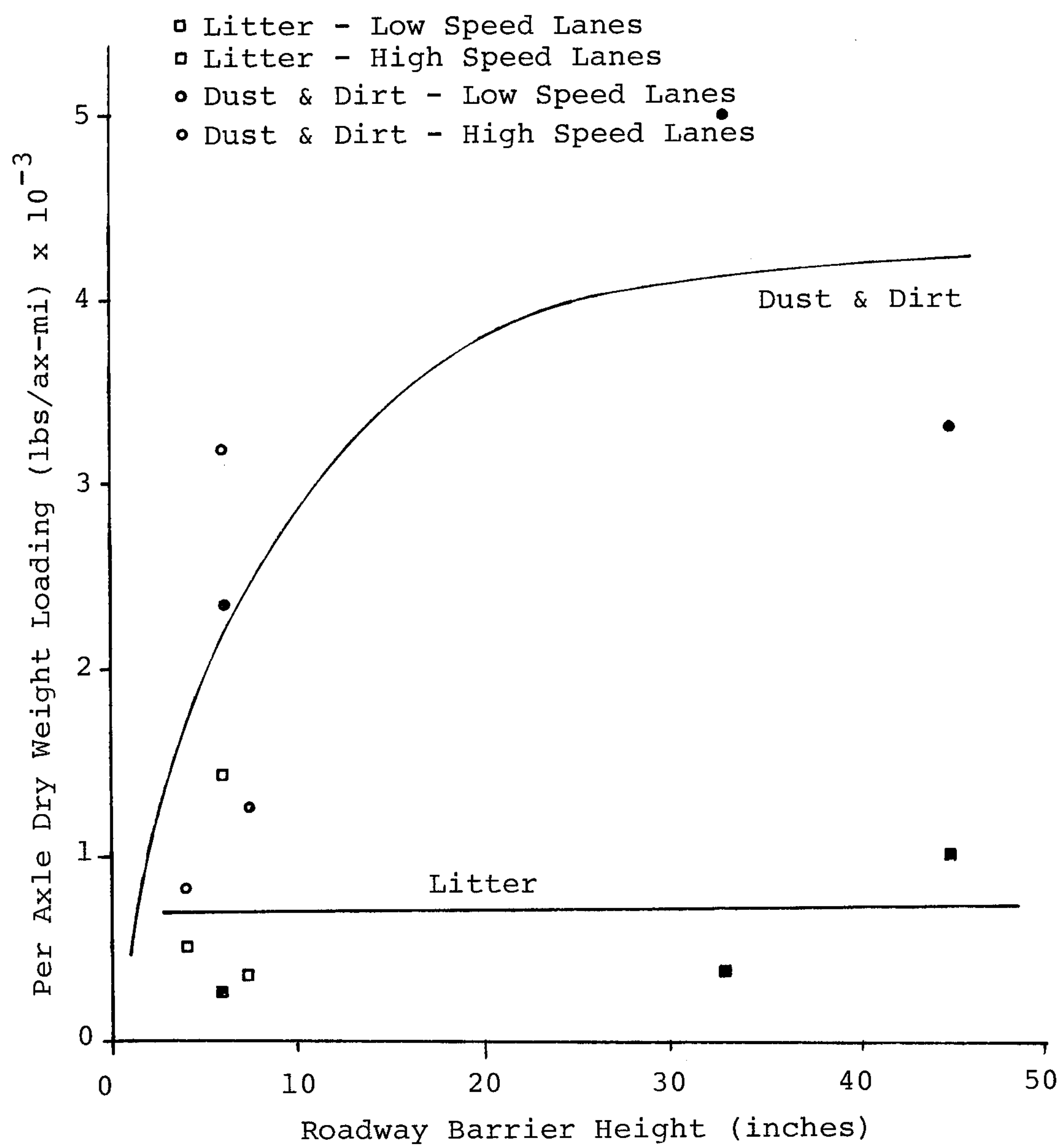


Figure 5. Per Axle Dry Weight Loading vs Roadway Barrier Weight (Shaheen, 1975).

traffic mix, or composition of the roadway material. Under a given set of conditions, it was found that deposition of materials occurred at a constant rate (gm/axle-km), although the materials did not appear to accumulate on roadways at a linear rate.

2. Non-Traffic Related Deposits

In addition to traffic related materials, other street surface contaminants are deposited on urban roadways through mechanisms unrelated to motor vehicular traffic. Litter, deicing agents and other chemicals, atmospheric fallout, and materials resulting from pavement decomposition find their way to urban roadway surfaces.

(a) Deicing Chemicals.

Salt, both sodium chloride and calcium chloride, have been used by state highway departments, turnpike authorities, municipal street departments, and other organizations for snow removal operations for many years. It has been estimated that approximately 9 million tons of salt and other deicing chemicals are purchased annually for snow removal purposes (Richardson, Terry, Metzger, and Carroll, 1974).

Because of its non-biodegradable nature, salt that is applied to roadways is ultimately washed off the roadway surface, either by rain, snowmelt, or street cleaners, and into streams and lakes. Several studies have been completed concerning environmental impacts of street salting. The pollutional aspects of deicing agents has been discussed in a previous section.

(b) Atmospheric Fallout.

Particulates, or dust, fall at annual rates of 500 to 900 tons/sq.mi. (1,123,000-2,021,000 kg/ha) in most metropolitan areas (APWA, 1969). These fine materials are of the same size range as a large fraction of the particulate matter collecting on city streets. Many forms of this fallout are virtually inert and would add only turbidity and suspended solids to receiving waters. Others are reactive and would impose loadings of oxygen demand, nutrients, toxic metals, and pesticides (Sartor and Boyd, 1972). It was found that for Madison, Wisconsin, the nutrient contribution from dry fallout was double that of precipitation, while for phosphorus it was up to three times that of rainfall (Uttormark, Chapin, and Green, 1974). Fallout rates and properties, however, are subject to many variables and their impact on water quality are difficult to evaluate.

(c) Pavement Materials.

The street itself is a possible source of surface contaminants. Included from this source are asphaltic and portland cement, their various products of decomposition, and aggregate materials. In addition, there are typically small amounts of road marking paints, crack fillers, and expansion joint compounds. On a weight basis, aggregate materials account for the largest contribution of contaminants from this source.

Sartor and Boyd (1972) have identified three important factors which appear to correlate with observed generation rates of such materials:

- the age and condition of street surfaces,
- the local climate,
- leaks and spills of fuels and oils which hasten the degradation of asphaltic pavements.

In their study of street surface contaminants, they found that concrete streets were much cleaner than asphaltic streets. Specifically, asphaltic streets had loadings of total solids about 80 percent higher than concrete streets, and streets paved with asphaltic materials were about 65 percent higher in pollution concentration than concrete. Streets rated "fair to poor" were found to have total solids loadings about 2½ times as heavy as those rated "good to excellent".

(d) Erosion.

Urbanization typically causes accelerated erosion, raising sediment yields by two to three orders of magnitude from 10^2-10^3 tons/sq mi/yr to 10^4-10^5 tons/sq mi/yr (Field, Tafuri, and Masters, 1977). At the present national rate of urbanization, 4000 acres/day, erosion must be recognized as a major environmental problem.

The importance of large sediment yields due to erosion was demonstrated in a 1961-1964 study of sediment movement in the Scott Run basin, Fairfax County, Virginia. It was determined that "... highway construction areas, varying from less than 1 to more than 10 percent of the basin at a given time, contributed 85 percent of the sediment" (Geological Survey, 1969). Highway construction resulted in a sediment yield 10 times that from cultivated land, 200 times that from grassland, and 2000 times that from forest land. In a study of the entire Potomac River, of which Scott Run is a suburban tributary, it was estimated that the Washington Metropolitan area, which consists of 2 percent of the basin, produced 25 percent of the sediment in the river (Geological Survey, 1969).

V. Urban Stormwater Pollution Control

There are many possible control alternatives that may be undertaken to alter the quantity and quality of stormwater runoff. Many of these alternatives will have other benefits for the urban community, allowing the costs associated with runoff pollution control to be distributed. In most cases, however, the efficiency of the many alternatives for improving stormwater runoff quality have not been evaluated, either in terms of pollution load reduction or cost effectiveness. As cities begin to examine the various measures for controlling pollution from separate storm-sewer discharges, more information will be available concerning the effectiveness of the alternatives.

The alternatives available for the reduction of stormwater pollution have been categorized as (1) abatement, (2) control, or (3) treatment (Lager and Smith, 1974). Abatement measures are those practices directed at prestorm reduction of pollutants for the primary purpose of improving the quality of the storm-water runoff. Control measures are those which influence the stormwater path, flow rates, or loadings and are directed toward a reduction in the quantity of stormwater. Treatment of storm-water generally involves the physical, chemical, and biological techniques that are applicable to the treatment of domestic and industrial wastewater flows. The ultimate control of pollution from separate storm sewer discharges will be a result of the application of many of these alternatives in an integrated, complex management system (Lager and Smith, 1974).

A. Abatement Measures

In general, practices leading to urban cleanliness will also lead to improvement in the quality of urban runoff. This is particularly important in developed urban areas, where "house-keeping techniques", as they are referred to, are one of the only cost effective methods available for the reduction of urban stormwater pollution. Examples of abatement measures for improving urban runoff quality include (Lager and Smith, 1974):

(1) decreasing dustfall on the area by reducing air pollution.

(2) erosion control during construction of buildings and highways.

(3) placing berms around small lots.

(4) improved street sweeping practices.

(5) improved methods for deicing pavements.

(6) catch basin cleaning between storm events.

(7) effective litter and solid waste control.

The effectiveness of each one of these alternatives will be discussed briefly.

1. Air Pollution Control.

It is extremely difficult to quantify the potential reduction in stormwater pollution from improved air pollution control. Contaminants scoured from the air would probably be reduced in proportion to the reduction of their airborne concentrations, and a reduction of the fallout rate would help in reducing the amounts of particulate matter collected on city streets.

While no attempt has been made to correlate the reduction of air pollution with urban stormwater runoff quality, it is generally accepted that improved air quality would result in improved stormwater runoff quality.

2. Solid Waste Management.

Although the accumulation of a certain amount of street surface contaminants in an urban area is inevitable, much of the litter that reaches the street surface can be eliminated or at least effectively controlled at its source. Convenient location of trash receptacles, increased frequency of trash pickup, and enforcement of anti-litter laws are a few approaches to the problem. Good solid waste management practices, including education of the general public on the pollutional impact of littering, provide significant aesthetic and water pollution control benefits. These benefits are difficult to measure in economic terms.

3. Erosion Control.

There are many methods available for reducing sediment yields from urban areas, especially for land undergoing development. This is important because of the extreme sediment yields often occurring on such land. For this reason, the EPA sponsored a project to develop guidelines for erosion and sediment control planning and implementation (Maryland Department of Water Resources and Hittman, Assoc., 1972). Among the techniques described to reduce sediment yields were: (1) sediment retention basins, (2) maintenance of native vegetation, (3) proper selection of building and highway sites, and (4) timing of clearing and grading during seasons when erosion is less. Four appendices of the report contained information concerning 42 sediment and erosion control products and practices. Many other state and government agencies have recently published information concerning erosion control (Field, Tafuri and Masters, 1977).

4. Chemical Controls.

Deicing chemicals (salts) are one of the major chemicals used in an urban area. In recent years, there have been a substantial number of reports of salt related environmental damage in the literature (Murray and Ernst, 1976). The adverse effects of deicing salts in surface waters include damage to groundwaters, public water supplies, farm supply ponds, and roadside soils, vegetation and trees. Deicers also contribute to deterioration of highway structures and pavements, and to accelerated corrosion of vehicles. Murray and Ernst (1976) recently completed a review of the literature concerning deicing chemical related damages. They estimated (as a lower bound) that the annual cost to the snowbelt states that resulted from the use of road salt was $2.91 billion, or about 15 times the annual cost for salt purchase and application. Hence, some sort of control over the application of deicing chemicals appears necessary.

In terms of abatement measures, several things can be done to minimize the contamination of urban runoff by deicing chemicals and abrasives. One possibility is to prohibit the use of certain chemicals such as cyanide and chromium compounds which are added to deicing salts as anti-caking agents and corrosion inhibitors. Although highway departments may be willing to accept prohibition of additives, few desire the prohibition of the use of deicing salts. In the 1973 assessment of the deicing chemical problem it was found that the "bare pavement" philosophy is very popular and considered by most highway authorities as the safest way for ice and snow removal. The major problems that were identified with the use of deicing chemicals were sloppy salt storage practices and over-application on road surfaces (Field, Struzeski, Masters, and Tafuri, 1973). As a result, two manuals of practice for improvement of handling, storage, and application techniques have been published (Richardson, Terry, Metzger, and Carroll, 1974; and Richardson, Campbell, Carroll, Hellstrom, Metzger, and O'Brien, 1974).

Increased public awareness of the problem of street salting and its effects on the environment has led to investigations into alternative snow and ice removal techniques. A search was conducted in 1972 to define alternatives, and a recent study has investigated hydrophobic substances (Murray and Eigerman, 1972; and Alborn and Poehlmann, 1976). Even though material and application costs for hydrophobic substances appear greater than for salt ($0.2-$0.25 vs $0.3/yd^2), when considering total damage to the environment, the costs appear to be acceptable (Field, Tafuri, and Masters, 1977).

Fertilizers, pesticides and other commonly used chemicals are also potential urban stormwater runoff pollutants. It appears that the only method available for the reduction of indiscriminate use of these chemicals is through public education.

5. Catch Basin Cleaning

Catch basins which are cleaned frequently have a greater capacity to retain solids and associated pollutants. Because a high percentage of the pollutants are associated with the fine particle size, the overall efficiency of pollutant removal for catch basins is low (APWA, 1969). Also, it has been found that uncleaned catch basins can be a source of stormwater runoff pollutants. Recognizing the difficulty of control of the fine materials in stormwater runoff and other problems associated with catch basins, Sartor and Boyd (1972) recommend that:

> Public works departments give serious consideration to how necessary catch basins are in their particular systems. When a simple stormwater inlet structure would suffice, it is probably desirable to get rid of the catch basin (either by replacing it or by filling it in).

Research on catch basin cleaning in Tulsa, Oklahoma, from 1967 to 1969 indicated that older catch basins were being replaced with "self-cleaning" devices that have direct connections to the storm sewer line and no holding capacity for solids or runoff water. Newer developments in Tulsa did not include catch basins in the street design (Adgate, 1976). This is true in other areas as it is now generally considered that the disadvantages of catch basins outweigh their benefits (WPCF, ASCE, 1970).

Several reviews of catch basin cleaning devices, procedures, and costs are available and will be useful in developing cost-effective catch basin maintenance programs which are certainly necessary in those areas where catch basins currently exist (Adgate, 1976; and Sartor and Boyd, 1972). Another study is currently underway that is concerned with the review and full-scale demonstration of catch basin technology in relation to its use in reducing stormwater runoff pollution (Field, Tafuri, and Masters, 1977).

6. Street Sweeping.

The effectiveness of street sweeping operations with respect to stormwater pollution has been analyzed in several EPA-sponsored studies (Sartor and Boyd, 1972; APWA, 1969; and Shaheen, 1975). It was found that current street sweeping practices are essentially for aesthetic purposes and even under well-operated and highly efficient street sweeping programs, their efficiency in the removal of the dust and dirt fraction of street surface contaminants is low. The removal efficiency of conventional street sweepers was found to be dependent upon the particle size range of the street surface contaminants, as shown in Table 32 (Sartor and Boyd, 1972). The overall removal effictiveness for the dust and dirt fraction was 50 percent, while the removal effectiveness for litter and debris (i.e., paper, wood, leaves, etc.) ranged from 95 to 100 percent (Sartor and Boyd, 1972).

More advanced street cleaning techniques have also been studied. Shaheen (1975) found that essentially quantitative re-

TABLE 32

Conventional Sweeper Efficiency for Various Particle Sizes (Sartor and Boyd, 1972)

PARTICLE SIZE (Microns)	SWEEPER EFFICIENCY (%)
2000	79
840-2000	66
246-840	60
104-246	48
43-104	20
< 43	15
Overall	50

TABLE 33

Advanced* Street Cleaner Pollutant Recovery Percentage (Field, Tafuri and Mooters, 1977)

PARAMETER	% RECOVERY
Dry Weight Solids	93
Volatile Solids	80
BOD	67
COD	84
Total PO_4-P	85
Heavy Metals	83-98

*Broom and vacuum combination

coveries of particulate materials could be attained by careful vacuuming of the road surface. By using a broom and vacuum combination, approximately 93 percent removal of dry solids was achieved. Removal efficiencies for other parameters using advanced street cleaning techniques are shown in Table 33.

Parked vehicles are one of the greatest obstacles to effective street sweeping. As discussed previously, most of the material that lies on a typical street surface is within 40 inches (1m) of the curb. Therefore, strict parking limitations must be enforced to ensure the effectiveness of a mechanical street sweeping program. Further verification of the benefits of street cleaning in relation to stormwater pollution control is currently being done in ongoing studies (Field, Tafuri, and Masters, 1977).

B. Control Measures

Control measures are those implemented to reduce the quantity or rate of stormwater runoff. Examples of such measures include (Lager and Smith, 1974):

(1) Use of roof storage

(2) Intentional ponding

(3) Use of porous pavements

The first two involve the use of on-site or upstream storage techniques, and the latter involves the use of a relatively new type of pavement that allows water to seep through rather than to run off.

1. <u>On-Site (Upstream) Storage</u>.

On-site or upstream storage refers to detention (short term) or retention (long term) of runoff prior to its entry into a drainage system. Simple ponding techniques are utilized on open areas where stormwater can accumulate without damage or interference to essential activities. Oftentimes, on-site storage can be designed to provide for the dual or multi-benefits of aesthetics, recreation, recharge, irrigation, or other uses (Lager and Smith, 1974). Detention/retention techniques have been applied at various places throughout the country and have been described in the literature. These include the utilization of roof tops, tennis courts, ponds, and plazas to detain or retain precipitation (Lager and Smith, 1974; Haro, 1973; Rice, 1974).

Apparent economic benefits of surface ponding for flood protection are also possible due to the savings over a conventional sewer project. Several surface ponding sites are listed in Table 34, where a cost comparison has been made between a drainage system using surface ponding to decrease peak flows and a conventional storm sewer system (Hydroscience, Inc., 1976). It is important to note that pollution and erosion control benefits of the basins were not included in this comparison. It appears, then, that if multi-benefit systems are developed, the costs associated with runoff pollution control may be partially negated.

TABLE 34

Cost Comparison between Surface Ponding Techniques and Conventional Sewer Installation (Hydro Science, 1976)

SITE	DESCRIPTION	COST ESTIMATE, S WITH SURFACE PONDING	COST ESTIMATE, S WITH CONVENTIONAL PONDING
Earth City, Missouri	A planned community including permanent recreational lakes with additional capacity for storm flow	2,000,000	5,000,000
Consolidated Freightways, St. Louis, Missouri	A trucking terminal using its parking lots to detain storm flows	115,000	150,000
Ft. Campbell, Kentucky	A military installation using ponds to decrease the required drainage pipe sizes	2,000,000	3,370,000
Indian Lakes Estates, Bloomington, Illinois	A residential development using ponds and an existing small diameter drain	200,000	600,000

2. Porous Pavements

Porous pavements are a rather unique approach to urban runoff control. Pavements for streets, sidewalks, and parking lots make up a large percentage of the impervious area of metropolitan areas. If precipitation could pass through the pavement and recharge the groundwater, stormwater could then become a resource rather than a disposal problem. This would require that the precipitation would be sufficiently treated in the soil, preventing local groundwater pollution.

Although porous pavements were originally developed for highway safety purposes, they have shown considerable promise as a method to attenuate urban runoff. Under pilot testing, porous pavements (open graded asphalt-concrete pavements) have allowed over 70 inches (1.75 m/hr) of stormwater to flow through. Stability, durability, and freeze-thaw tests have been positive and this material is comparable in cost to conventional pavement. In cases where storm quantities exceed soil infiltration, the coarse sub-base and porous nature of the pavement can serve for ponding capacity (Thelen, Grover, Hoiberg, and Haigh, 1972). Long term tests are still required, however, to evaluate clogging resistance and the quality of water that filters through (Field, Tafuri, and Masters, 1977).

3. Treatment Measures

In virtually every treatise written to date concerning the treatment of urban stormwater, it has generally been assumed that processes suitable for the treatment of combined sewer overflows are also suitable for the treatment of separate sewer discharges. While combined sewer overflows and separate storm sewer discharges have much in common, treatment alternatives used for their control will probably be different due to their differing natures. The fact that combined sewer overflows contain human wastes causes them to be considered a greater threat to receiving waters than separate storm sewer discharges, and hence treatment of combined sewer overflows is a larger and more immediate problem for many cities. This is demonstrated by the fact that there have been over 35 studies conducted on the application of specific processes for the treatment of combined sewer overflows, while only 3 studies have investigated treatment of urban land drainage. Treatment technology concerning separate storm sewer discharges is largely speculation, not only in process effectiveness, but in whether or not treatment of such discharges is necessary.

It is difficult to adapt any existing treatment method to storm-generated discharges. The flow rate and pollutant variations of urban runoff are substantially different from the flow rate and pollutant variations encountered at sewage treatment plants. Urban stormwater is an intermittent source of large flows whereas municipal waste is typified by continuous discharge at a relatively constant rate. Also, due to the intermittency and variability of separate storm sewer discharges, there is no "average" design condition for stormwater treatment facilities. Therefore, a unit or process must perform under varying conditions in order to be applicable to the treatment of separate storm sewer discharges (Field and Lager, 1975). A widely varying intermittent input is not conducive to effective biological treatment because microorganisms require continuous feeding with minor variations in input quantity. It appears that a physical-chemical process would be the most appropriate.

(a) Physical-Chemical Processes

In his studies at Durham, N.C., Colston (1974) investigated the applicability and effectiveness of plain sedimentation and chemical coagulation of urban land runoff through jar test procedures. It should be noted that no storm sewer system existed as such in the study area. Excess surface waters follow natural drainage patterns through a system composed of overland flow, street gutters, small pipes, and culverts under roads.

The effectiveness of plain sedimentation was determined by allowing one-liter samples to settle quiescently for 15 minutes. On the average, 60 percent of the COD, 77 percent of the suspended solids, and 53 percent of the turbidity was removed utilizing this procedure. Cationic polyelectrolytes and inorganic coagulants were found to provide significant residual removal increases over sedimentation. Alum was judged the best coagulant and produced average removals of COD, suspended solids, and turbidity of 84, 97, and 94 percent, respectively.

Table 35 shows the coagulant ranking as determined in the study.

TABLE 35

COAGULANT RANKING ON AVERAGE RESIDUAL REMOVAL EFFICIENCY OF COD, SUSPENDED SOLIDS, AND TURBIDITY (Colston, 1974)

RANK	COAGULANT	AVERAGE RESIDUAL REMOVAL EFFICIENCY (%)
1	Alum + Calgon Aid 18	88
2	Alum	83
	Lime	83
4	Alum + Montmorillonite Clay	82
5	Calgon 2660 + Montmorillonite Clay	79
6	Calgon 2870 + Montmorillonite Clay	77
	Alum + Dow C-32	77
	Alum + Calgon 2870	77
	Dow C-32 + Montmorillonite Clay	77
10	Ferric Chloride + Dow C-32	76
	Dow C-32 + Calgon Aid 18	76
12	Dow C-31 + Montmorillonite Clay	72
13	Calgon 2870	67
14	Ferrous Chloride	66
15	Ferric Chloride + Calgon Aid 18	64
16	Dow C-32	62
	Dow C-41	62
18	Dow C-31	59
	Ferric Chloride + Calgon Aid 18	59
20	Calgon 2660	52
21	Dow C-31 + Calgon Aid 18	49
22	Ferric Chloride	45
23	Dow A-22	40
24	Dow A-23	32
25	Dow N-17	22
26	Dow N-11	14
27	Calgon 3000	0

Batch scale chemical treatment studies indicated little, if any, scaleup difficulties for chemical treatment, and areal overflow rates of up to 6000 gal/day/ft^2 under ideal conditions produced 92 to 97 percent removal of suspended solids. It was recommended in the study that plain sedimentation, being much less costly than chemical coagulation, should be considered as the first alternative in the treatment of urban land runoff, and that chemical coagulation should be considered as an effective tool for preventing adverse effects of urban land runoff on water quality.

Mische and Dharmadhikari (1971) have also reported on research involving treatment aspects of urban drainage. Two natural watersheds, the High School and Arcadia watersheds, were sampled during wet weather for treatment studies. Neither of these areas had storm sewers, and all of the runoff flowed through natural drainageways. The processes studied were chemical treatment using alum, polyelectrolyte (Nalco No. 2), combinations of the two, and plain sedimentation.

Treatment using alum alone resulted in the most efficient removals of COD and bacteria. In the High School watershed, COD removals were greater than 85 percent using alum doses of 51 and 68 mg/ℓ. Total coliform analyses indicated that approximately 98 percent of the organisms were removed at similar doses. Sedimentation alone removed approximately 70 percent of the COD, thus indicating an economical means of treatment. Unfortunately, the detention times used throughout the study were not reported.

About twice as much alum was required to achieve similar COD reductions in samples from the Arcadia watershed. Sedimentation alone removed 60 percent of the COD. The differences between the two watersheds were attributed to the fact that the runoff from the Arcadia watershed was more turbid and contained finer, more silty particles.

The removals obtained with a combination of alum and polyelectrolyte were comparable to the removals reported for alum treatment alone. However, the doses of polyelectrolyte required was relatively high and a faint white color was imparted to the supernatant. Polyelectrolyte used separately was not effective in clarifying the stormwaters. It was concluded in the study that coagulation of urban runoff is effective.

In another article, Samar, Sarai, Razeghi, Jamshidnia and Hakimipour (1976) have reported on research that was carried out in Tehran, Iran, which involved the physical-chemical treatment of urban land drainage. The treatment train consisted of coagulation with alum, sedimentation, and adsorption using powdered activated carbon. All experiments were conducted through jar testing. As was in the case in the two previous studies that have been discussed, no "storm sewer system" existed as such in the study area. The drainage system consisted mainly of a network of channels rectangular in cross-section, with concrete linings, and open except in road crossings.

The average removals by coagulation with alum, flocculation and sedimentation were 95, 82, and 97 percent for turbidity, COD, and lead, respectively. The optimum dosages of alum ranged from 20 to 60 mg/ℓ with an average of 48 mg/ℓ. The detention times used during sedimentation were not mentioned. Further increases were observed in the removal efficiencies by using powdered activated carbon in the coagulation process. An average removal of 97, 85, and 100 percent resulted for turbidity, COD, and lead, respectively. The optimum carbon dosages ranged from 40 to 60 mg/ℓ and were generally limited because of the relatively poor settling characteristics of powdered carbon.

Plain sedimentation proved to be a reliable alternative to the physical-chemical treatment system. The average removal in plain sedimentation for turbidity, COD, and lead was 63, 64, and 82 percent, respectively. Again, detention times utilized in the study were not mentioned in the article.

(b) Complex Systems

The most promising approach to urban stormwater management involves the integrated use of abatement, control, and treatment systems with an areawide, multi-disciplinary perspective. Many programs have been developed with this idea in mind, however, they have been primarily concerned with combined sewer overflows (Lager and Smith, 1974; and Field, Tafuri, and Masters, 1977). As the importance of the effects of separate storm sewer discharges increases, it is likely that many areas will incorporate measures to control pollution from this source.

Discharges from separate sewer systems can also be considered a potential water source. Preliminary investigations have been made of possibilities for augmenting neighborhood water supplies with stormwater collected on individual residential lots (Beers, 1973). Even though the technology exists to treat and reclaim urban runoff waters, the economics of such facilities must first be thoroughly analyzed.

VI. Non-Urban Land Stormwater Runoff

Constituents contained in the runoff from non-urban land originate from a variety of sources including the rainfall itself, wastes from wildlife, leaf and plant residue decay, applied nutrients, herbicides and pesticides, nutrients and organic matter initially in the soil, and wastes from pastured animals. It is very difficult to separate the natural from the controllable pollutant sources. The climate, soil type, topography, type of vegetation, and agricultural practice play a major role in determining the rate of runoff and subsequent erosion and nutrient losses (Benoit, 1973).

Nitrogen and phosphorus are major components of fertilizers and are also considered important factors for aquatic plant growth in surface waters. Thus, concern has been expressed that possible nitrogen and phosphorus enrichment of surface runoff from agricultural lands may be accelerating the eutrophication of lakes and rivers (Timmons, Burwell and Holt, 1973). Because of this, most of the research into agricultural runoff quality has been concerned with the presence of nutrients.

Because of the diverse agricultural production situations, constituents in runoff from different types of non-urban should be examined separately. In the past few years, there have been several reviews of the literature concerning the quality of stormwater runoff from lands utilizing a wide variety of non-urban uses. Table 36 is a listing of these results presented by Loehr (1974).

Between March of 1964 and February of 1965, Weibel, Weidner, Cohen and Christianson conducted one of the earlier and more complete studies concerning pollutant concentrations in runoff from crop land. The area studied consisted of a 1.45 acre field cultivated in winter wheat near Coshocton, Ohio. The constituent concentrations in the runoff samples collected are summarized in Table 37.

Weidner, et al. (1969) also obtained runoff quality data from the watersheds near Coshocton, Ohio and from a 5-acre apple orchard at Ripely, Ohio. Most of the material losses from the land occurred as a result of high intensity rain storms during the summer months. The organic losses were small. BOD values ranged from 3.7 to 120 lbs/acre/yr (4.5-146 kg/ha/yr) and COD losses ranged from 27.8 to 1300 lbs/acre/yr (33.3-1586 kg/ha/yr).

TABLE 36

Nitrogen and Phosphorus in Runoff from Rural and Crop Land (Loehr, 1974)

Location	Area Yield Rate for Given Constituent (kg/yr/ha)*					Remarks
	TKN	NO_3-N	Total N	Soluble P	Total P	
Catoctin Creek (Potomac)	2.8	23.5†	—	—	1.8	80% Farm 20% Forest
England	—	—	4	—	—	Unused land
	—	—	8	—	—	Grassland
	—	—	13	—	—	Clay soils
Germany/Switzerland	—	—	3	—	0.9	Unused land
	—	—	8	—	0.4	Grassland
	—	—	33	—	0.1	Arable land
North Carolina (kg/ha)	—	0.06	0.8	—	0.033	Unfertilized (Apr.–Oct.)
	—	0.07	0.9	—	0.045	Fertilized (Oct.–Apr.)
Ohio	1.2	3.4	—	—	0.056	Farmland (1967–69)
Canadarago Lake, N. Y.	—	—	7.13	0.056	0.187	Agriculture plus one small town
Ohio‡	—	43	—	—	6.2	Tillage—corn
	—	53	—	—	3.0	No tillage—corn
England						
Great Ouse River	—	—	11.7	—	0.06	Drainage from rural lands
Other rivers	—	—	0.6–22.5	—	0.6–2.3	—
Wisconsin						
Continuous corn	—	—	14	—	—	2-yr averages, loam soil
Corn	—	—	5.5	—		
Oats	—	—	6.0	—	—	
Hay	—	—	3.5	—	—	
Fallow	—	—	63	—	—	
Missouri (kg/ha)						
Fallow	—	0.[illegible]	—	—	—	Data from two rains totaling 4.5 in.
corn, oats	—	0.33	—	—	—	
Rotation	—	0.45	—	—	—	
Continuous corn	—	0.10	—	—	—	
Wisconsin drainage area tributary to						
Lake Monona	—	—	6.6	—	—	Runoff from agricultural areas with no domestic or industrial waste contribution
Lake Waubesa	—	—	7.5	—	1.3	
Lake Kegonsa	—	—	9.2	—	0.45	
Arkansas	—	—	3.6	—	2.3	Watershed 80% agriculture
Illinois	—	8.1	—	—	0.06	No significant municipal or industrial waste, 80% crop land, rich organic soil
Wisconsin	—	—	1.2	—	0.11	Stream base flow, 90% farm land

* Unless otherwise noted.
† NO_2 + NO_3-N.
‡ Data indicate the effect of an 11 in. rain and resultant flooding.

TABLE 37

Constituent Concentrations in Rural Land Runoff from a 1.45-Acre (0.59 ha) Cultivated Field in Winter Wheat* (Weibel, Weidner, Cohen, and Christianson, 1966)

Parameter	Range	Average
SS (mg/ℓ)	5 - 2,074	313
COD (mg/ℓ)	30 - 159	79
Total-N (mg/ℓ)	2.2 - 12.7	9
Hydrolyzable-PO_4 (mg/ℓ)	.25 - 3.3	1.7
Organic Cl^- (mg/ℓ)	.15 - .79	.43

*Contour plowed, adequate fertilization and pest control, corn, wheat, 1st year meadow, and 2nd year meadow, annual rotation.

A study concerning the general quality of runoff from crop land was done by Dornbush, Anderson, and Harms (1974) at seven sites near Brookings, South Dakota. Nutrient losses were found to range from .03 to 3 lbs/acre/yr (0.036-3.66 kg/ha/yr) for nitrogen, and from .01 to .72 lb/acre/yr (.012-0.87 kg/ha/yr) for phosphorus. It was also found that most of the annual nutrient load came from snowmelt runoff, and a large percentage was in the soluble form. Soil losses ranged from less than 10 lbs/acre/yr to a maximum of less than 1000 lbs/acre/yr (12-1200 kg/ha/yr).

SECTION 3

EXPERIMENTAL PROGRAM

I. Introduction

Boulder, Colorado, with a population of approximately 75,000, is located where the foothills of the Rocky Mountains meet the high plains. Elevations in the city range from 5300 to 5600 feet (1615-1700 m) above sea level. The Continental Divide with elevations of more than 12,000 feet (3660 m) is 20 miles (32 km) to the west.

The climate of Boulder is strongly influenced by the mountains to the west. Precipitation is light in the winter (16% of annual during the months November through February) and heaviest in the spring (52% of annual March through June). About one-third of the precipitation occurs as snowfall. In the early spring months, precipitation often falls in the form of heavy snow which melts rapidly. The highest monthly average snowfall amounts occur in March and April, when temperatures are usually high enough to remove snow cover quickly. Even in midwinter, the frequent occurrence of warm days usually removes any snow cover in a short time. The normal values of precipitation and snowfall are of 18.6 inches (472 mm) and 81 inches (2057 mm), respectively. A listing of the precipitation parameters for the study area during the period of sampling is shown in Table 38. It can be noted that a drought condition existed and the major reason for the negative departures from normal was due to a

TABLE 38

Precipitation Data for Boulder, Colorado During the Study Period

	Total Precipitation (inches)			Departure from Normal (inches)		
	1975	1976	1977	1975	1976	1977
January		0.42	0.08		-0.35	-0.69
February		0.36	0.45		-0.41	-0.30
March	1.23	1.19	0.53	-0.50	-0.54	-1.20
April	2.85	1.99	3.32	+0.54	-0.32	+1.01
May	4.32	2.14	0.93	+1.11	-1.07	-2.28
June	2.01	1.25	0.66	-0.19	-1.05	-1.64
July	1.67	1.62		-0.08	-0.13	
August	1.31	1.43		-0.37	-0.25	
September	1.06	2.73		-0.25	+1.42	
October	0.68	1.02		-0.82	-0.48	
November	1.20	0.21		+0.19	-0.80	
December	0.57	0.32		-0.02	-0.27	

reduction in the frequency of large storms. 23 of the 28 months of record show less than normal precipitation. This situation somewhat limited the number of storms available for sampling.

II. The Study Areas

Four areas were selected for the study, two stormsewered areas in the urbanized sections of the City of Boulder, one unsewered and uninhabited mountain watershed west of the city and an unsewered agricultural field east of Boulder. Most of the studies were concentrated on the urban watersheds.

A. Urban Area

Boulder, Colorado is served by separate sanitary and storm sewer systems. The area chosen has a separate storm sewer system and is located on the University Hill area in Boulder. The boundaries are Baseline Road on the South, about 9th Street on the west, 14th and Broadway on the east, and to Arapahoe and Boulder Creek in the north direction. This can be seen on the map shown in Figure 6. The sewer system in this area is rather old. It was constructed in the late 1920's or early 1930's. The stormsewer system was in fair to good condition. The characteristics of the drainage area are given in Table 39.

The population density in the study area is higher than the average for Boulder. It is dominately a residential area with a small portion of commercial use and no industry. The residential area can be classified as older, probably about 40

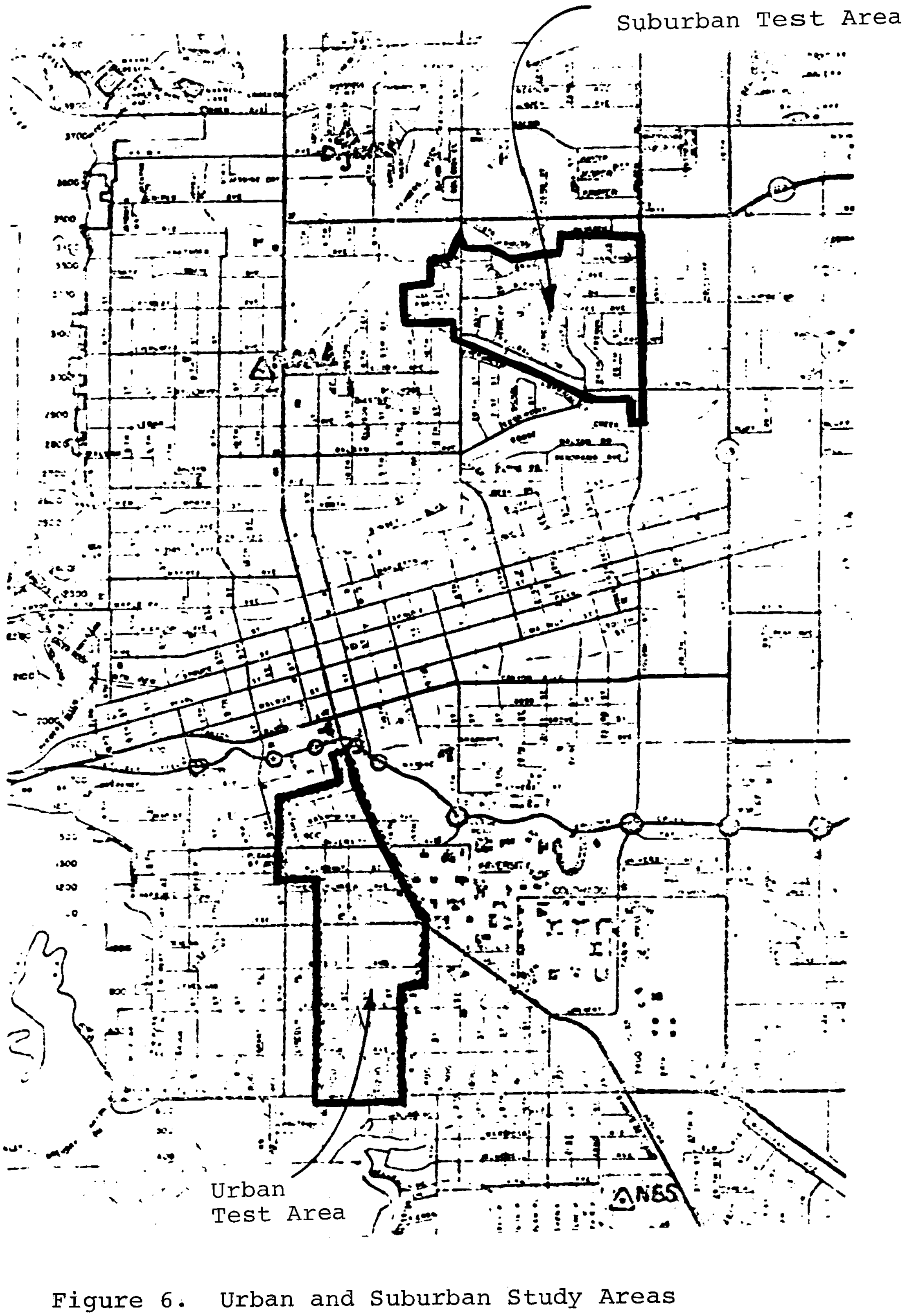


Figure 6. Urban and Suburban Study Areas

TABLE 39

Urban Study Area Characterization

Drainage area:	≃ 74 ha = 183 acres ≃ 0.29 sq. miles		
Population density:	Ave. ≃ 25 persons/acre (62 persons/ha)		
Land-use:	Residential	= 88.8%	
	Greenbelt (parks, etc.)	= 5.2%	
	Commercial	= 6.0%	
Percent impervious:	Paved streets and parking lots	= 41.3%	56.7%
	Roofs	= 15.4%	
Percent pervious:	Greenbelt (parks, etc.)	= 5.2%	43.3%
	Yards, lawns, etc.	= 38.1%	
Mean surface (land) slope:	5.5 ft/100 ft	≃ 3.15 degrees	

to 50 years, but the buildings appeared to be in good condition. It is populated mostly by university students, living mostly in apartments and houses converted to rooming houses. In the south and west end of the area there were also family residences, single and duplex. The percentage values given in Table 39 for impervious and pervious were estimated from airphotos supplied by the City of Boulder.

It has been observed that the storm sewer under study carried a constant base flow of about 0.35 to 0.40 cubic feet per second (0.01 m^3/s). This base flow existed at all times and was due to infiltration into the storm sewer from groundwater. Chemical analysis of the base flow during dry weather indicated this to be true. The data are shown in Table 40. The sampling on 9-9-75 was performed at the beginning of a rainstorm, just prior to the time of runoff reaching the sampling point. A small increase in organics (COD) may have already occurred.

TABLE 40

Chemical Analysis of the Base Flow in the Storm Sewer

Parameter	Concentrations (mg/ℓ) 7/9-75 @ 4:00 p.m.	9/9-75 @ 7:30 p.m.
COD	8.6	19.2
BOD_5	-	4.6
SS	5.0	24.0
VSS	4.0	4.0
Total P	-	0.19
Ortho P	-	0.12
TKN	-	1.7
NO_3	-	2.2
Pb	-	0.022
pH	7.8	7.5
Flow (cfs)	0.38	0.45

The sewer system was made up mostly of concrete pipe and brick manholes. The system appears to have been well maintained.

Traffic densities on some of the streets in the area are rather high. A major arterial street, Broadway (17,000 vehicles/day) passes through the drainage area and a steep hill on this street is heavily salted during snow storms. The city street department used a 99 percent sodium chloride salt, with the trade name "Quick Salt", that was mixed with sand and other abrasives. Salting and plowing were done simultaneously during snow storms and were generally limited to the major collector roads. There was no set salting and plowing schedule. These were done at the discretion of the street department personnel as weather conditions warranted. For an average snow storm of 6 inches, approximately 70 lbs/curb mile of salt was used. This is low compared to application rates of 200 to 400 lbs/curb mile and 400 to 1200 lbs/highway mile reported in other cities (EPA, 1971).

B. Suburban Area

The suburban study area used in this study is located in the northern section of Boulder and is serviced by separate storm and sanitary sewer systems (Figure 6). The area is bounded on the east by Folsom Street, on the south by Valmont Street and Floral Drive, on the west by 19th Street and on the north by Grape Street and Iris Avenue. The 125 acre area is made up almost entirely of single family houses, and has an average population density of 12 persons per acre. A brief summary of land use characteristics for the area is found in Table 41.

TABLE 41

Study Area Characteristics

Total Drainage Area	= 125 acres (50 ha)
Population Density	= 12 persons/acre (30 persons/acre)
Land Use:	
Residential	= 89%
Greenbelt	= 10.9%
Commercial	= 0.1%
Impervious Areas	= 41%
Mean Surface (Land) Slope	= 2.0 ft/100 ft
	= 1.15 degrees
Zoning = Low Density Residential - Established	

Traffic volumes within the study area are relatively low due to the fact that it is well isolated from the main business districts, and the University of Colorado campus. Folsom Street and Valmont Street act as local collectors and experience slightly higher traffic densities during rush hours.

Street sweeping is practiced in Boulder, with the larger routes being cleaned approximately once a week. The smaller streets receive a cleaning on the average of three times a year. These cleanings typically remove leaves, paper, and other debris.

The storm sewers in the study area are approximately 20 years old and are considered to be in good condition. Curb, gutter, and combination inlets are utilized throughout the system, and driveway ramps are present in many of the gutters. These were a factor in attenuating the flow of stormwater to the sewer inlets, due to the fact that the runoff ponds behind the ramps before flowing down the gutter.

The storm water runoff from the study area was discharged through a 36 inch (0.91 m) diameter concrete pipe onto a splash-block which diverted the runoff approximately 45 degrees, and into Goose Creek. This outfall pipe was located immediately southwest of the intersection of Folsom Street and Valmont Street. Goose Creek served as a major drainage creek for much of the north Boulder area. It was piped underground for much of its journey through Boulder, and many small storm sewer outlets discharge into it upstream from the study area. It was not uncommon, therefore, for the stage of Goose Creek to change very dramatically (as much as 2 ft (0.61 m) in 30 minutes) as precipitation passed over the northern part of the city.

C. Mountain Watershed

An uninhabited watershed in Boulder canyon was selected for a brief study of runoff quality. No storm sewers are present in the area. All of the runoff collects at a point and flows through a corrugated metal culvert and then into Boulder Creek. The culvert was used to measure flow and as the sample collection point. A map of the area is shown in Figure 7 and the characteristics of the watershed are given in Table 42.

TABLE 42

Mountain Watershed Study Area Characteristics

Area, 0.18 mi^2 (115 acres) 47.77 ha
Population density < 1 person/acre
Land use, natural
Percent impervious, 0
Percent pervious, 100
Mean surface slope, 15 ft/100 ft

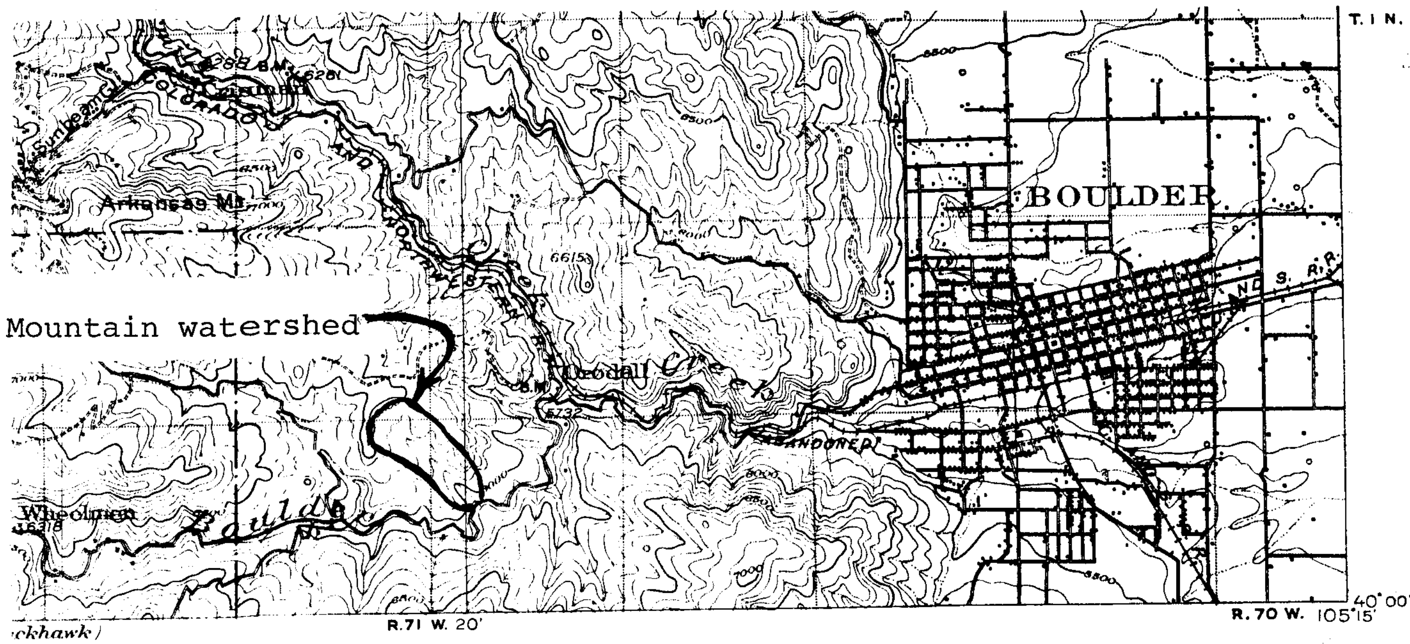


Figure 7. Mountain Watershed Study Area

D. The Agricultural Study Area

The agricultural lands east of Boulder are used for crop production and employ both irrigation and dryland farming techniques. Fields cultivated in alfalfa, winter wheat, and corn are common. This area was chosen for a preliminary investigation into the constituents contained in stormwater runoff from agricultural lands.

In the selection of an agricultural study area, several difficulties arose. First, the area had to be of a slope and configuration that would provide a central drainage system so that samples of the runoff could be taken. Secondly, the area had to be close to the City of Boulder, and accessible so that time would not be wasted in reaching the area when storm events did occur.

With these considerations in mind, the primary agricultural area chosen was a 15 acre (6 ha) alfalfa field located just southwest of the intersection of Arapahoe Road and 75th Street (Figure 8). The area was part of a farm owned by Bernice DeBacker and was accessible from the east. The field was flood irrigated during the summer months and was harvested several times during the year. The field had an average slope of 2.5 feet per 100 feet, and drained to a central outlet located at its lower end next to the access road.

E. Boulder Creek

Boulder Creek is a high quality mountain stream before entering the urban area. Non-point sources enter the stream

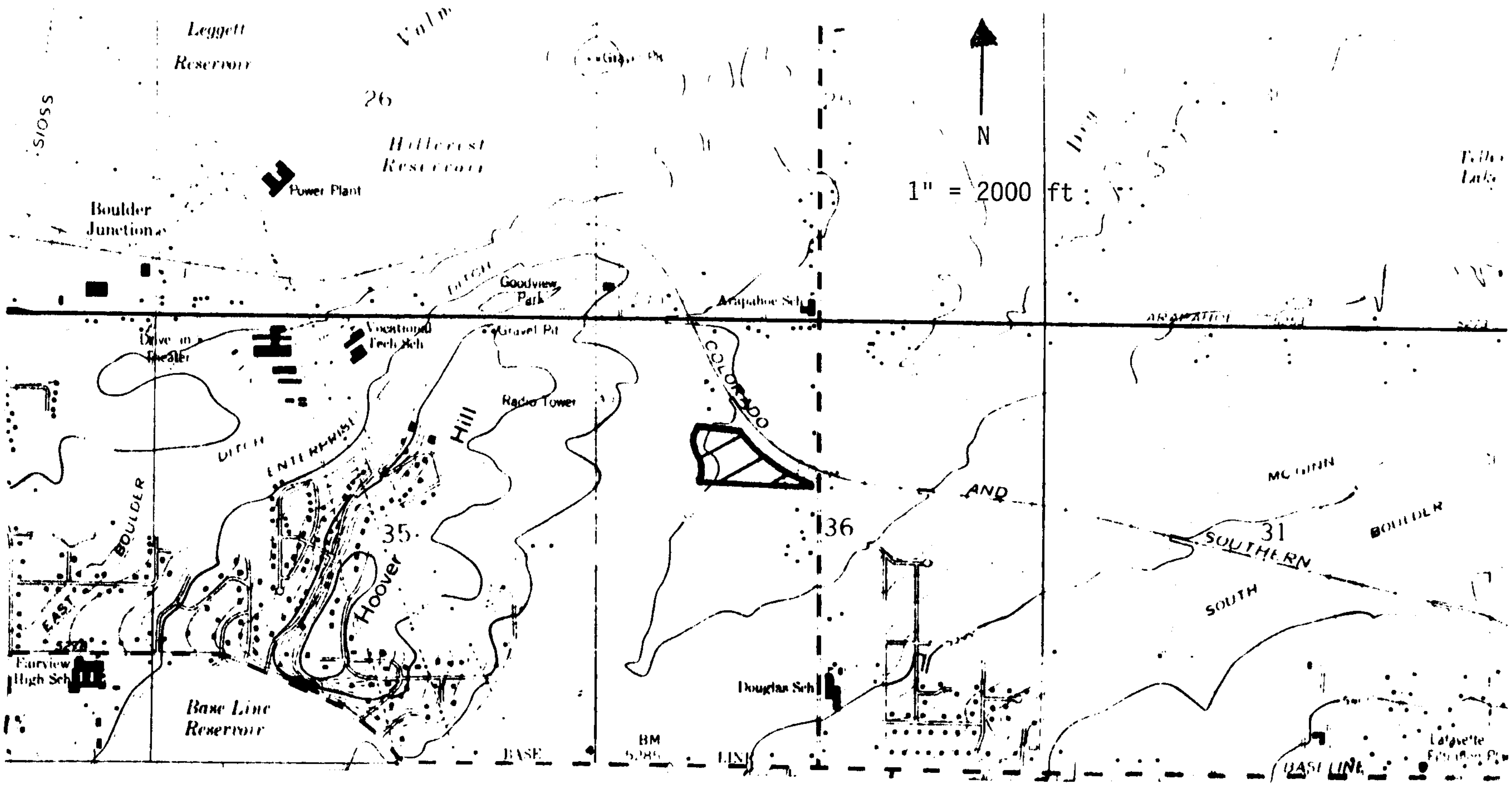


Figure 8. Location of the Agricultural Study Area.

as it flows from west to east through the city and onto the plains. Nine storm sewer outfalls have been identified in the reach of the stream as it flows through the city.

The average monthly streamflows in Boulder Creek at the Orodell gaging station, based on 1969 through 1972 water years, are shown in Figure 9. The Orodell gage is directly west of the city. The release of high quality snowmelt by mountain reservoirs provides the main streamflow throughout the year. However, during the winter months, large daily fluctuations in flow can occur, and are attributed to the hydroelectric plant located above Orodell. The low flows during the winter months occur when the plant is not in operation. Several headgates for irrigation ditches are located along the stream within the city and these can have a major effect on streamflow for different reaches of the stream, especially in late summer. The flow in the stream is almost completely controlled by reservoir releases and the large flows in the summer months represent irrigation releases carried by the stream.

Measurements of the water quality of Boulder Creek have been taken as a part of this study. These data are shown in Table 43. The change in quality at 75th Street reflects the effluent discharge from the city wastewater treatment plant. The City of Boulder has conducted a sampling program and a listing of their data for a five month period as shown in Table 44.

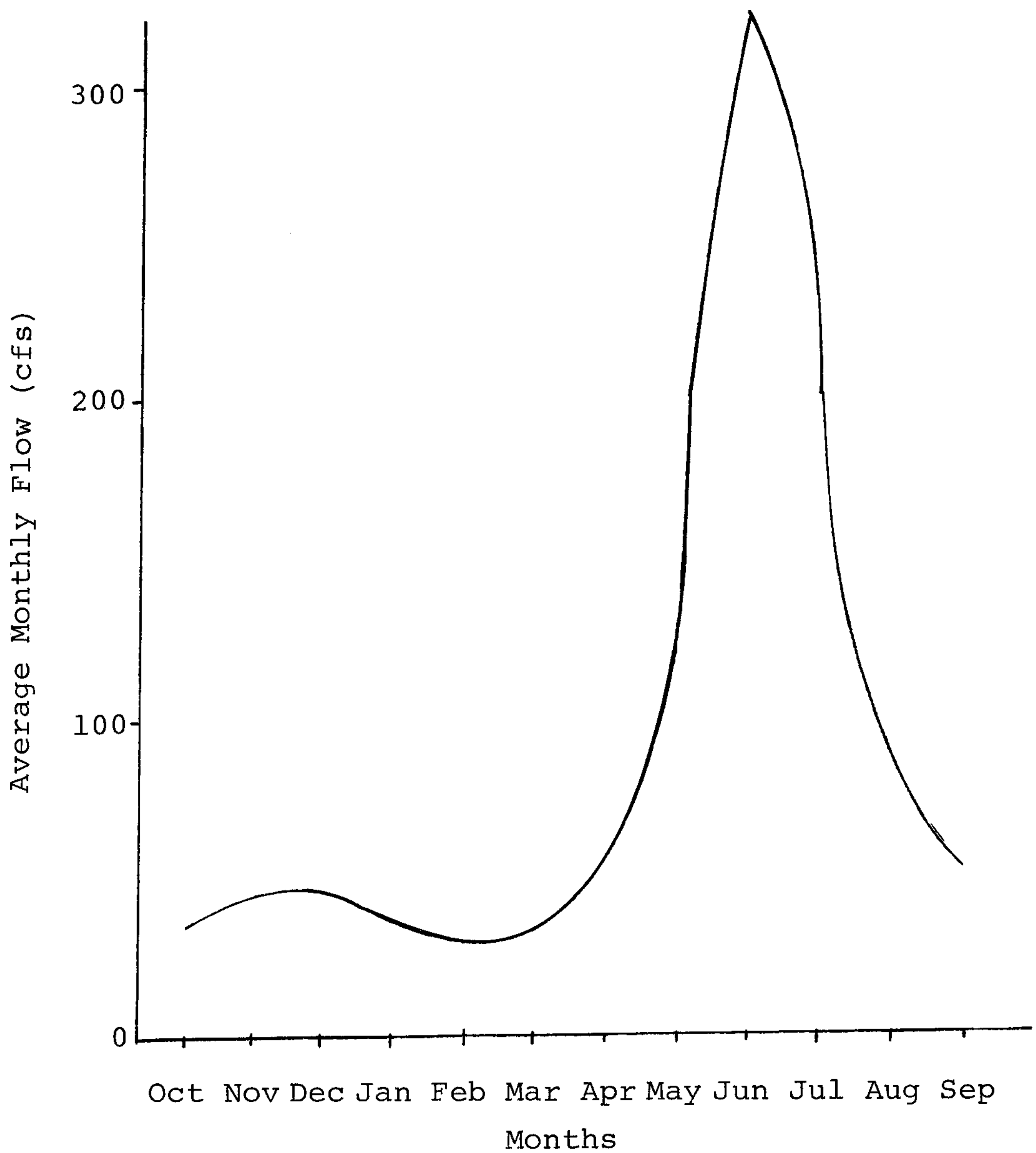


Figure 9. Average Annual Streamflow - Boulder Creek at Orodell (Water Years 1969-72).

Table 43

Dry-Weather Data of Boulder Creek
February 22, 1975

Sampling Site	Concentrations (mg/ℓ) COD	TS	SS
(1) Mouth of Canyon	3.0	162	3.0
(2) 13th Street	3.0	155	2.4
(3) 48th Street	3.2	175	1.2
(4) 75th Street	48.0	377	11.0
(5) 95th Street	28.0	437	8.5

Dry-Weather Data of Boulder Creek at Broadway

Parameter	Concentrations (mg/ℓ) 9/9-75 @ 7:30 p.m.
COD	9.1
SS	8.0
VSS	3.0
BOD_5	3.1
Tot. P.	0.09
Ortho. P.	<0.09
TKN	0.28
NO_3^-	0.75
pH	6.9
Flow (cfs)	18.0

Table 44

Dry-Weather Data of Boulder Creek at 17th Street.*

DATE	TIME	TEMP (°C)	FLOW (cfs)	D.O. (mg/l)	TURB. (ftu)	SS (mg/l)	NH_3-N (mg/l)	$PO_4^=$ (mg/l)	pH	TOT. COLIF. (#/100 ml)
6/17	10 am	12.0		9.3	9	58	.16			93
6/26	10 am	10.0		9.4	4		.10			
7/1	10 am	15.0		9.2	5	11	.13	.07		
7/8	10 am	14.5		8.4		8	.16	.55	7.2	9
8/7	10 am	16.0		--	3	3	.14		7.2	700
8/12	10 am	16.5		7.7	2	10	.12		7.6	304
9/2	10 am	16.0		6.8	2	5	.52	.52		344
9/23	10 am	11.0		7.6	3	1	.48			18,700
9/30	3 pm	11.0		9.5	8	7	.48	.2	7.0	
10/7	3 pm	12.0		9.7	2		.26	.8	7.2	460
10/21	11 am	9.5	5	9.8	2	< 1	.28	.13	8.0	121
10/28	1 pm	9.5	9	9.5		10	.22	0	8.0	143
11/4	2 pm	9.0	10	9.3	3	.6	.14	.07	7.9	
11/11	2 pm	6.5	1.2	10.2	3		.12		7.6	176
11/18	2 pm	3.0	7	11.2						

*Downstream (4 to 5 blocks) from the storm sewer.

III. Sampling Program

The primary objectives of this part of the program involved the pollutant characterization of runoff from the urban study area. A review of the literature concerning urban stormwater runoff revealed that a variety of pollutants have been found in separate storm sewer discharges. Therefore, a wide variety of pollutants were investigated, and are listed in Table 45. Several of the parameters shown were examined on every sample that was taken in each storm event, while other parameters were examined on selected storm events. Stormwater flow measurements were also performed in order to evaluate pollutant mass loadings.

Periodic grab samples were taken at the storm sewer outfall before, during, and after each storm event to obtain a complete pollutant distribution curve. The frequency of sampling times varied throughout the course of each storm event. Care was taken to obtain samples during times of peak pollutant concentrations and runoff. The samples were taken from the mouth of the outfall pipe.

Several containers were utilized at each sampling to facilitate the storage of samples. One gallon Nalgene containers were used to collect samples for routine chemical analyses that were either performed immediately, or needed little or no preservation. Samples for coliform analyses were taken using 250 ml wide-mouth Nalgene bottles that were previously sterilized in an autoclave. One-quart glass canning jars were utilized for taking oil and grease samples, and 125 ml wide-mouth Nalgene bottles were used for COD samples.

TABLE 45

Constituents Investigated in the Characterization Study of Urban Runoff

*Total Solids (TS)
*Total Volatile Solids (TVS)
*Suspended Solids (SS)
*Volatile Suspended Solids (VSS)
*Total Dissolved Solids (TDS)
Oil and Grease
*Chemical Oxygen Demand (COD)
Soluble Chemical Oxygen Demand
Biochemical Oxygen Demand (BOD)
Total Coliform Bacteria
Fecal Coliform Bacteria
*Total Kjeldahl Nitrogen (TKN)
Ammonia Nitrogen
*Nitrate Nitrogen plus Nitrite Nitrogen
Nitrite Nitrogen
Soluble Ortho-Phosphorus
Soluble Total Phosphorus
*Total Phosphorus
*pH
Alkalinity
*Chlorides
Total Hardness
Phenols
Turbidity

*Analyses performed on all samples

The samples were returned to the laboratory for analysis (or further preservation) within an hour after the time of sampling. Samples collected for BOD and coliform analyses were analyzed immediately. The other samples were analyzed as time permitted, but in no case did the length of time between sampling and analysis exceed the accepted holding times for the various chemical tests (APHA, AWWA, WPCF, 1976; and EPA, 1974).

A. Flow Measurements

In order to evaluate mass loadings of pollutants, the discharge of stormwater throughout the runoff events was monitored. Manning's equation and the continuity equation were utilized to estimate the velocity of flow and discharge through the outfall pipe:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

and

$$Q = A V$$

The average slope of the outfall pipe was determined to be 1.26 feet per 100 feet for the suburban area and 2.3 feet per 100 feet for the urban area. A constant value of Manning's n, equal to 0.015, was utilized (Chow, 1959).

On-site recordings of flow were taken using a ruler and tape measure. To ensure comparable results, all measurements were based on the depth and width of flow exactly one foot inward from the edge of the outfall pipe. A small baseflow, 0.01 m^3/s urban area and 0.001 m^3/s suburban area, existed at all times of the day throughout the study period. This flow was assumed to be a result of groundwater infiltration, and was taken into account in all flow measurements during and after a storm.

B. Precipitation Measurements

A recording rain gage was operated on the roof of the Engineering Center as a part of the study. Rain and snowfall data were also obtained from a standard 8 in. (20 cm) precipitation gage at the National Bureau of Standards located about one-fourth mile (½ km) to the south. The data from this station were reported in the "Climatological Data" report, published monthly by the Environmental Data Service of NOAA, located at the National Climatic Center in Ashville, North Carolina.

Investigations into the pollutional characteristics of rainfall and snowmelt were also undertaken. Samples of rainfall were obtained using prewashed aluminum trays to divert rainfall to a large glass funnel, and into a clean glass sample bottle. Care was taken to use sample bottles that were free of residues that may have interfered with the laboratory test results. Snowfall samples were obtained by placing prewashed aluminum trays out of doors to collect the snow as it fell throughout a storm event. The melt water was then analyzed for various pollutants, which are listed in Table 46. All samples were collected atop the Civil, Environmental, and Architectural

TABLE 46

Pollutants Investigated in Undisturbed Rainfall and Snowmelt

Total Solids
Total Volatile Solids
Suspended Solids
Volatile Suspended Solids
Chemical Oxygen Demand
**Soluble Chemical Oxygen Demand
pH
**Alkalinity
**Hardness
Ammonia Nitrogen
Nitrate Nitrogen
**Nitrite Nitrogen
Total Kjeldahl Nitrogen
*Ortho-Phosphorus
*Total Phosphorus

*Rain only

**Snowmelt only

Engineering wing at the University of Colorado. Analyses were conducted immediately, eliminating the need for sample preservation techniques.

IV. Treatability of Urban Runoff

Along with the characterization aspects of urban runoff, the treatability of urban runoff was also investigated. The objectives were to examine the effectiveness of plain sedimentation, chemical clarification, and filtration for the removal of suspended solids, COD, and turbidity from storm sewer discharges. Soluble COD and total solids determinations were also performed in order to evaluate the relative contribution and removal efficiencies of dissolved materials.

A. Sampling Method

Samples for the treatability studies were taken at the same time as the samples for the characterization study for the suburban area. At first, it was thought that sampling proportioned to the stormwater flow throughout the runoff event, was necessary and this was done during the first storm runoff that was sampled. However, because the concentrations of pollutants varied throughout the runoff event, any on-line treatment process would have to be effective enough to treat that portion of the wastewater flow containing the greatest pollutant concentrations. Therefore, in subsequent storm runoff events, sampling for treatment studies was performed as close as practicable to the time at which the pollutional strength of the stormwater flow was at a maximum.

Actual field sampling consisted of filling several 5 gallon carboys with the stormwater using a plastic bucket. In general, only enough stormwater was collected to perform the treatment tests. This volume varied from 30 to 40 gallons. Care was taken to avoid the collection of sticks, trash, leaves, and other debris that was typically present in the runoff waters. The samples were returned to the laboratory and placed into a 50 gallon Nalgene drum.

B. Treatment Procedures

The effectiveness of the various treatment processes was determined immediately after completion of the sampling program. The processes investigated were plain sedimentation, chemical coagulation with alum, lime, and ferric chloride, and filtration. The exact procedures for the evaluation of each of these processes were as follows:

1. Plain Sedimentation

The contents of the storage drum were thoroughly mixed, and an initial sample was taken. The stormwater was then allowed to settle quiescently. Sampling was performed at various time intervals. A siphon mechanism was utilized to take the samples approximately 1 inch below the surface of the stormwater, to eliminate the collection of floating matter. Turbidity measurements were performed immediately on each sample, and were utilized in the determination of the sampling frequency.

Sampling was discontinued when there was no further significant reduction in turbidity. This resulted in detention times of between 4.5 and 7 hours. Samples taken for COD and solids analyses were immediately preserved in 250 ml Nalgene plastic bottles for future analysis.

2. Chemical Coagulation

Upon completion of the sedimentation procedure, the remaining stormwater sample was thoroughly mixed. One liter samples were taken and placed in 1500 ml beakers. The beakers were then placed on a 6 paddle, Phipps and Bird jar test apparatus. Appropriate amounts of coagulant were introduced into each beaker as a concentrated solution (5000 mg/ℓ), and each sample was then rapid mixed at 100 RPM for 30 seconds. The doses of coagulant varied from 0 to 350 mg/ℓ for Alum ($Al_2(SO_4)_3 \cdot 18H_2O$), 0 to 80 mg/ℓ for Ferric Chloride ($FeCl_3$), and 0 to 350 mg/ℓ for Lime ($Ca(OH)_2$). Adjustments in pH or alkalinity were not made in order to evaluate the effectiveness of the coagulants on "natural" stormwater. Following rapid mixing, each sample was flocculated at 20 RPM for 20 minutes, and allowed to settle undisturbed for 30 minutes. A siphon mechanism was then utilized to remove the supernatant, which was divided and placed in various plastic storage bottles for further preservation and analysis.

During the last runoff event that was sampled, it was desired to investigate the effect of alkalinity and pH changes on the coagulation process. Excess alkalinity was added (200 mg/ℓ as $CaCO_3$) as a concentrated solution (5000 mg/ℓ as $CaCO_3$).

Adjustments in pH were made after the addition of the coagulant using HCl, $Ca(OH)_2$, and a pH meter. The procedure was as follows:

(a) Perform coagulation of the runoff water using lime doses of 0, 25, 50, 75, 100, and 150 mg/ℓ; alum doses of 0, 25, 50, 75, 100, and 150 mg/ℓ; and ferric chloride doses of 0, 25, 37.5, 50, 67.5, and 75 mg/ℓ. Adjustments in pH and alkalinity were not made.

(b) Perform coagulation of the runoff water using alum and lime in the same doses as above. The alkalinity was increased by 200 mg/ℓ as $CaCO_3$ in each sample. Ferric chloride was also used, but as dosages of 0, 20, 40, 60, and 80 mg/ℓ.

(c) Perform coagulation of the runoff water using 0, 25, 50, 75, 100, and 150 mg/ℓ of alum. The pH was adjusted to 7.0 using lime after the alum addition.

(d) Perform coagulation of the runoff water using the optimum doses as determined in step (a). The pH was adjusted to 4, 5, 6, 7, 8, and 9.0 using lime and HCl after the coagulant addition.

3. Filtration

The preliminary evaluation of the filtration process involved the passage of the stormwater runoff through a 4 ft by 1.5 inch diameter column of 30 mesh sand. The sand in the column was washed with 5 gallons of deionized water and allowed to dry prior to sample filtration. This washing and drying was performed in advance so that filtration of the stormwater could be performed immediately. Approximately one bed volume (1400 ml) of the stormwater from the storage vat was allowed to filter through the column, which took approximately 6 to 8 hours. Samples were taken before and after filtration to evaluate removal efficiencies, and were preserved for further analyses.

V. Analytical Methods

All laboratory testing was performed in accordance with the procedures given in Standard Methods for the Examination of Water and Wastewater and Methods for Chemical Analysis of Water and Wastes, (APHA, AWWA, WPCF, 1976; and EPA, 1974). A brief discussion of each of the testing procedures is given to illustrate the method used and the minor modifications that were applied.

pH: Determined from direct meter reading.

Total Solids and Total Volatile Solids (TS & TVS): The standard gravimetric method was used.

Chlorides: The standard silver nitrate titration was used.

Suspended Solids: In addition to the glass fiber disk, a coarse asbestos mat with a thickness of about 0.06 to .13 inches was added to the Gooch crucibles (Harada, Reid, Bennett, and Linstedt, 1973).

Alkalinity: The standard acid titration method was used.

Hardness: The standard versene titration method was used.

BOD_5: Biochemical oxygen demand; secondary effluent was used as seed water, and it was added to the dilution water in the same proportions (2 ml/ℓ) as the nutrients and the phosphate buffer.

COD: Mercuric sulfate was added to each flask to eliminate any interference from chlorides.

Coliform: Both fecal and total coliform were tested using the dilution tube MPN method or the millipore filter technique.

Oil & Grease: The Soxhlet extraction technique was used, with trichlorotrifluoroethene as the organic solvent. This was later recovered by distillation.

Lead (Pb): Final lead determinations were done by the laboratory of the Denver Water Department, on their Varion atomic adsorption unit. The preparation of the samples prior to adsorption were done in the CU laboratory. Extraction of the lead from solution was done using 5 ml of a 4 percent solution of ammonium pyrrolidine dithiocarbonate and 10 ml of methyl isobutyl ketone. This was followed by two digestions with nitric acid.

Some of the lead samples were also evaluated using the colorimetric method. In the preliminary treatment of samples, the digestion with nitric and perchloric acids were preferred. During the procedure, the removal of tin and bismuth interference was dropped because no differences were shown in the results from the first trials on the storm water runoff samples.

Total and Ortho-Phosphorus: The persulfate digestion method was utilized in determining the total phosphorus fractions. The total phosphorus determination involved filtration through a 0.45 μ filter following digestion, while the total dissolved phosphorus determination involved filtration prior to digestion. Phosphorus concentrations were determined using two methods, the stannous chloride method for the urban and mountain area and the automated single reagent Ascorbic Acid method for samples from the suburban area (APHA, AWWA, WPCF, 1976). Ortho-phosphorus concentrations were determined on filtered samples, due to the interference of suspended solids and turbidity.

Ammonia Nitrogen: An ion probe that was selective for ammonia was utilized. Due to the low levels encountered, verification of the accuracy of the selective ion probe was necessary. This was performed by comparison with the phenate method (APHA, AWWA, WPCF, 1976).

Nitrate Nitrogen: Two methods were used to determine nitrate content. All samples were first filtered through a 0.45 μ millipore filter to eliminate any interference from turbidity. For the samples from the urban and mountain watersheds, the Brucine method was used for this determination, and a Baush and Lamb "Spec 24" was used for all the readings.

For the samples from the suburban area, the automated cadmium reduction method was utilized. All samples were filtered through a 0.45 μ filter to eliminate interference from turbidity. This method measured nitrate and nitrite nitrogen simultaneously. Hence, the nitrite concentration was subtracted when evaluating nitrate concentrations.

Nitrite Nitrogen: An automated procedure that was an adaptation of the diaznotization method of Standard Methods was utilized

(Technicon Industrial Systems, 1974). Each sample was filtered through a 0.45 μ filter prior to analysis to eliminate interference from turbidity.

Due to the large number of chemical analyses that were performed, the use of various sample preservation methods was necessary. In each case, the accepted methods, which are outlined in Methods for Chemical Analysis of Water and Wastes and Standard Methods, were utilized. Every attempt was made, however, to complete the various analyses as quickly as possible, utilizing preservation methods only when necessary.

SECTION 4

STORMWATER POLLUTION RESULTS

The emphasis of the research studies related to the urban and suburban watersheds and the relationships between rainfall runoff and snowmelt runoff pollutional characteristics. An analysis was made for each of several storms. The studies include the storm sewer discharges, the receiving stream and the precipitation prior to reaching the surface environment.

A. Precipitation Quality Data

Precipitation events were sampled and analyzed to evaluate the quality of stormwater prior to contact with the watersheds. The pollutional characteristics that were found are shown in Table 47. It can be noted that the precipitation does dissolve and adsorb pollutional materials from the air. In general, pollutant levels were low. The pH of the rainfall and snowmelt waters that were sampled was 5.3, indicating the absence of high airborne concentrations of strong acids. Low levels of alkalinity were also found. The largest pollutant loading was associated with the total solids. However, these values were also low when compared to other pollutant sources. The results are in the same range as those reported by Loehr (1974). The annual nitrogen loading based on these limited data would be approximately 3 kg/ha/yr, which is higher than suggested by Uttormark, Chapin and Green (1974).

B. Urban Area Runoff Data

Grab samples were taken throughout the runoff period for

TABLE 47

Pollutant Properties of Undisturbed Rainfall and Snowmelt

PARAMETER	SNOWMELT CONCENTRATION[a] (mg/ℓ)	RAINFALL CONCENTRATION (mg/ℓ)	
		RANGE	AVERAGE[b]
COD	10.4	8.9-20.5	15.6
Soluble COD	7.1	-	-
TS	86.5	21.0-162.0	108.3
TVS	41.0	12.0-53.0	29.0
SS	16.0	2.5-18.8	9.4
VSS	9.5	1.2-6.1	3.3
NH_4^+-N	.023	.33-1.28	.74
NO_3^--N	.15	.84[c]	-
NO_2^--N	0	-	-
TKN	.19	.61	-
Ortho-P	-	.01-.06	.036
Total-P	-	.04-.06	.047
Hardness	2.0	-	-
Alkalinity	11.2	-	-
pH	5.3	5.3[d]	-

[a]Sample taken 10/26/76 at mouth of Boulder Canyon

[b]Average of 3 samples taken between 5/21/76 & 5/23/76

[c]Sample of 5/21/76 only

[d]Sample of 5/23/76 only

sixteen rain and snow storms. A listing of the storm characteristics is shown in Table 48. Complete data of the measured chemical characteristics is given in Appendix A.

1. Stormwater Runoff Concentrations

At the initiation of the study, it was necessary to establish the sampling times that would produce the most useful results. Several storms were sampled using different intervals. The proper sampling schedule was established with the rainfall of 9-9-75. For a storm sewer system of this size, a sampling interval of ten to fifteen minutes will result in a good definition of the pollution profile with data points on the increasing portion of the curve and at the peak concentration and flow points. It is essential to obtain a base flow point just prior to the beginning of the runoff.

Establishing the sampling pattern for snowmelt runoff was somewhat easier. Maximum runoff occurred near noon, in the warmest part of the day. Hourly sampling from 9 a.m. until 1 p.m. and approximately two hour sampling intervals in the afternoon until 8 p.m. provided a good profile of the chemical characteristics of the runoff. This was established with the snow of 1-18-76 and was utilized for all of the following storms that were sampled.

Pollutant concentration profiles as a function of time during the runoff are presented in the following graphs.

TABLE 48

Data Collected from Storms That Were Analyzed for Chemical Parameters (Urban Area)

Date	Rain / Snow	Rain or Snowmelt(3) (inches)	Average Intensity (in/hr)	Duration (hrs)	Antecedent Dry Period (days)	Stormsewer Peak Flow (cfs)	Boulder Creek Flow (cfs)	
							Above	Below
7-5-75	Rain	0.10	0.05	2.0	15.0	3.5	372.3	-
7-9-75	Rain	0.08	0.06	1.25	1.5	3.1	397.5	227.3
8-12-75	Rain	0.10	0.20	0.5	12.0	4.9	18.5	-
9-9-75	Rain	0.12	0.07	1.75	18.0	5.0	18.9	5.3(5)
11-8-75	Rain(2)	0.07	0.07	1.0	15	2.0(4)	12.5	2.3(5)
3-11-75	Snow(1)	0.16 (2.7")	0.0084	19	1.5	-	-	-
3-31-75	Snow	0.71 (12.1")	0.0203	35	3.7	-	-	-
10-23-75	Snow	0.68 (5.8")	0.027	25	22.5	2.5	17.8	17.0(5)
11-9-75	Snow(2)	0.45 (2.2")	0.031	14.5	2.5 hrs	0.8(4)	12.5	1.1(5)
1-18-76	Snow	0.35 (4.3")	0.044	8	11	1.8	-	-
1-25-76	Snow	0.06 (3.1")	0.004	16	5	0.6	11.7	12.2
2-20-76	Snow	0.27 (4.8")	0.021	13	14	1.51	11.5	- (5)
3-2-76	Snow	0.26 (3.8")	0.022	12	11	2.63	-	- (5)
3-3-76	Snow	0.11 (2.6")	0.005	21	0	2.63	-	- (5)
3-4-76	Snow	0.33 (5.1")	0.016	20	0	1.26	-	- (5)

(1) Snow fell the two preceding days; 0.5" (0.08" precip) and 2.1" (0.12" precip).
(2) Partially sampled.
(3) Values in parenthesis are measured snowfall.
(4) Not believed to be peak flow; samples were taken late.
(5) All flow in Boulder Creek was diverted to Left Hand Ditch, except for a small leak (0.3 cfs).

The data from the rainstorm of 9-9-75 are shown in Figure 10. It can be noted that the peak concentration of all pollutants occurs before the flow peak, indicating that a first flush effect was apparent in pollutant concentration. All of the curves have a pronounced, short-term peak except those of pH and Nitrate. For pH and NO_3, the value for the runoff was lower than that of the base flow and a dilution depression was observed.

The snow runoff of 2-20-76 had nearly the same valume as the rain runoff of 9-9-75. The pollution profile of the snowstorm is shown in Figure 11. The time scale is compressed on the snowmelt profiles. It can be noted that the pollution peaks are at lower concentration and that the flow rate is less. In general, for many of the pollutants, the total amounts released to the receiving stream are similar but the slow release of the water to the stream results in low peak concentrations. A plot that shows the time relationship more clearly is given in Figure 12. The time scales are the same for the rain and snow runoff and the plots of total solids, suspended solids, COD and flow rate are shown. The pollution concentration-time curves for the runoff from six of the snowmelt sampling periods are shown in Figures 13 through 18.

The peak concentration of pollutants for rain and snowmelt runoff occur before the maximum flow arrives at the storm sewer outfall. When the mass flow rate of pollutants (concentration multiplied by flow rate) is plotted, a different pattern results. The mass flow rate (kg/hr) of pollutants for the rainfall

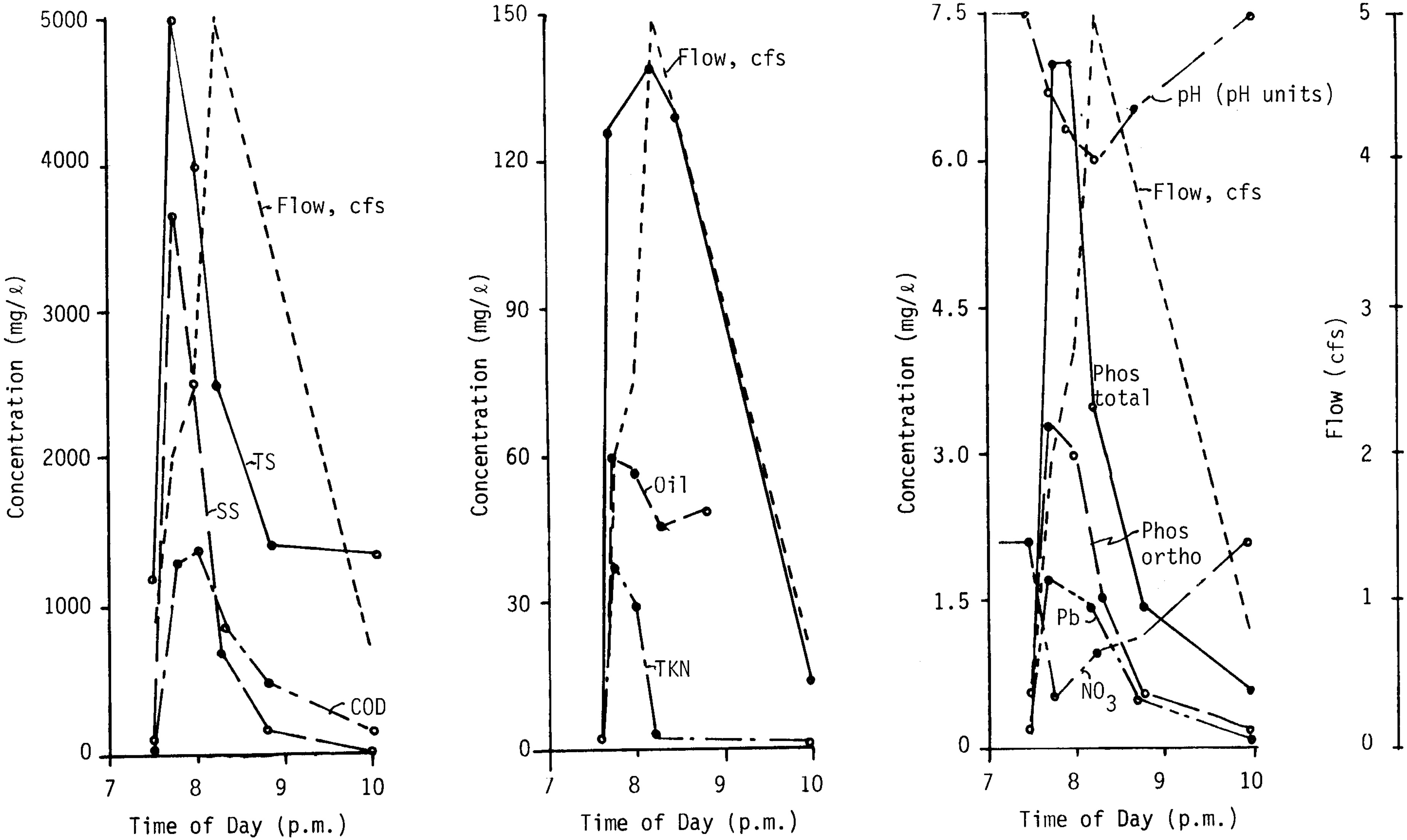


Figure 10. Pollutant Concentration Profiles for the Rainstorm of 9-9-75 on the Urban Study Area (precip = 0.12 in.).

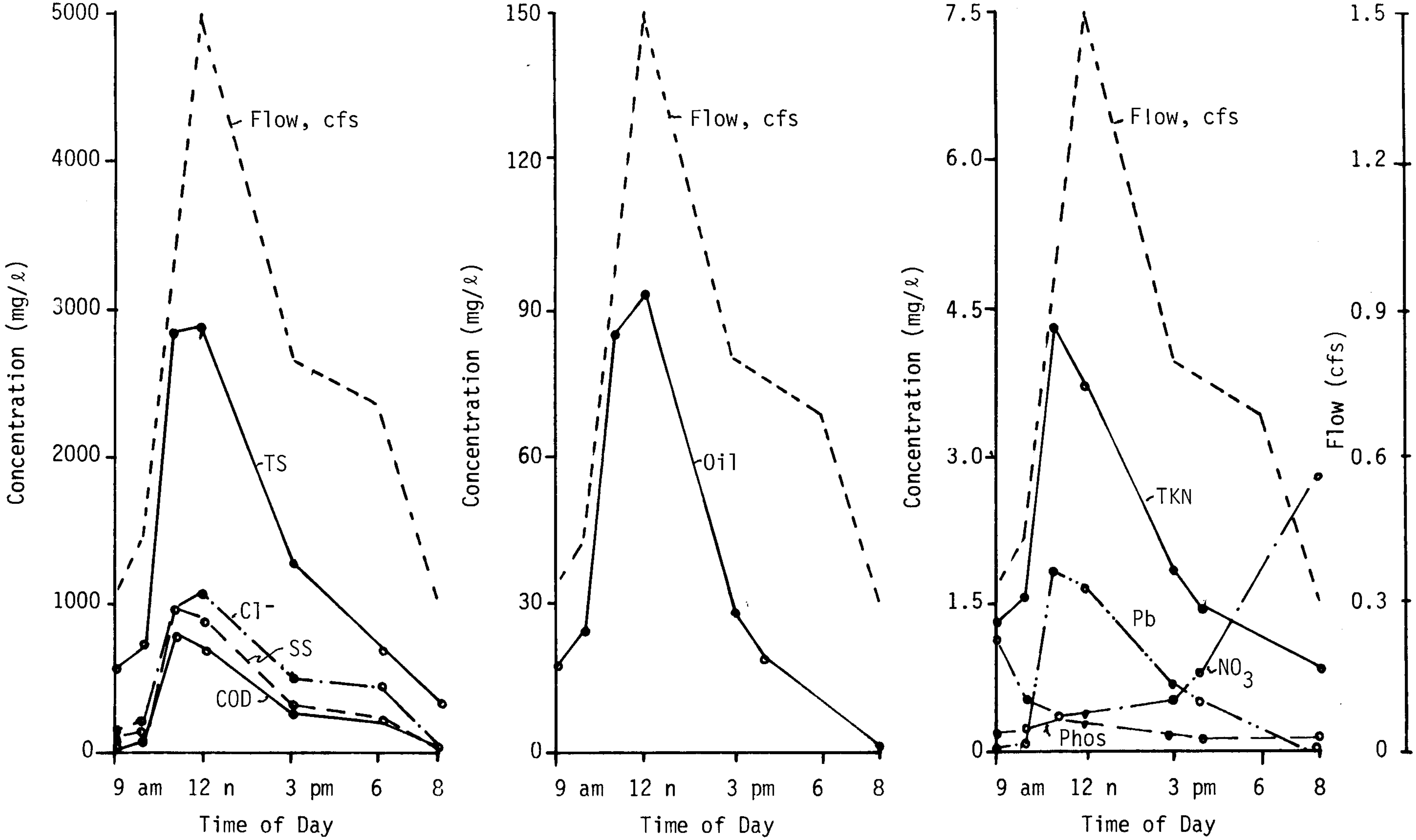


Figure 11. Pollutant Concentration Profile for Snowmelt of 2-20-76 on the Urban Study Area (snowfall - 4.8 in., precip = 0.27 in.).

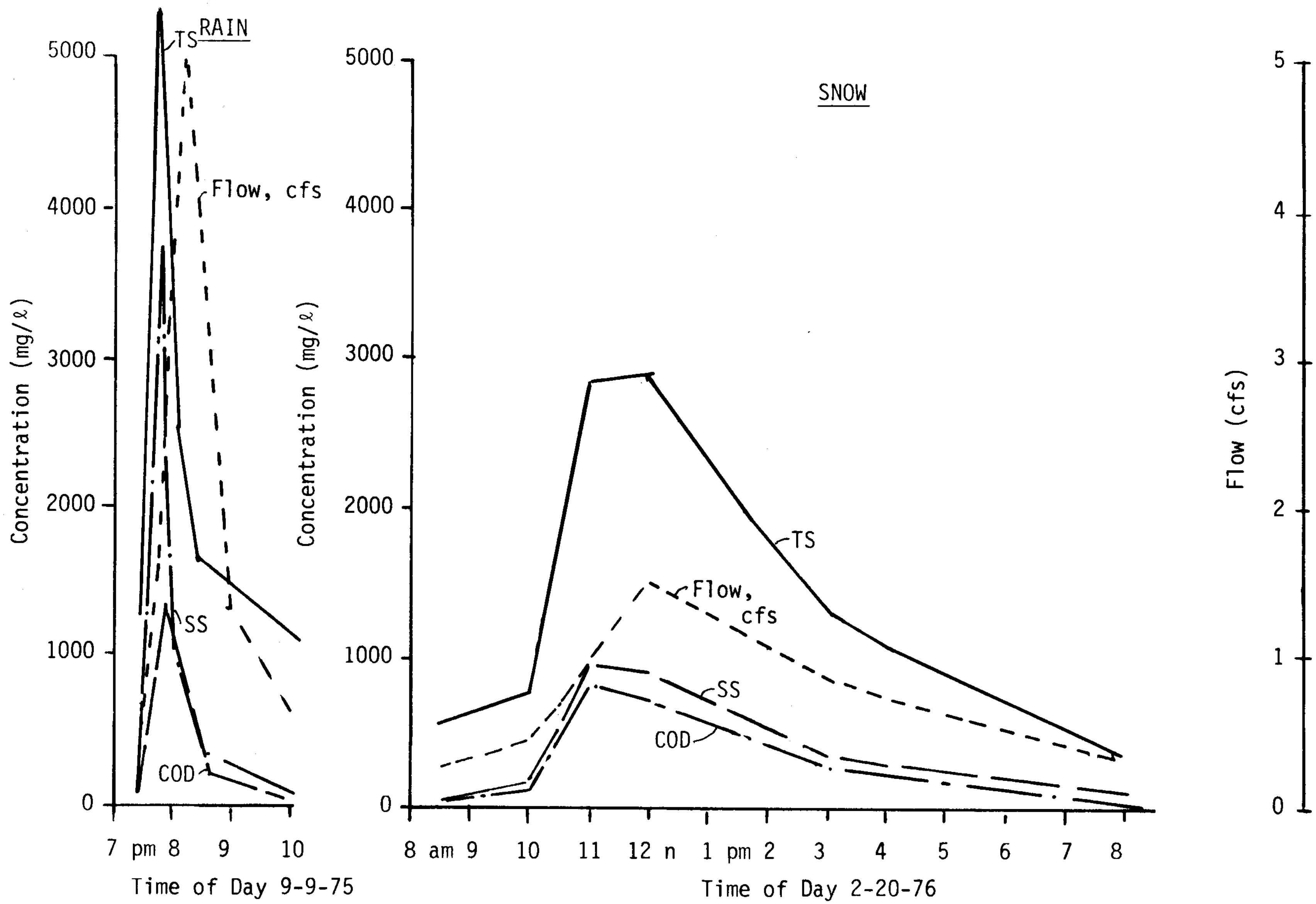


Figure 12. Comparison of Rain and Snow Pollutant Concentration Profiles on the Urban Study Area

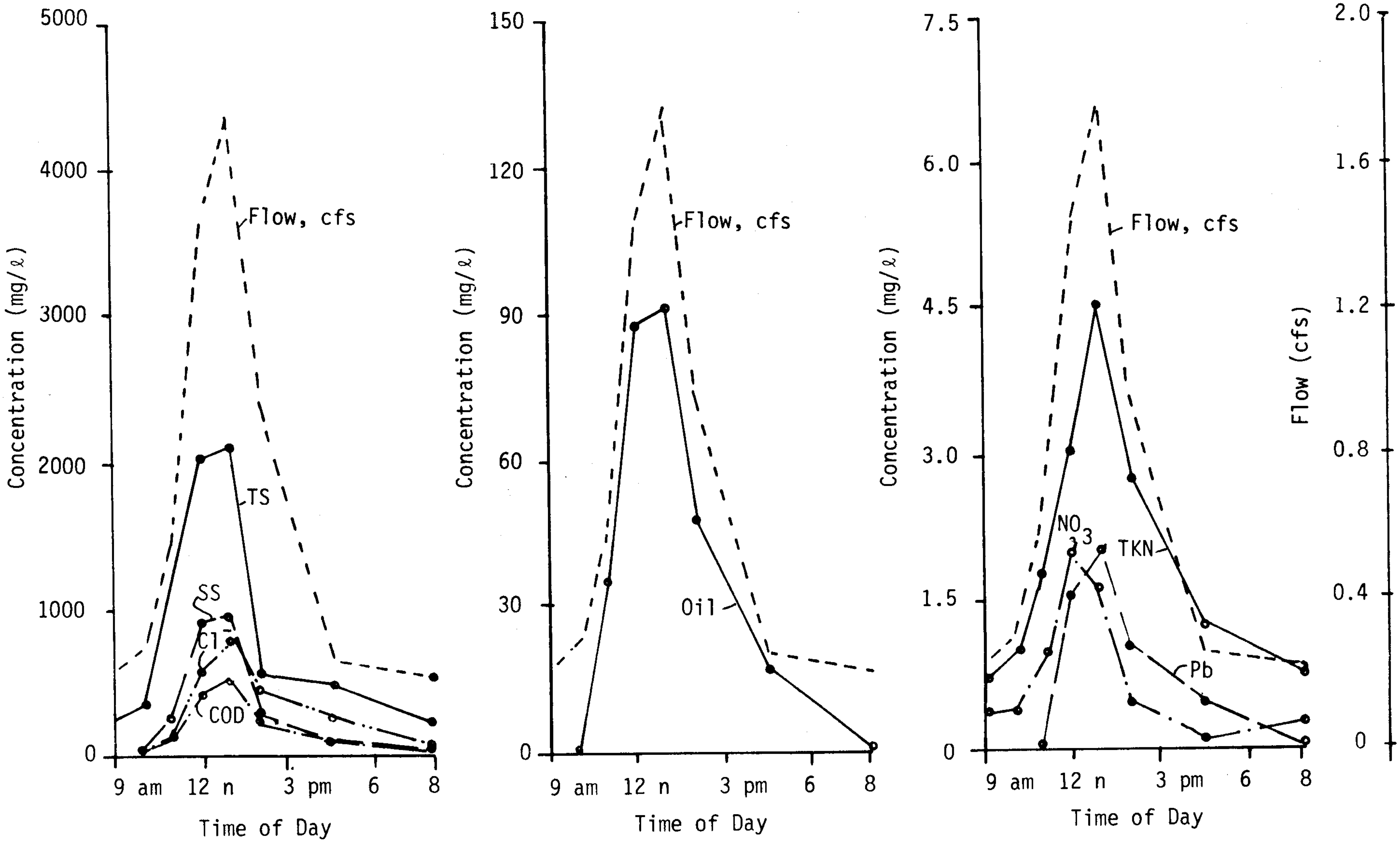


Figure 13. Pollutant Concentration Profiles for the Snowmelt of 1-18-76 on the Urban Study Area (snow = 4.3 in., precip - 0.35 in.).

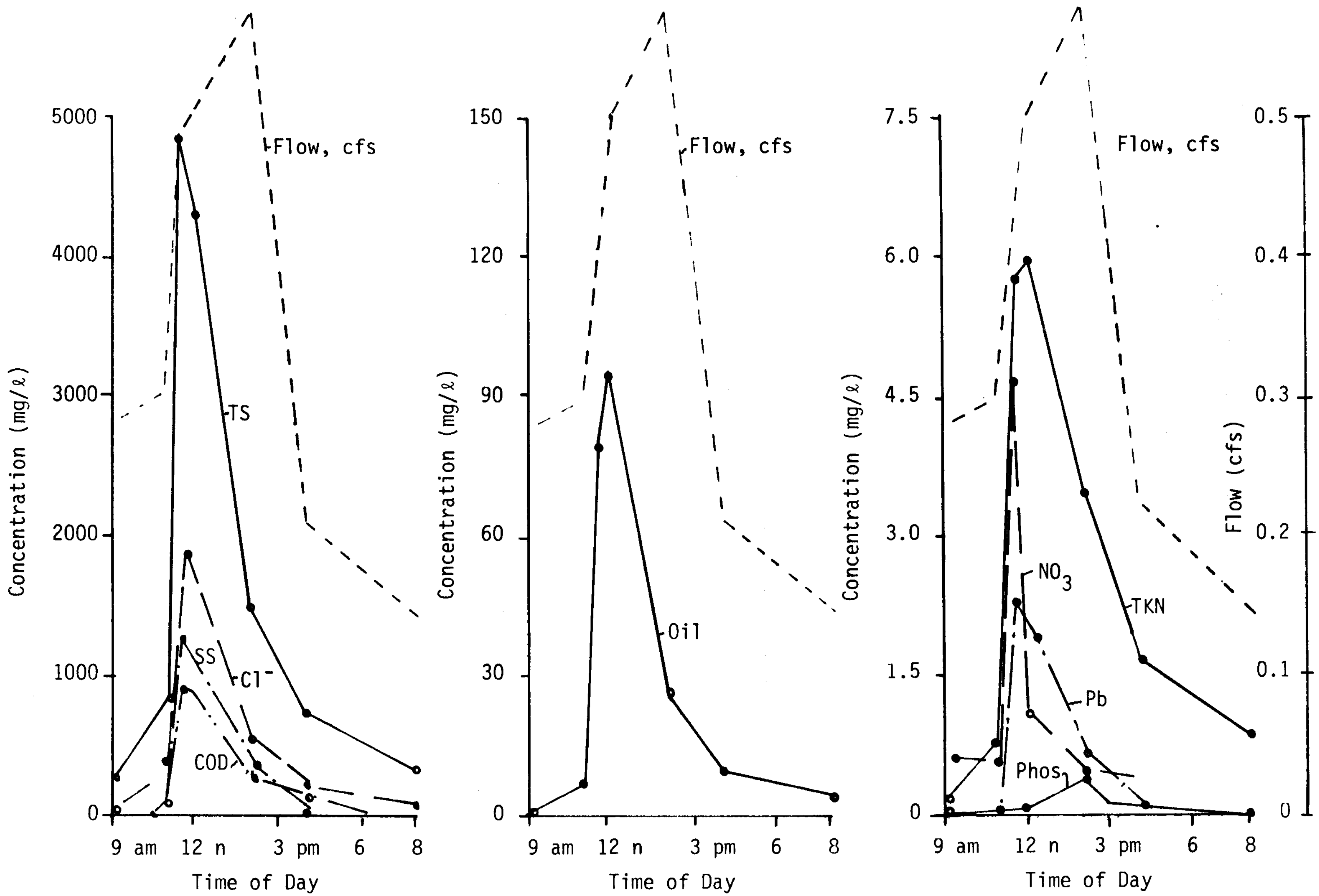


Figure 14. Pollutant Concentration Profiles for Snowmelt of 1-25-76 on the Urban Study Area (snowfall = 3.0 in., precip - 0.06 in.).

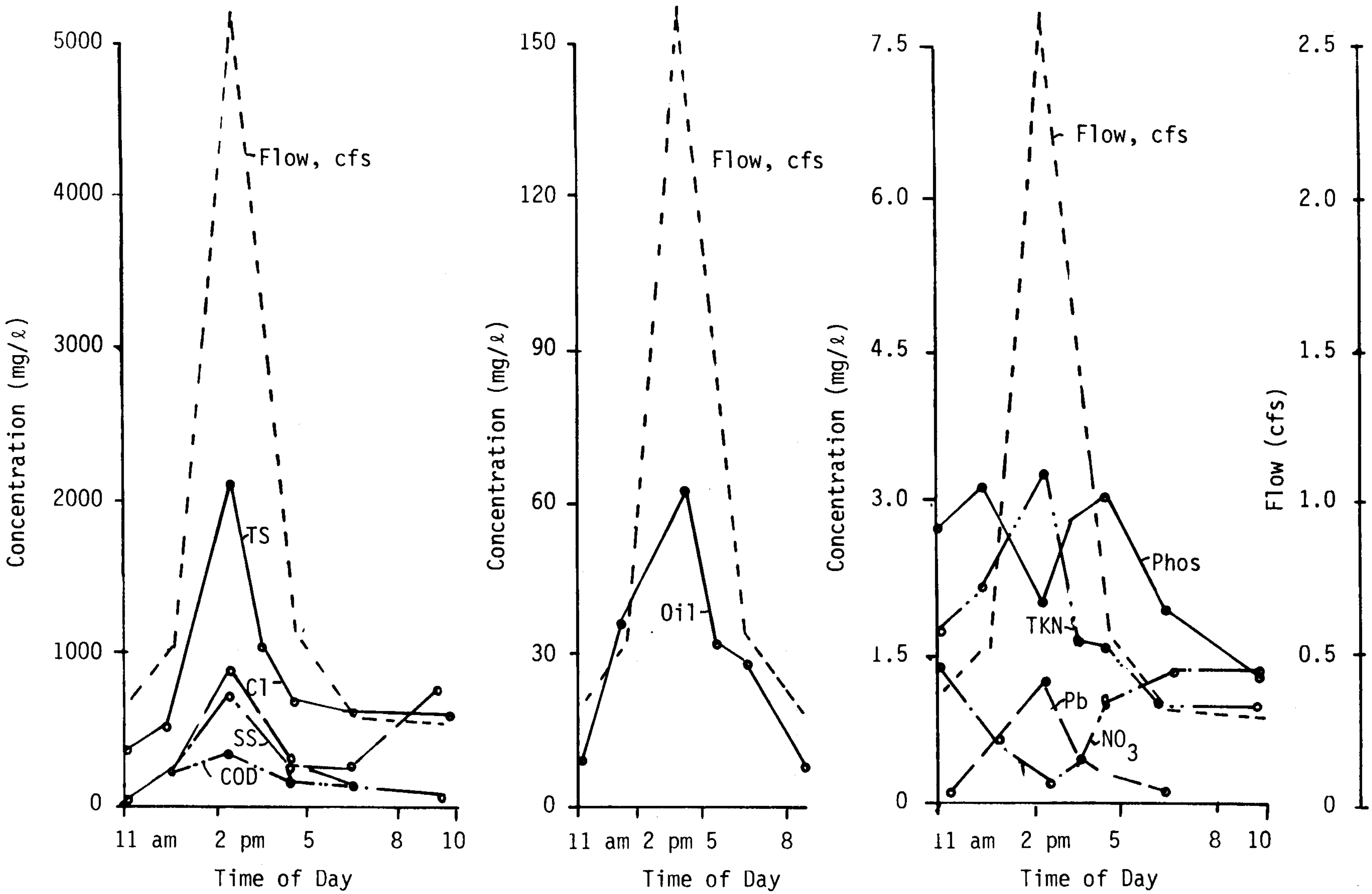


Figure 15. Pollutant Concentration Profiles for the Snowmelt of 3-2-76 on the Urban Study Area (snowfall = 3.8 in., precip - 0.26 in.).

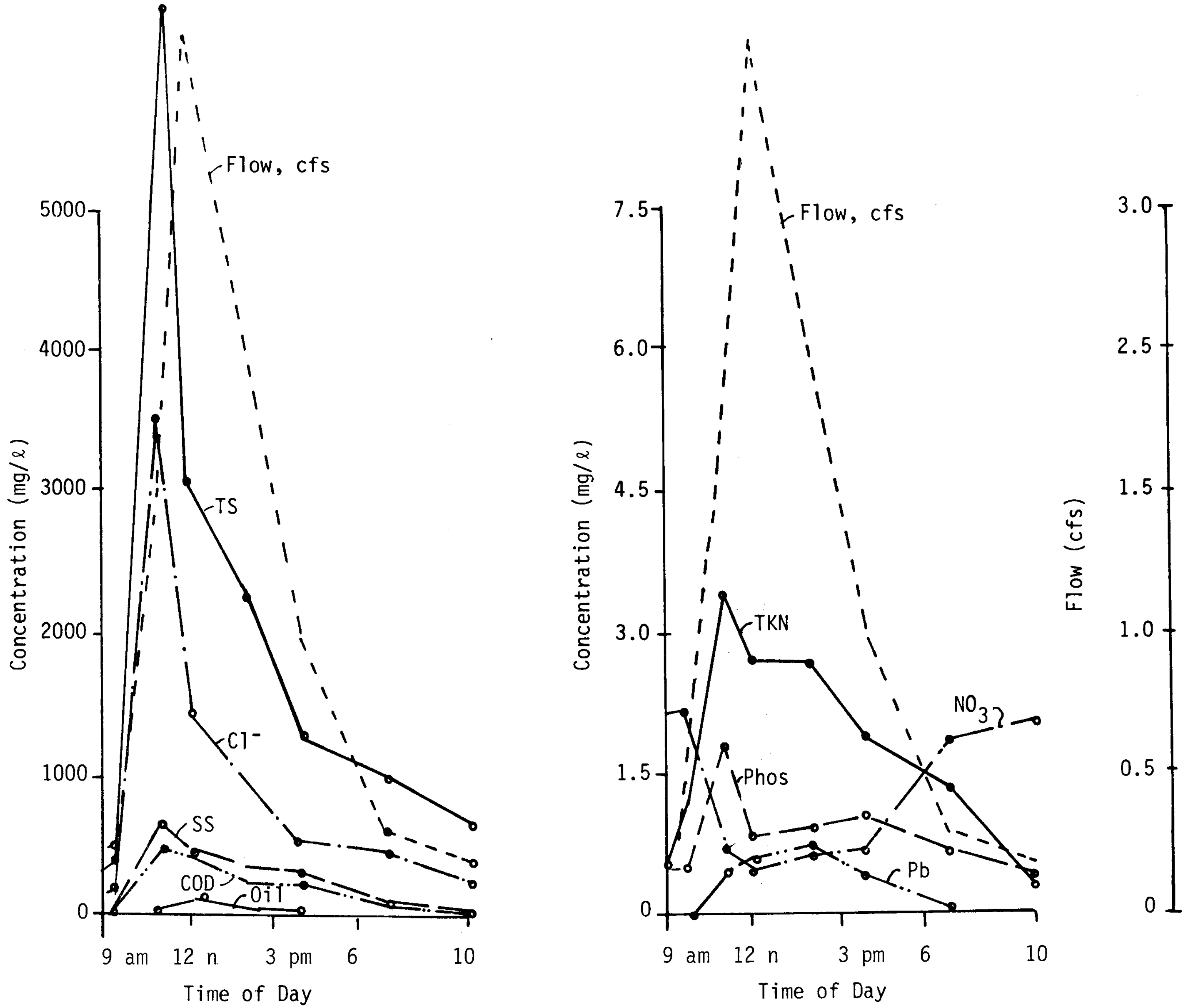


Figure 16. Pollutional Concentration Profiles for Snowmelt of 3-3-76 on the Urban Study Area (snow - 2.6 in., precip - 0.11 in.).

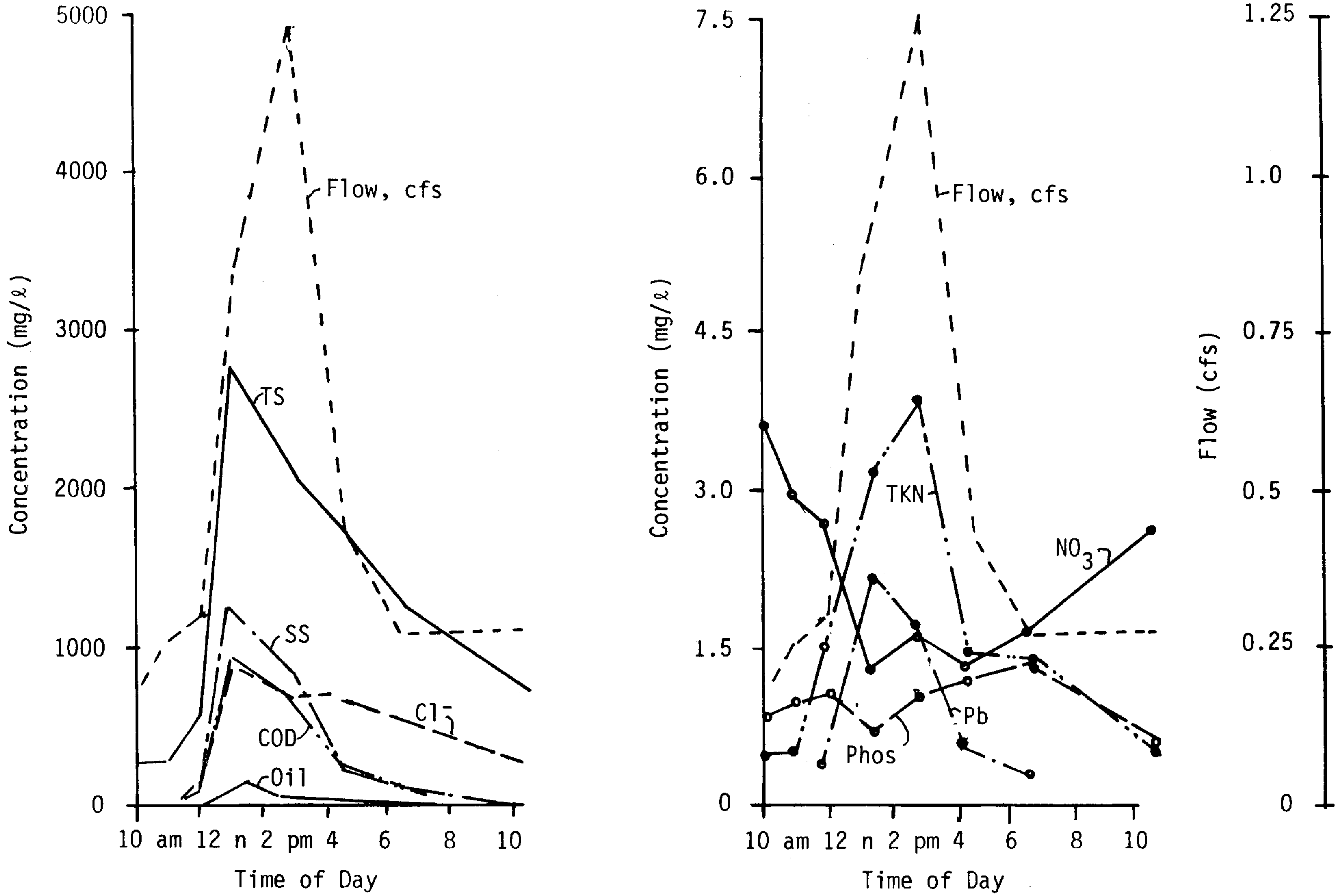


Figure 17. Pollutant Concentration Profiles for the Snowmelt of 3-5-76 on the Urban Study Area (snow = 0 in., precip = 0 in., no new snow).

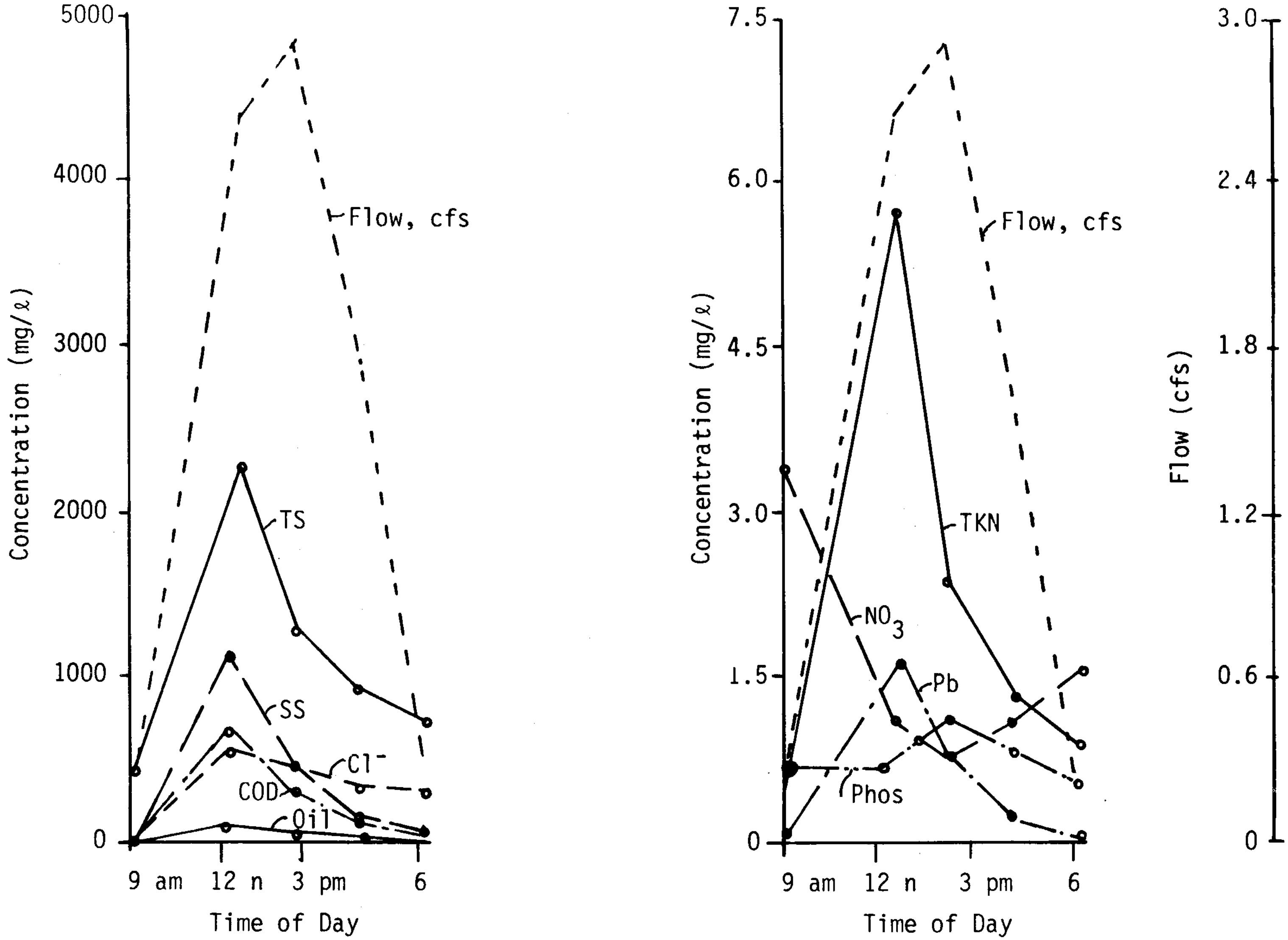


Figure 18. Pollutant Concentration Profiles for the Snowmelt of 3-6-78 on the Urban Study Area (snow = 0 in., precip = 0 in, no new snow).

runoff of 9-9-75 and the snowmelt of 2-20-76 is shown in Figure 19 and 20. The maximum mass flow rate of pollutants coincides with the peak runoff flow rate for all measured constituents for both the rain and snow runoff. There was only one exception, the maximum mass flow rate of suspended solids occurred ahead of the peak discharge. No first flush was observed with pollutant mass flow rate except for this one condition.

It can be noted from the graphs that the mass flow rate of pollutants is greater and occurs over a shorter time period for the rain runoff than for the snow. It is difficult from the curve to compare the total mass of pollutants discharged during a storm event for rain or snow. The total mass of pollutants integrated over the total rainoff period for nine runoff events is given in table 49. The mass of pollutants in the base flow must be accounted in order to establish the amount due solely to the runoff. The mass of pollutant is insignificant for all parameters except total solids and nitrates. Two numbers are presented for total solids. The number in brackets is the total, including base flow and the other number represents the mass with the contribution of base flow subtracted.

The concentration curves shows a dilution effect of the base flow concentration of nitrate due to the runoff. The values shown in the table are the net nitrate mass due to the runoff (total measured nitrate minus that due to the base flow). The snowment nitrate had a net value accountable to the runoff of zero.

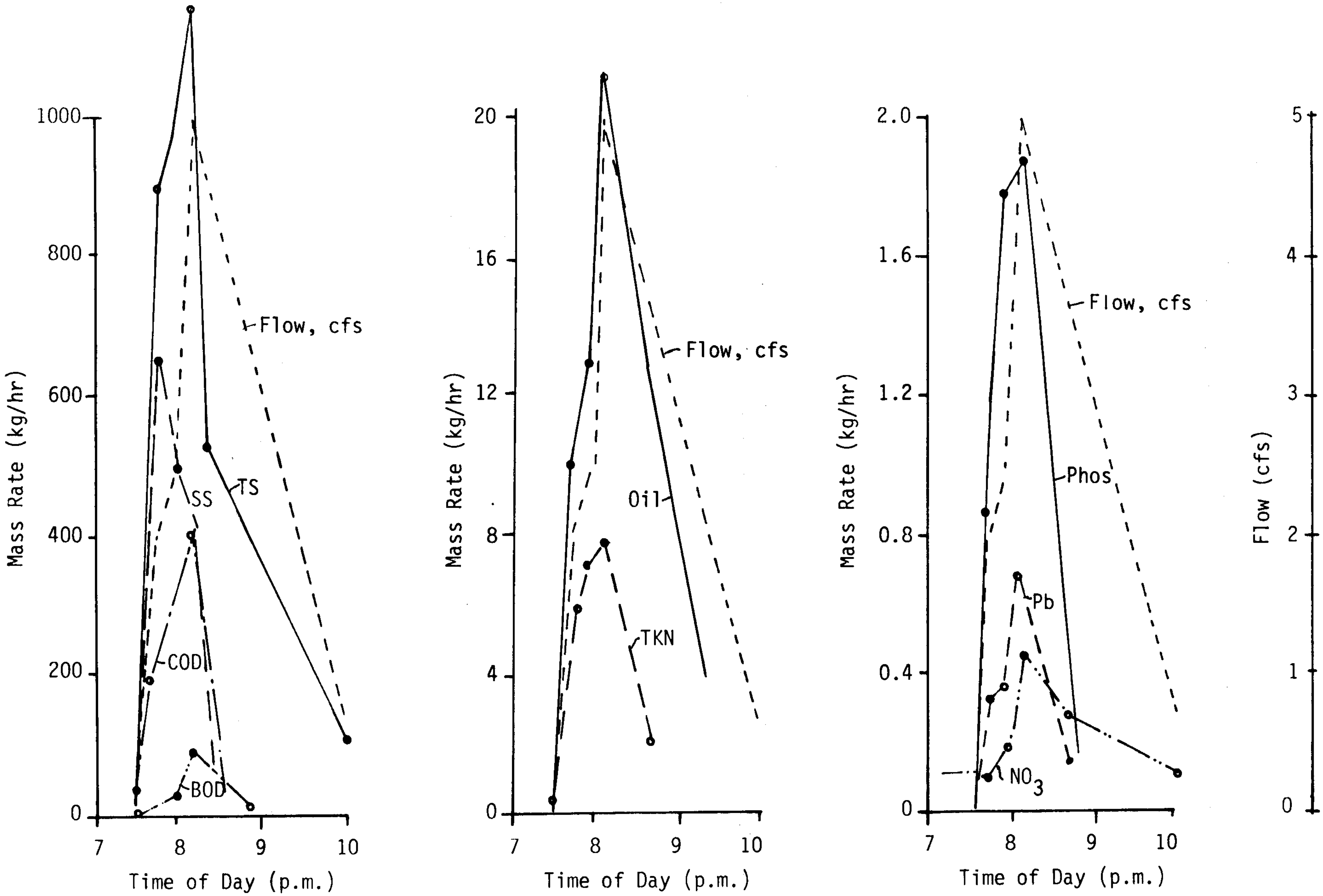


Figure 19. Pollutant Mass Profiles for the Rain of 9-9-75 on the Urban Study Area (precip = 0.12 in.).

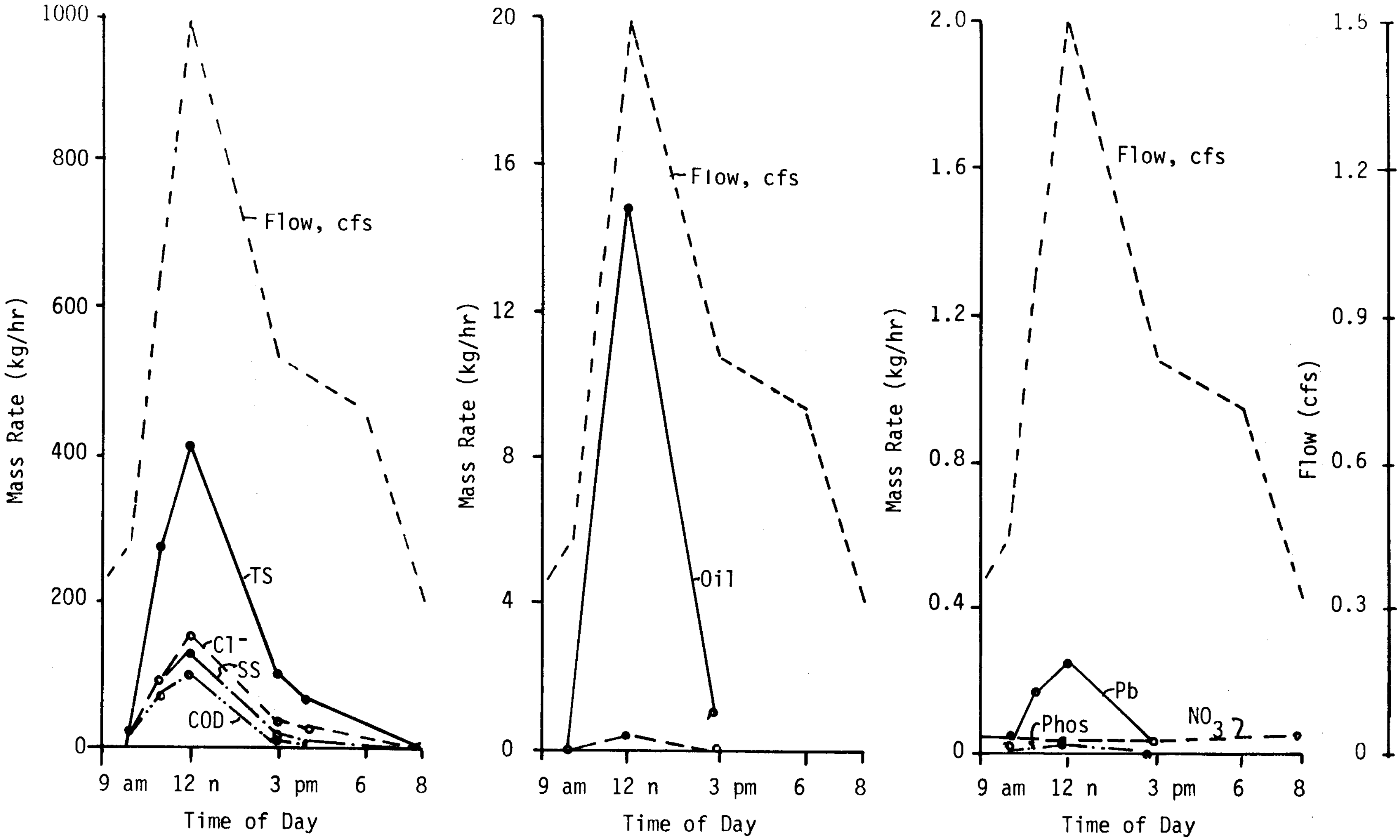


Figure 20 Pollutant Mass Profiles for the Snowmelt of 2-20-76 on the Urban Study Area (snowfall = 4.8 in., precip - 0.27 in.).

TABLE 49

Mass of Pollutants Entering Boulder Creek at Broadway During Storm Events

Date Type	Rainfall Snowfall (Precip)	Volume of Runoff (10^6 ℓ) Tot	w/inf.	Runoff Duration	Runoff Coliforms	Total Pollutant Mass (kg) COD	TS	SS	Cl	NaCl	Oil & Grease	P	TKN	NO_3	Pb
9-9-75 Rain	0.12" 3.05 mm	0.65	0.53	2.67 hr	0.23	362	1090 (1237)	426			22	1.45	6.41	0.45	0.52
2-20-76 Snow (4.8")	0.27" 6.86 mm	0.88	0.67	10 hr	0.13	344	1385 (1465)	434	540	895	42	0.18	2.08	0	0.82
1-18-76 Snow (4.3")	0.35" 8.89 mm	0.74	0.50	11 hr	0.08	188	750 (837)	324	317	522	37	-	1.62	0	0.74
1-15-76 Snow (3.1")	0.06" 1.52 mm	0.36	0.19	9 hr	0.17	111	545 617	113	226	373	11	0.034	0.95	0	0.25
3-2-76 Snow (3.8")	0.26" 6.60 mm	1.12	0.79	15.5 hr	0.27	212	950 1070	310	364	491	33	1.60	1.84	0	0.55
3-3-76 Snow (2.6")	0.11" 2.79 mm	1.43	1.14	13.5 hr	0.27	393	3450 3556	478	1420	2343	120	0.76	3.24	0	0.66
3-4-76 Snow (5.1")	0.33" 8.38 mm	0	0	0	0.27										
3-5-76 Snow	0	0.63	0.32	14.5 hr	0.27	246	890 1007	311	333	550	31	0.26	1.17	0	0.58
3-6-76 Snow	0	1.58	1.39	9 hr	0.27	516	2025 2097	754	647	1068	71	0.47	3.90	0	1.14

Using the pollutant mass values and flows shown in Table 49, the average flow weighted concentrations of Table 50 were developed. Several observations can be made from these data for the comparison of snow and rainfall runoff pollutional data. The range of values for the various snowstorms for COD, total solids, suspended solids and lead was found to extend from below that of rainfall to above, with an average of similar magnitude of slightly less than that of the rain runoff.

The concentration of oil and grease in snowmelt runoff appears to be higher than for rain. The slush on the streets during snowmelt tends to wash the underside of automobiles and this may be responsible for the increased concentration.

The concentrations of the nutrients, phosphorous, Kjeldahl nitrogen and nitrate, in the snowmelt were found to be much lower than that of rain runoff. The melting rate of snow produces a much lower runoff rate than with rain and snowmelt percolates into the soil in vegetated areas, minimizing the run-off from fertilized locations. Snowmelt occurs in the winter when fertilization is not being used. Nutrient concentrations of snowmelt are in the range of one-fourth of that of rain runoff.

The total solids in snowmelt runoff are more variable than with rainfall and are influenced by the amount of deicing chemicals used. Sodium chloride is the chemical used in the study area. Chloride concentrations were measured as a part of the testing program. Since sodium chloride was the deicing

TABLE 50

Pollutant Average Flow Weighted Mean Conc (mg/ℓ)

Date Type	Volume Runoff (10^6 ℓ)	COD	TS	SS	Cl	NaCl	Oil	P	TKN	NO_3	Pb
9-9-75 Rain	0.53	684	2060	805			42	2.74	12.1	0.85	0.98
2-20-76 Snow	0.67	516	2077	651	810	1342	63	0.27	3.12	0	1.23
1-18-76 Snow	0.50	375	1500	648	634	1044	74	-	3.24	0	1.48
1-25-76 Snow	0.19	577	2868	594	1189	1961	58	0.18	5.00	0	1.32
3-2-76 Snow	0.79	269	1206	394	462	623	42	2.03	2.34	0	0.70
3-3-76 Snow	1.14	345	3036	421	1250	2062	106	0.67	2.85	0	0.58
3-5-76 Snow	0.32	767	2777	970	1039	1716	97	0.81	3.65	0	1.81
3-6-76 Snow	1.39	371	1458	543	466	769	51	0.34	2.80	0	0.82
Flow weighted average for snow events		(402)	(2000)	(545)	(770)	(1250)	(69)	(0.66)	(3.96)	(0)	(0.95)

chemical used in the study area, a calculation of NaCl in the runoff was made on a chemical equivalent basis. For the snowmelt data given, the sum of NaCl and the suspended solids concentration was nearly equal to the measured total solids concentration. This indicated that most of the dissolved solids in snowmelt runoff were deicing chemicals. The total solids concentration of snowmelt runoff can be highly variable and is dependent on the amount of street salting practiced during any individual storm.

The rate of snowmelt runoff is not directly related to the precipitation event as it is for rainfall runoff. The snowmelt flow rate is dependent on ambient temperature and sunshine intensity of the day following the snowfall. It is indirectly related to the total amount of snowfall, but the rate on intensity of the snowfall does not affect the flow rate on the pollutional strength of the runoff. Sunlight intensity, ambient air temperature or a combination of the two produces the snowmelt. From the data in the appendix it can be noted that intense sunlight produced the runoff for the days 3-2-76 and 3-3-76. The day 3-6-76 was cloudy with ambient air temperature as high as 42°F resulting in high runoff flows.

A correlation of pollutional loading variables with snowfall precipitation characteristics has been made utilizing the total mass of a pollutant discharged in a day as a function of the volume of runoff for that day. The seven snow runoff days provide a somewhat limited amount of data for this type of analysis, but a clear tendancy can be seen in the relationships. A plot of total daily mass of suspended solids and total Kjeldahl nitrogen transported to the receiving stream as a function of flow volume is shown in Figure 21. The data seems to conform to a linear function as shown. Since a straight line can be fit to the data, the flow weighted mean concentrations for each of the runoff periods should have nearly the same value. It can be seen from Table 50 that this is true, although the scatter is fairly large. The slope of the line in Figure 21 represents a flow weighted mean concentration of suspended solids of 556 mg/ℓ and for TKN a value of 2.78 mg/ℓ. All of the other pollutional parameters provide similar linear plots with runoff volume. This relationship can be used to estimate annual pollutant loadings for a stormsewer system to a receiving stream by using measured precipitation values multiplied by a representative runoff coefficient and a flow weighted mean concentration established from field measurement of the runoff from a few storms.

2. Impact on Boulder Creek

The effect of the stormsewer drainage from the study area on Boulder Creek can be considered on a short term basis during the maximum runoff period of a storm and on a long term basis of annual loadings. The long term effects will be considered in a later section of this report.

Water quality data were measured for Boulder Creek at the same time as the storm sewer was sampled for five runoff events. The results are shown in Table 51. Pollutional loads have been

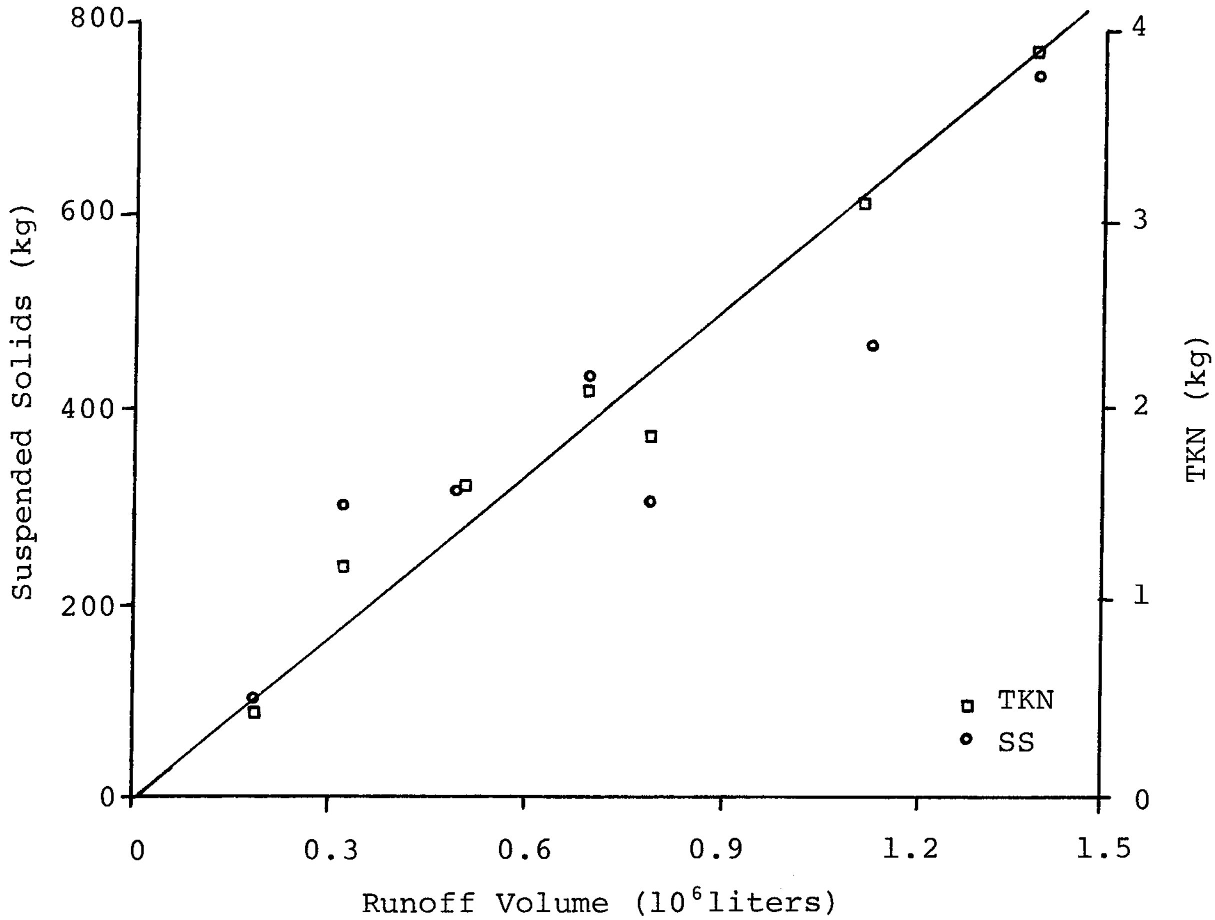


Figure 21. Mass of Pollutants, Suspended Solids and TKN, as a Function of Runoff Volume.

TABLE 51

Instantaneous Pollutional Load Effect of Peak Runoff Flow

Date	Time	Location	Flow (cfs)	COD kg/hr	TS kg/hr	SS kg/hr	Total P kg/hr	TKN kg/hr	Oil & Grease kg/hr	Pb kg/hr	kg/hr
					Rainstorms						
7-5-75	6:55 pm	creek	372.3	680	125,000	409					
	6:50 pm	storm sewer	3.5	226	1,480	97					
7-9-75	8:45 pm	creek	363.4	443	8,810	195					
	8:45 pm	storm sewer	3.1	147	1,153	147					
9-9-75	8:25 pm	creek	18.9	167	1,236	153	0.72	2.08			
	8:10 pm	storm sewer	5.0	406	1,174	414	1.75	7.85			
					Snowstorms						
10-23-75	12 noon	creek	17.8	110	211	93	0.30	1.25	3.0	0.43	
		storm sewer	2.2	41	208	54	0.20	0.66	2.38	0.08	
1-25-76	12 noon	creek	11.7	6.3	208	14.6	0.082	0.4	2.34	0.46	41
		storm sewer	0.5	44	1,693	54	0.006	0.3	4.8	0.10	81

calculated in terms of instantaneous mass flow rate (kg/hr) for each pollutant for the creek and the storm sewer. It can be noted that during the rainstorms in July, the flow in the creek was quite high (363 and 372 cfs) and the storm water flow rate was about one percent of the total flow. The high stream flows were due to irrigation releases from upstream reservoirs and only a minor portion of the flow was due to the storm. The storm sewer contributed COD and suspended solids masses of about one-third of that already in the stream. This increased the stream concentrations by four to six mg/ℓ .

The rainstorm of September 9, 1975 shows a more drastic impact. The irrigation season was over and the stream flow was less than 20 cfs. In this case the storm sewer flow increased the mass of pollutant in the stream by approximately 250 percent (COD concentration increased from 93 to 318 mg/ℓ in the stream). Similar large increases in pollutant mass and concentration increases occurred for the other measured parameters. These data represent the most severe conditions happening at peak flow in the storm sewer and the analysis points out the large instantaneous impact that stormwaters can have on a stream.

The two snow runoff events show an interesting contrast. Mass flows of pollutants in the stream are lower in winter than in summer due to the slow melting of the snow which carries less suspended matter from forested mountain areas into the stream. The snow of October 23, 1975 was a very wet snow falling on warm ground. It melted quite rapidly, carrying pollutants into

Boulder Creek from the wooded areas upstream of the city. The stormsewer discharge increased the streamflow about twelve percent at peak discharge but the pollutants were increased about fifty percent on a mass basis.

The storm of January 25, 1976 occurred during very cold weather. The creek water was very clear and carried a low pollutant load. The light snow melted from the streets due to deicing chemicals and sunlight and contributed pollutant loadings similar to those of the 10-23-75 storm. The stormsewer discharge increased the mass of COD in the stream by a factor of seven. The COD concentration increased from 5 to 41 mg/ℓ. Although these values are small compared to normal summer time concentrations, the impact of the snowmelt is very apparent.

Rainfall runoff has a greater instantaneous effect on the receiving stream than snowmelt because of its rapid runoff period and high peak flows. Snowmelt is released over a longer period of time, with lower flows and pollutant mass discharge rates. The critical conditions for producing high pollutant concentrations in Boulder Creek are produced from high intensity rainfall in the early spring or in the fall when the streamflow is very low.

3. Parameter Loadings

One method of comparing the pollutional effects of precipitation events is based on parameter loading in terms of mass of pollutants for a certain rainfall amount over a unit area. The data of Table 49 have been calculated in this manner and

TABLE 52

Pollutant Loadings

	COD	TS	SS	Cl	NaCl	Oil & Grease	P	TKN	NO_3	Pb
SI System (kg/ha·cm)										
Rain										
9-9-75	16.0	48.2	18.8	-	-	0.97	0.062	0.280	.0017	0.022
Snow										
2-20-76	6.7	27.2	8.5	10.6	17.7	0.82	0.004	0.039	0	0.015
1-18-76	2.4	11.3	4.9	4.8	7.8	0.56		0.023	0	0.011
1-25-76	9.8	48.2	10.0	20.0	33.0	0.97	0.003	0.084	0	0.022
3-2-76 3-6-76	10.3	54.8	13.9	20.8	33.5	1.91	0.023	0.076	0	0.022
Ave. Snow (flow wt)	7.5	38.1	10.4	14.5	23.9	1.33	0.012	0.057	0	0.017
English System (lb/acre·in)										
Rain										
9-9-75	36.2	109	42.6	-	-	2.2	0.14	0.64	0.04	0.005
Snow										
2-20-76	15.2	61.5	19.3	24.0	40.0	1.85	0.008	0.092	0	0.036
1-18-76	5.4	25.5	11.0	10.8	17.7	1.26	-	0.055	0	0.025
1-25-76	22.2	109.0	22.6	45.2	74.6	2.20	0.007	0.190	0	0.050
3-2-76 3-6-76	23.2	124.3	31.5	47.0	75.7	4.33	0.052	0.172	0	0.050
Ave. Snow (flow wt)	17.1	86.2	23.5	32.8	54.0	3.0	0.028	0.13	0	0.040

the results in lbs/acre/in. of precipitation and kg/ha/cm of precipitation are shown in Table 52. The average values can be used to estimate annual pollution contribution of an area based on the precipitation characteristics. The multiple snow storms of 3-2-76, 3-3-76 and 3-4-76 have been considered as a single precipitation event because the snow was on the ground throughout the period 3-2-76 to 3-6-76 and it is impossible to separate the runoff volumes on the basis of individual snowfalls.

It can be noted from the table that pollutant loadings are generally lower for snowmelt than for rainfall. Suspended solids and COD loading for snowfall precipitation are approximately one-half of those for rainfall. Total solids loadings for snow are highly variable and related to the amount of deicing chemicals used. Nutrients such as total phosphorus, total Kjeldahl nitrogen, and nitrate are much lower for snowfall in the range of one-fourth or less than that of rain. The loadings for lead are approximately the same for the two forms of precipitation. Oil and grease loading for snowfall precipitation are higher than for rainfall, probably due to the washing of the undersides of vehicles with the accumulated snow and slush.

C. Suburban Area Runoff Data

This portion of the study was conducted during the period of May, 1976 through February, 1977. During the time period, the Front Range of Colorado was experiencing a rather severe drought. Snowfall was fifty percent below normal and the precipitation events that did occur were in the form of very small storms that melted very rapidly. Small storms falling on dry, warm streets tend to have a very low runoff coefficient due to the fact that a large portion of the moisture is evaporated before reaching the storm sewer system.

Six precipitation events, one rainfall and five snowstorms, were sampled in the characterization studies. The rain event that was sampled resulted in the greatest peak flow rate and had the shortest duration of all the storm events. Because most of the snow storms occurred at night, the figures presented for the average intensity and duration for the snowmelt events are estimates based on National Weather Service data. The precipitation characteristics of the six storms are given in Table 53. Two of the snowstorms were quite small. The base flow in the storm sewer ranged from 0.034 to 0.077 cfs and, as a result, these storms (11/29/76 and 12/31/76) produced very small amounts of runoff.

1. Concentrations

A wide variation of pollutant concentrations was found to exist for the chemical parameters studied during this investigation. The initial pollutant concentrations were largely determined by the baseflow which existed at all times of the day throughout the study period. The pollutional characteristics of this baseflow were as shown in Table 54. The concentrations of the parameters are relatively low except for that of oxidized nitrogen (as measured by the sum of NO_2-N and NO_3-N). This was most likely due to lawn fertilization. As shown in the table,

TABLE 53

Data Collected from Storms That Were Analyzed for Chemical Parameters

DATE OF STORM	DATE OF RUNOFF	TOTAL RAINFALL (inches)	TOTAL SNOW (inches)	TOTAL SNOWMELT (inches)	AVERAGE INTENSITY (in/hr)	DURATION (hrs)	ANTECEDANT DRY PERIOD (days)	STORM SEWER PEAK FLOW (CFS)
9/15/76	9/15/76	.24	0	0	.073	3.27	1	5.31
10/26/76	10/26/76	0	1.8	.84	.071	11.75	8	2.86
11/26-27/76	11/29/76	0	1	.07	.009	7.5	10	.05
12/24-25/76	12/25/76	0	.9	.02	.003	6.0	13	.121
12/29-30/76	12/31/76	0	4.2	.19	.023	8.0	4	.077
2/25/76	2/25/76	0	1.4	.07	.016	4.25	10	.723

TABLE 54

Base Flow Characteristics for All Storms

PARAMETER	CONCENTRATION[1] RANGE	FLOW WEIGHTED MEAN[1]	PARAMETER	CONCENTRATION RANGE	FLOW WEIGHTED MEAN
Flow (CFS)	.034-.077[2]	.05	NO_2-N	.005-.021	.016
Total Solids	236-360	309	Soluble Ortho-P[4]	.014-.034	.020
Total Volatile Solids	69-105.5	83	Soluble Total-P[4]	.014-.04	.022
Suspended Solids	1.25-11.5	8.7	Total-P	.004-.044	.013
Volatile Susp. Solids	1.25-11.5	7.9	Chlorides	9.4-34	19.5
Total Dissolved Solids	297-350	322	Alkalinity	210-272	224
BOD[2]	.8-1.4	1.1	Hardness[5]	240-244	241
COD	0-11	5.8	Oil & Grease[6]	2	2
Soluble COD Fraction[3]	85-100%	95%	Turbidity[7] (JTU)	1-7	-
TKN	0-1.34	.78	pH	7.4-8.3	-
NH_4-N[4]	0-.06	.04	Total Coliform[8] (org/100 ml)	4,000-6,000	-
NO_3-N + NO_2-N	4.44-5.8	4.9	Fecal Coliform[8] (org/100 ml)	597-1,000	-

[1] mg/ℓ unless otherwise noted
[2] Samples taken 9/15/76 & 12/25/76 only
[3] Samples taken 9/15/76, 12/31/76 & 2/25/77
[4] Samples taken 9/15/76 & 2/25/77
[5] Samples taken 11/29/76, 12/25/76, 12/31/76 & 2/25/77
[6] Samples taken 9/15/76, 12/31/76 & 2/25/77
[7] Samples taken 12/25/76, 12/31/76 & 2/25/77
[8] Samples taken 9/15/76, 11/29/76 & 12/25/76

most of this oxidized nitrogen was in the nitrate form. The total dissolved solids, alkalinity, and hardness concentrations were also found to be relatively high and are characteristic of groundwaters. Total and fecal coliform bacteria were also found.

The minimum and maximum pollutant concentrations found in the stormwater runoff are shown in Tables 55 and 56 for the rain generated runoff and the snowmelt runoff events, respectively. In addition to the concentration ranges found, the flow-weighted mean concentrations have been calculated and are also shown. Because the flow rates encountered during the rain generated runoff event were high relative to the baseflow, the pollutants contained in the baseflow were of little significance and were included in the data of Table 55. The flow rates that occurred due to snowmelt runoff, however, were similar in magnitude to those of the baseflow for some of the storms. In this case, the baseflow tended to dilute the pollutants contained in the runoff waters. Therefore, the baseflow pollutant contributions of flow and strength were subtracted from the total in calculating the values in Table 56 in order to accurately evaluate the pollutants contained in the snowmelt runoff.

Figures 22 and 23 show pollutant concentrations as a function of time for the rainfall event and the largest of the snow storms. The data for each of the storms is given in Appendix B. It can be noted that the concentration curves are similar to those of the urban area except that the magnitude of the peak concentrations is significantly lower for the suburban

TABLE 55

Pollutional Characteristics of the Rain Generated Runoff of 9/15/76

PARAMETER	CONCENTRATION RANGE, (mg/ℓ)	FLOW WEIGHTED MEAN (mg/ℓ)	PARAMETER	CONCENTRATION RANGE, (mg/ℓ)	FLOW WEIGHTED MEAN (mg/ℓ)
Total Solids	96-675	236	TKN	0-2.8	2.0
Total Volatile Solids	42-186	-	NH_4-N	.007-.029	.026
			NO_3-N	.76-4.44	1.10
Suspended Solids	11.5-463	179	NO_2-N	.005-.14	.072
Volatile Susp. Solids	11.5-123	-	Soluble Ortho-P	.001-.021	.019
			Soluble Total-P	.018-.054	.048
Total Dissolved Solids	303-26	77	Total-P	.018-.14	.121
BOD	0.8-48.5	18	Oil & Grease	1.76-18.6	8.4
COD	3.2-295	123	Chlorides	15.0-2.5	4.5
Soluble COD	3.2-101.6	43	Alkalinity	272-20	45
Total Coliform (org/100 ml)	4,300-1,008,000	-	pH	8.3-6.6	-
Fecal Coliform (org/100 ml)	300-268,000	-			

TABLE 56

Pollutional Characteristics of the Snowmelt Runoff from the Suburban Area

Parameter	Concentration Range (mg/ℓ)	Flow Weighted Mean (mg/ℓ)
Total Solids	117-1548	165[a]
Total Volatile Solids	42-305	75[a]
Suspended Solids	0.5-554	81[a]
Volatile Suspended Solids	0.5-150	19[a]
BOD	6.7-17.9	9[a]
COD	4-388	54[a]
TDS	55-1403	84[a]
Total Coliforms (org/100 ml)	3000-100,000[c]	
Fecal Coliforms (org/100 ml)	0-33,000[c]	
TKN	0.15-4.42	2
NH_4^+-N	0-.43	0.12
NO_3+NO_2	0.11-5.8[b]	*
NO_2	0.021-0.13[b]	0.066
Soluble Ortho-P	0-0.014[b]	0.001
Soluble Total-P	0.002-0.004	0.003
Total-P	0.002-0.061	0.017
Oil & Grease	1.91-25.9	4.5[a]
Chloride	1.5-693	*
Alkalinity	12-222	10[a]
Hardness	18-224	29[a]
pH	6.6-8.2	-
Turbidity (JTU)	1-100	29[d]
Phenols	0-12	0.002[e]

[a]One storm only (10/26/76)

[b]Two storms only (10.26/76 and 2/25/77)

[c]Three storms only (10/27/76, 11/29/76 and 12/24/76)

[d]Time weighted mean

[e]One storm only (12/25/76)

*Total measured mass of pollutant $\leq$ amount expected from baseflow.

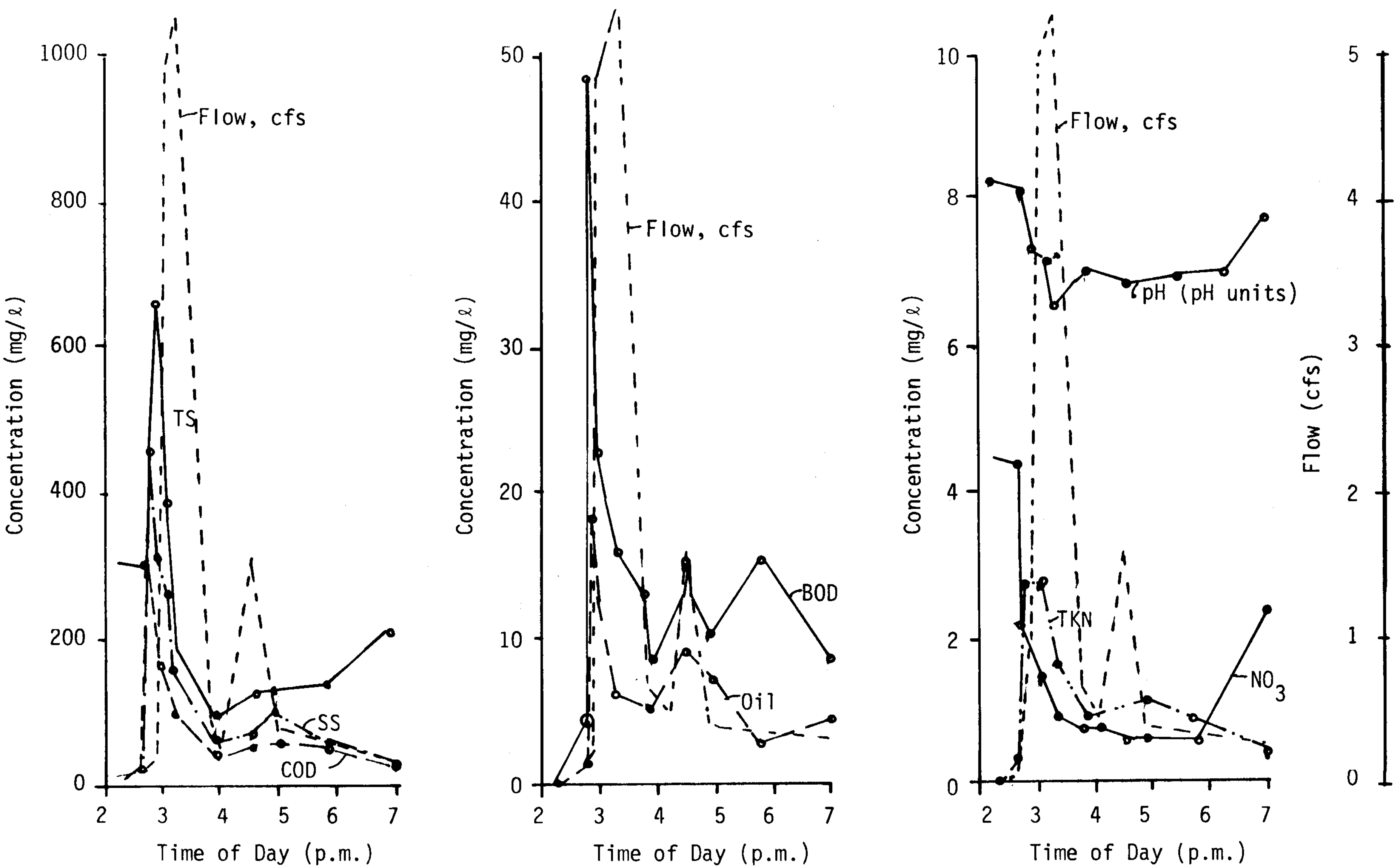


Figure 22. Pollutant Concentration Profile for the Rain of 9-15-76 on the Suburban Study Area (precip - 0.24 in.).

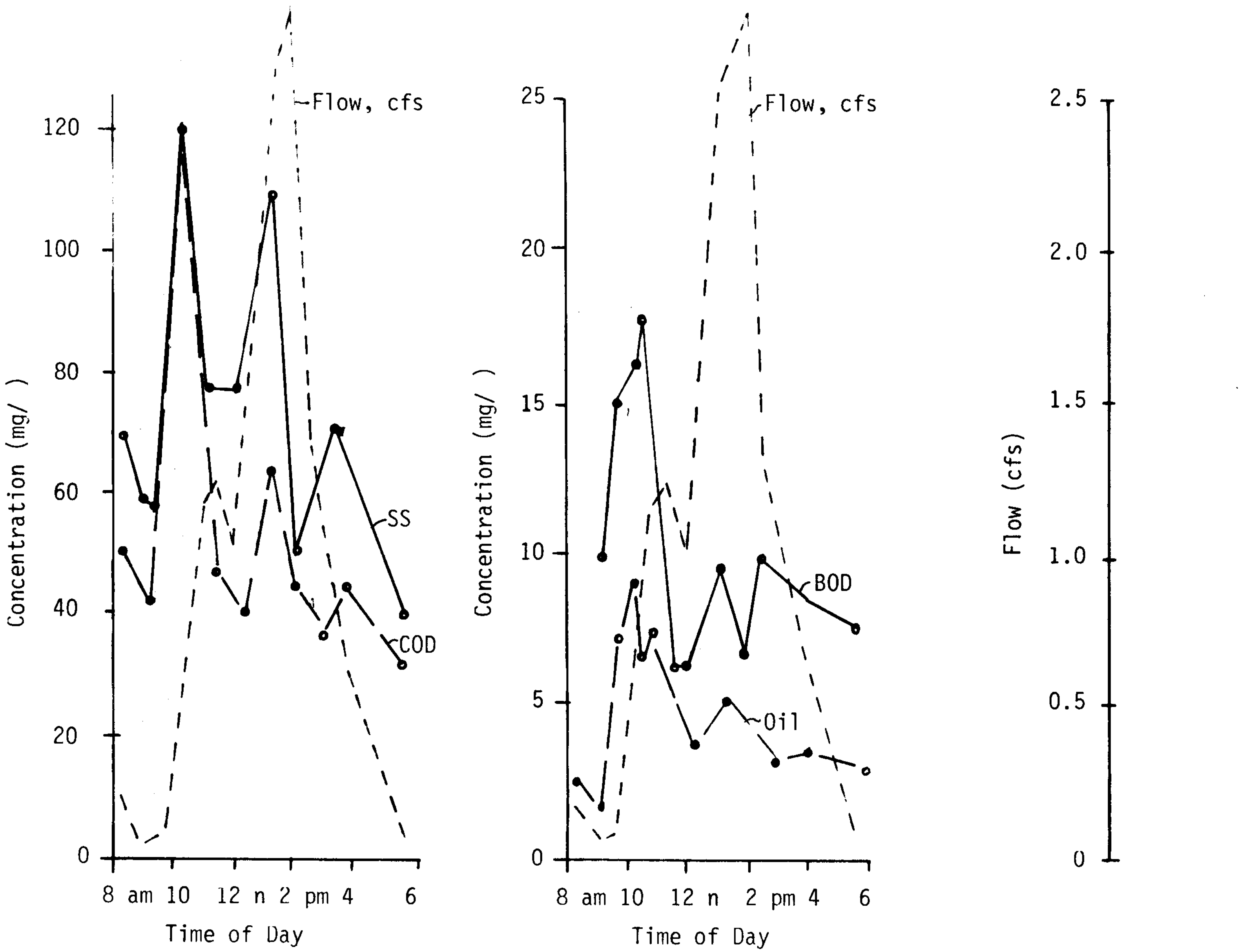


Figure 23. Pollutant Concentration Profiles for the Snowmelt of 10-26-76 on the Suburban Study Area (snow - 1.8 in., precip - 0.84 in.).

area. The first flush effect on concentration is apparent but as shown with the urban area studies, the maximum mass flow of pollutants corresponds with the maximum discharge.

Analyzing the data in Appendix B shows that for some of the pollutants, the concentration in the baseflow was higher than that of the runoff. For this condition, the minimum concentration in the stormwater pattern occurred at the time of maximum discharge. This type of curve was shown for pH, nitrate, alkalinity, and hardness for the rain and snow events. The dilution type curve also resulted for chlorides during the rainstorm and for total and dissolved solids after the initial flush had occurred.

Precipitation absorbs pollutants from the air while it is falling. In order to evaluate the amount of pollutants from this source, several samples were taken of rain and snow by allowing the precipitation to fall into a clean container. In this way undisturbed samples were obtained. The results of these measurements are given in Table 57.

During the course of the snowmelt runoff events it was observed that a significant amount of snow and melt water was kicked up from the road surface and frozen on the undercarriages of moving automobiles. As these ice deposits melted and fell from the automobiles, the associated pollutants were deposited on the road surface.

The analysis of the melt water from such an ice deposit revealed the constituent concentrations shown in Table 58. The melt water was extremely high in COD, total and suspended solids,

TABLE 57

Undisturbed Rainfall and Snowfall Quality Data

	Concentration (mg/ℓ)			
Parameter	5/21-22/76 Rain	4:00 pm 5/23/76 Rain	7:00 pm 5/23/76 Rain	10/26/76 Snow
COD	20.5	17.5	8.95	10.4
Ortho-P	.037	.06	.01	-
Total-P	.04	.06	.042	
NH_4-N	.33	1.28	.62	0.023
NO_3-N	.84	-	-	0.15
TS	21	142	162	86.5
TVS	12	22	53	41
SS	18.8	6.8	2.5	16
VSS	6.1	1.2	2.5	9.5
TKN	.61	-	-	0.19
Soluble COD	-	-	-	7.1
NO_2	-	-	-	0
Hardness	-	-	-	2
Alkalinity	-	-	-	11.2
pH	-	-	-	5.3

TABLE 58

Chemical Properties of Melt Water from Ice That Has Been Frozen to the Undercarriage of an Automobile

COD	= 4,382 mg/ℓ
Alkalinity	= 96 mg/ℓ $CaCO_3$
Hardness	= 200 mg/ℓ $CaCO_3$
pH	= 6.88
TKN	= 15.12 mg/ℓ
TS	= 14,484 mg/ℓ
TVS	= 2,580 mg/ℓ
SS	= 11,635 mg/ℓ
VSS	= 2,290 mg/ℓ
TDS	= 2,849 mg/ℓ
ClO	= 1,050 mg/ℓ
Oils & Greases	= 825 mg/ℓ

Sample taken during storm of 11/27/76

and oils and greases. It was noticed that the volume of this redistributed material was relatively small, which suggests that the redistribution of pollutants by this phenomena is most likely of minor significance. The large pollutant concentrations found, however, indicate that washing of pollutants from automobiles may be significant.

2. Pollutant Loadings

The storm sewer runoff data has been presented in terms of pollutant concentrations and their variations. To show the significance of a stormwater problem, however, it is valuable to evaluate pollutant loadings.

By calculating the total pounds of pollutants discharged in each runoff events, the pollutant loadings in pounds of pollutant per inch of precipitation per acre of drainage area (kg/ha/cm) were determined. These data are presented in Table 59 and include the pollutant contributions due to the baseflow. The variations that occurred from storm to storm are very apparent.

D. Mountain Watershed Runoff Data

Eight storms were sampled and analyzed over the period August 1976 through June of 1977. Three snowmelt events were studied and analysis of the data showed a very low runoff coefficient (less than 0.01) and high quality runoff water. The highly pervious soil materials and the slow runoff conditions produced by snowmelt resulted in runoff quality that was essentially the same as that for undisturbed samples collected in a clean pan. BOD concentrations were in the range of 1 to

TABLE 59

Pollutional Parameter Loadings of the Suburban Study Area

Rain	Precip (in)	COD	BOD	TS	SS	Total P	TKN	Oil & Grease	Cl^-	NO_3-N
				kg/ha/cm of Precipitation						
9/15/76	0.61	1.24	0.22	2.33	1.89	0.0013	0.022	0.093	0.062	0.00
Snow										
10/26/76	2.14	0.45	0.08	1.52	0.66	0.0004	0.004	0.044	0.031	0.00
11/29/76	0.18	0.04	-	1.33	0.00	0.0001	0.004	-	0.212	0.02
12/25/76	0.05	2.03	-	12.46	0.80	0.0002	0.048	-	3.943	0.12
12/31/76	0.48	0.19	-	1.94	0.18	0.0000	0.004	0.017	0.738	0.01
2/25/77	0.18	5.75	-	23.1	7.47	0.009	0.075	0.402	6.895	0.04
ave. snow (precip wt)		0.72	0.08	3.00	0.95	0.0004	0.008	0.053	0.619	0.0075
				lb/acre/in of Precipitation						
Rain										
9/15/76	0.24	2.81	0.5	5.28	4.27	0.003	0.05	0.21	0.14	0.0
Snow										
10/26/76	0.84	1.02	0.18	3.4	1.5	0.0010	0.01	0.10	0.07	0.00
11/29/76	0.07	0.09	-	3.0	0.0	0.0002	0.01	-	0.48	0.04
12/25/76	0.02	4.59	-	28.2	1.8	0.0007	0.11	-	8.92	0.27
12/31/76	0.19	0.43	-	4.4	0.4	0.0000	0.01	0.04	1.67	0.02
2/25/77	0.07	13.0	-	52.2	16.9	0.0020	0.17	0.91	15.6	0.10
ave. snow (precip wt)		1.63	0.18	6.8	2.15	0.0008	0.02	0.12	1.40	0.017

2 mg/ℓ, COD and suspended solids of 20 mg/ℓ, total solids from 100 to 400 mg/ℓ, total and fecal coliforms less than 10 organisms/100 ml and very low concentrations of nitrate (<0.2 mg/ℓ), NH_4^+-N (<0.02 mg) and phosphorus (<0.001 mg/ℓ).

Four of the rain events sampled were low intensity storms. Each of these storms had a very low runoff coefficient (<0.01) and produced a very high quality runoff water of approximately the same chemical concentrations as the snowmelt and undisturbed pan samples.

It is apparent that only high intensity rainstorms result in significant pollution to the receiving stream. One storm of this type was sampled, the rain of 6/11/77. This was a brief storm of 0.07 inch precipitation but with intensity approaching one inch per hour. The data for this storm is shown in Table 60. Concentration profiles of the significant pollutants are presented in Figure 24.

Pollutional characteristics of runoff from mountain watersheds is dependent on many factors. One of the most important is rainfall intensity and amount. The rainfall intensity must be great enough to cause erosion of the soil particles in order for significant pollution to result. This study was conducted during a drought period and it was not possible to establish the relationship between rainfall intensity and pollutional load.

The loadings in pounds/acre/inch of precipitation concentration ranges and flow weighted concentrations given in Table 61 are based on the single rainstorm of 6-11-77.

TABLE 60

Pollutional Characteristics of the Mountain Watershed Rain of 6-11-77
(Precipitation 0.07 Inches)

Time	Flow (cfs)	BOD	COD	Coliform		NO_3	NO_2	NH_3	TKN	Phos	TSS	VSS	TS	TVS	Temp °F	pH	Turb
				Total	Fecal												
1515	.030	1.6	28.2	443	2,710	.074	.006	.010	0.96	0.10	50	36	129	77	60	7.7	18
1525	.180	6.6	40.4	14,800	12,300	.065	.010	.001	1.37	0.56	308	70	268	154	50	7.6	58
1531	.700	3.9	407.8	TNTC	12,300	.043	.008	.005	8.92	0.10	3,012	392	2,875	395	59	7.3	>1000
1545	.450	1.8	166.9	13,700	2,445	.296	.014	.002	7.31	0.60	2,284	240	2,846	345	55	7.1	>1000
1630	.140	2.7	45.0	4,210	830	.420	.015	<.001	1.97	0.55	584	88	733	113	56	7.4	250
1740	.020	2.5	20.6	1,278	703	.065	.015	<.001	0.74	0.5	77	22	168	90	58	7.9	40

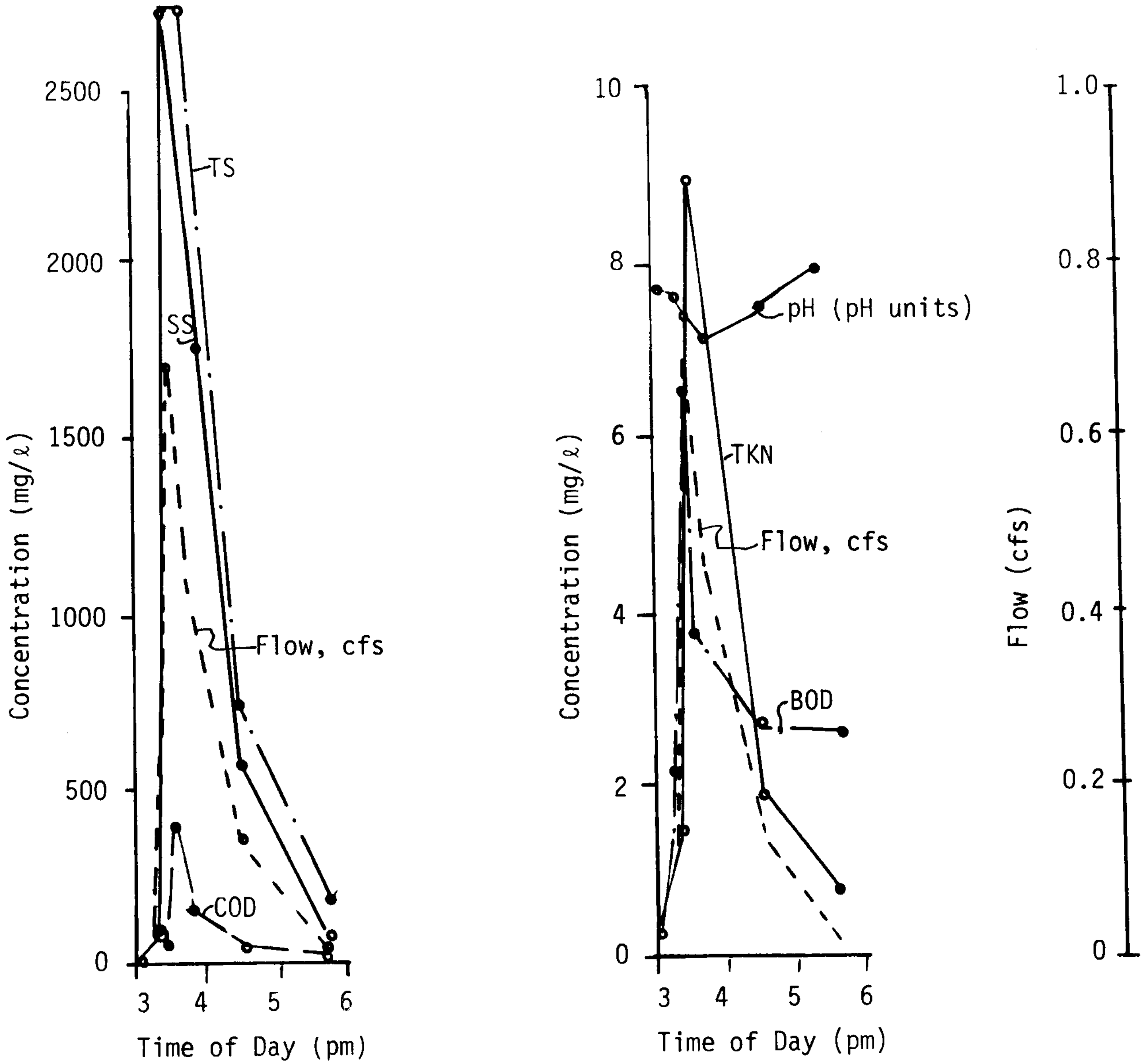


Figure 24. Pollutant Concentration Profiles for the Rain of 6-11-77 on the Mountain Watershed (rain = 0.07 in.)

TABLE 61

Flow Weighted Mean Concentration and Loadings for the Runoff from the Mountain Watershed for the Rain of 6-11-77

Precip = 0.07 inch, Runoff Coef = 0.06, Volume = 2000 ft^3

Parameter	Concentration Range, mg/ℓ	Flow Weight Mean Conc. mg/ℓ	Loading	
			lb/acre/inch	kg/ha/cm
COD	296-407.8	148	2.1	0.93
BOD	1.6-6.6	2.8	0.04	0.018
NO_3	0.065-4.2	0.24	0.0034	0.0015
NH_4^+	0.001-0.01	0.0016	0.00002	0.000009
TKN	0.74-8.92	4.86	0.068	0.03
P	0.10-0.6	0.48	0.007	0.003
Sus. Solids	50-3012	1536	21.6	9.55
Tot. Solids	129-2875	1752	24.5	10.83

E. Agricultural Watershed Runoff

The agricultural watershed was observed during several rain and snow storms. Even during the most intense rain events, no runoff was observed. The reason for this was the high infiltration capacity of the soil and the fact that the farmer had plowed and furrowed the soil to capture as much precipitation as possible. The study area was an irrigated field that was prepared to hold several inches of water at each application. It would require an extremely large rain or snow storm to exceed the holding capacity of the field. Several other irrigated and dryland farming areas were observed during storm events and the same conditions existed. No runoff was observed from any of the prepared fields during the period of observation.

These preliminary results indicate that stormwater runoff pollution from agricultural fields in semi-arid areas, such as eastern Boulder County, is small and much less significant than that of developed areas.

SECTION 5

SUMMARY OF RUNOFF POLLUTION STUDIES

Analytical results have been presented for rain and snowmelt runoff data for an urban area and a suburban location as well as rainfall runoff data for a high intensity storm on a mountain watershed.

The results of the studies are listed together in Tables 62, 63 and 64. The pollutant concentration data of Table 62 show a wide range of values under each of the conditions. The results of the study show the differences that exist for runoff from various land use types. These relationships are quite general. It will require a very large study of many storms under a wide range of conditions to establish functional relationships between hydrologic, land use and pollutional parameters. A large number of measurements, taken with automatic samples in a matrix of testing locations throughout the nation, will be needed to accurately establish the role of stormwater in the total water pollution assessment program. Such a study is being initiated by the U.S. Geological Survey.

The flow weighted average concentrations of Table 63 show that rainfall runoff has a greater impact on a receiving stream than snowmelt and that the more urbanized areas generate significantly more stormwater pollutants than less developed locations.

The comparison of mass loadings in Table 64 shows that relatively low loadings of nutrients and organics are associated

TABLE 62

Comparison of Concentration Ranges
(mg/ℓ)

	Urban		Suburban		Mountain
	Rain	Snow	Rain	Snow	Rain
COD	8.6-1557	8.2-936	0.8-485	4-388	296-408
TS	1190-7830	245-6492	96-675	115-1548	129-2875
SS	24-3730	1-1229	11-463	0.5-554	50-3012
Oil & Grease	8.9-56.5	95-155	1.7-18.6	1.9-25.9	-
P	0.2-7.0	0.6-3.34	.018-.14	.002-.061	0.1-0.6
TKN	1.7-3.7	.22-5.44	0-2.8	.15-4.42	0.74-8.92
NO_3	0.3-2.2	.17-4.70	0.76-4.44	.11-5.8	0.065-4.2
NH_4^+	-	-	.007-.029	0-.43	0.001-0.01

TABLE 63

Comparison of Flow Weighted Means
(mg/ℓ)

	Urban		Suburban		Mountain
	Rain	Snow	Rain	Snow	Rain
COD	684	402	123	54	148
TS	2060	2000	236	165	1752
SS	805	545	179	81	1536
Oil & Grease	42	69	8.4	4.5	-
TKN	12.1	2.96	2	2	4.86
NO_3	0.85	0	1.1	0	0.24
P	2.74	0.66	.121	.017	0.48
Pb	0.98	0.95	-	-	-
NH_4	-	-	0.026	0.12	0.0016

TABLE 64

Comparison of Mass Loadings (lb/acre/inch)

	Urban		Suburban		Mountain
	Rain	Snow	Rain	Snow	Rain
COD	36.2	17.1	2.81	1.63	2.1
TS	109	86.2	5.28	6.8	24.5
SS	42.6	23.5	4.27	2.15	21.6
Oil & Grease	2.2	3.0	0.21	0.12	-
TKN	0.69	0.13	0.05	0.02	0.068
NO_3	0.04	0	0.0	0.017	0.0034
P	0.14	0.028	0.003	0.0008	0.007
Pb	0.05	0.04	-	-	-
NH_4^+	-	-	-	-	0.00002

with suburban areas and uninhabited mountain watersheds. The loadings for the two types of areas were very similar. Total and suspended solids loadings were higher for the mountain watershed because the intensity of rainfall was great enough to produce some erosion of mineral matter.

The urban area showed much higher loadings in all categories. From these results, it is apparent that treatment of storm runoff may be important only for highly developed areas and that each outfall must be evaluated to establish if the runoff has a substantial impact on a receiving stream.

Snow runoff loadings are lower than those for rainfall for the urban and suburban areas, significantly lower for the nutrients, nitrogen and phosphorus. Low intensity storms on mountain watersheds and nearly all storms on agricultural areas seem to have zero or minimal runoff and therefore do not impact the stream.

One method for assessing the relative impact of stormwater pollutant loadings is to compare the annual contribution of this source with that of the treated municipal sewage effluent for the same population as that of the stormwater study area. The urban study area contained 183 acres and had a population density of 25 persons per acre, on a total calculated population of 4575. The suburban area contained 125 acres at an estimated density of 12 persons per acre on 1500 population. Records from the Boulder wastewater treatment plant were used for secondary effluent quality and the average flow was estimated from in-plant flow recorders to be 140 gallons per person per day. Average precipitation for Boulder, based on NOAA records is 18.8 inches of which two-thirds falls as rain and one-third as snow. A comparison of the sources for the two areas is shown in Table 65.

It can be seen from this comparison that the contributions of nutrients, nitrogen and phosphorus, are relatively small for stormwater flows. The contributions of organic pollutants and suspended matter from stormwater are significant and become extremely important for highly developed areas. Any considerations for sewage treatment plant improvements must include the impact of stormwater on overall stream quality. Instantaneous shock loadings of pollutants from storm sewers during a storm are much greater than pollutant levels from wastewater plant effluents.

TABLE 65

Comparison of Pollutants on an Annual Basis

Parameter	Assumed Secondary Effluent Concentration, mg/ℓ	Annual Secondary Effluent Load (lbs)	Annual Stormwater Load (lbs)	% of Total	
				Effluent	Stormwater
		URBAN AREA			
COD	70	134,470	102,638	56.7	43.3
TS	350	672,350	348,810	65.9	34.1
SS	20	38,420	124,642	23.6	76.4
Total-P	8	15,368	354	97.8	2.2
TKN	20	38,420	1,730	95.7	4.3
Flow	-	-	-	71.5	28.5
		SUBURBAN AREA			
COD	70	44,088	5,670	88.5	11.5
TS	350	220,530	9,470	95.6	4.4
SS	20	12,600	8,360	60.0	40.0
Total-P	8	5,040	5	99.9	0.1
TKN	2.0	12,600	94	99.3	0.7
Flow	-	-	-	54.6	45.4

The annual loading of pollutants to a stream are of the same or greater magnitude for stormwater as compared with secondary treated effluent, for highly developed areas. There is a wide variation in stormwater pollutant loadings from different types of land use areas. Individual sampling of stormwater outfalls will be necessary to establish the relative significance of each discharge to the overall stream pollution problem.

One of the initial objectives of the study was to assess the relative importance of all of the discharges on a receiving stream; in this case, the discharges on Boulder Creek from its origin to a point downstream of the 75th Street Wastewater Treatment Plant. The great variation found in stormwater quality from different land use types and the undefined relationship between storm intensity and mountain watershed runoff quality introduces factors that makes it unjustified to attempt a quantitative analysis based on this limited study. To make such a study would take a large and very expensive effort using automatic samplers at all discharge points over an extended period of time.

It is obvious that stormwater pollution from the stormsewers of the City of Boulder is a significant source of pollution to Boulder Creek and that imposing much higher effluent standards on the wastewater treatment plant for organics or suspended matter would not be justified unless a very extensive study of stormwater pollutant sources were made and treatment plans included at least the most significant stormwater sources. This situation would appear to exist for all communities.

On the other hand, stormwater was not found to contain significant concentrations of nutrients compared to sewage effluents. If the pollution abatement plan is based on reducing nutrients or un-ionized ammonia, tertiary sewage treatment methods could accomplish the result of markedly changing stream quality with respect to these pollutants.

The high coliform counts for pathogen indicator organisms in stormwater brings into question the use of very stringent requirements for disinfection levels in sewage treatment plants.

SECTION 6

TREATABILITY EVALUATIONS OF STORMWATERS

The purpose of this portion of the study was to evaluate the effectiveness of several processes for the treatment of storm sewer discharges. Plain sedimentation, chemical clarification using alum, lime, and ferric chloride, and filtration through a soil media where the processes examined.

The samples collected from the suburban study area for treatment analyses were highly variable in pollutional characteristics, as shown in Table 66. This was a result of the variable nature of the storm sewer discharges, and was desirable since any treatment process must be effective over a wide range of pollutant concentrations. With the exception of the rain generated runoff, an attempt was made to collect samples at the time of peak pollutant concentrations, when treatment would be most difficult.

A. Plain Sedimentation

The effectiveness of plain sedimentation was highly dependent upon the nature of the individual stormwater samples. Figures 25 and 26 show the variation in suspended solids and turbidity for the samples taken during the snowmelt event of 2/25/77 and the rainfall event of 9/15/76. The trends shown in these figures are typical of the results found in each of the runoff events sampled, although the exact removal efficiencies varied.

TABLE 66

Pollutant Characteristics of Samples Taken for Treatment Studies[a]

RUNOFF DATE	RUNOFF TYPE	TOTAL SOLIDS	TVS	SS	VSS	TDS	COD	SOLUBLE COD	TURBIDITY (JTU)	pH UNITS	ALKALINITY
9/15/76	Rain	208	65	186	103	22	91.2	42.4	34	6.90	50
10/26/76	Snow-melt	227	75.5	93	31.5	134	88.6	43.8	54	6.50	48
12/31/76	Snow-melt	1562	103	125.7	111.4	1437	120	33.3	54	7.68	172
2/25/77	Snow-melt	1000	256	300	102	700	318.8	-	80	7.20	40

[a]Concentrations in mg/ℓ unless otherwise noted.

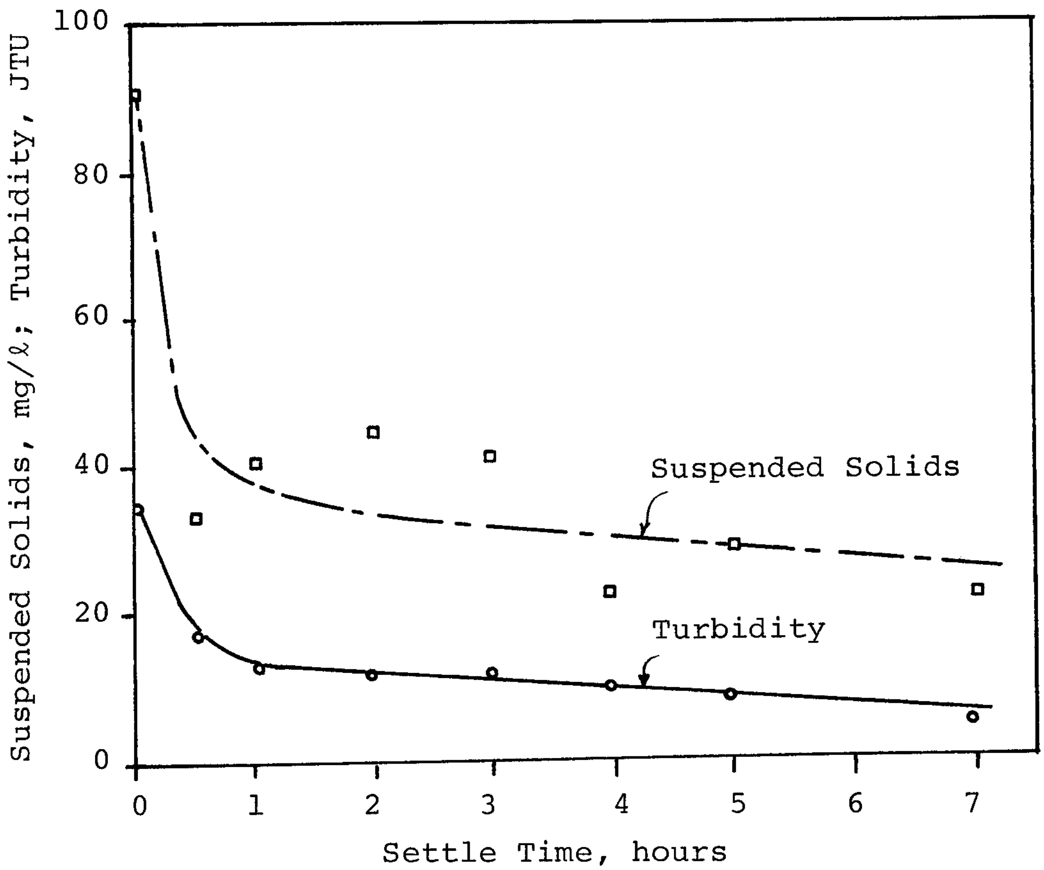


Figure 25. Suspended Solids and Turbidity vs Time for Batch Settling Test, Rain of 9/15/76.

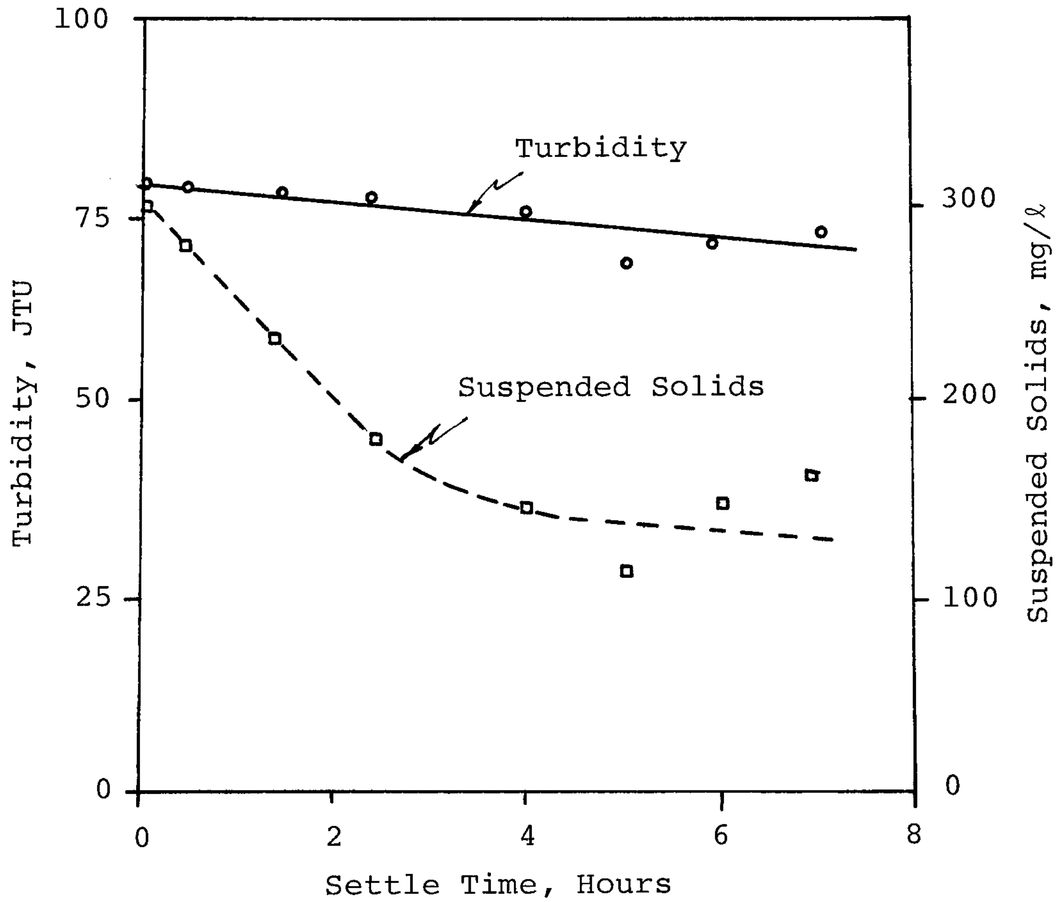


Figure 26. Suspended Solids and Turbidity vs Time, Batch Settling Test, Snowmelt of 2/25/77.

Overall removal efficiencies for suspended solids were found to vary between 19 and 63 percent for a two hour detention time, and 30 and 67 percent for a four hour detention time. These ranges correspond to an average removal of 41 percent for a two hour detention time and 51 percent for a four hour detention time. In general, the majority of the settleable solids settled within two hours or less, under the quiescent conditions that were maintained during the test.

It should be noted that three of the four sedimentation tests resulted in supernatant suspended solids concentrations that exceeded 30 mg/ℓ, even though detention times as long as seven hours were utilized. The only exception was the composite sample taken during the rain of 9/15/76. This indicates that sedimentation alone may not be adequate to meet suspended solids standards that are currently imposed on wastewater treatment plants.

Turbidity removals were found to vary from 3 to 65 percent for a two hour detention time, and 6 to 71 percent for a four hour detention time. Average turbidity removals were 29 percent for a two hour detention time and 36 percent for a four hour detention time. These average removals were significantly lower than those found for suspended solids, indicating that a significant amount of the turbidity causing materials consisted of unsettleable solids and colloids. Significant reductions in suspended solids occurred without appreciable clarification. This apparently happened in the sample that was taken on 2/25/77

(Figure 26), where 50 percent of the suspended solids were removed after four hours of settling, while only a 6 percent reduction in turbidity occurred.

COD removals tended to correspond to those of the suspended solids. Typical removal curves are shown in Figures 27, 28, and 29. Turbidity variations are also shown for comparison.

Average COD removals of 34 percent and 38 percent were found after two hours of settling (10 to 58 percent range) and four hours of settling (15 to 63 percent range), respectively. Soluble COD was not found to be removed to any significant degree. Overall, these removal efficiencies were relatively low when compared to those that have been reported in the literature. Colston found that an average COD removal of 60 percent resulted after 30 minutes of settling, and removals as high as 70 percent have been reported (Colston, 1974; Mische and Dharmadhikari, 1971; and Samar, et al., 1976). It should be noted, however, that these investigators also expeirenced higher suspended solids and turbidity removals.

B. Chemical Clarification

Chemical clarification of the stormwater runoff samples was evaluated by utilizing jar test procedures. The results obtained for each of the coagulants that were investigated are as follow.

1. Alum

Alum ($Al_2(SO_4)_3 \cdot 18H_2O$) was found to be very effective in clarifying the stormwater samples and was evaluated in each of

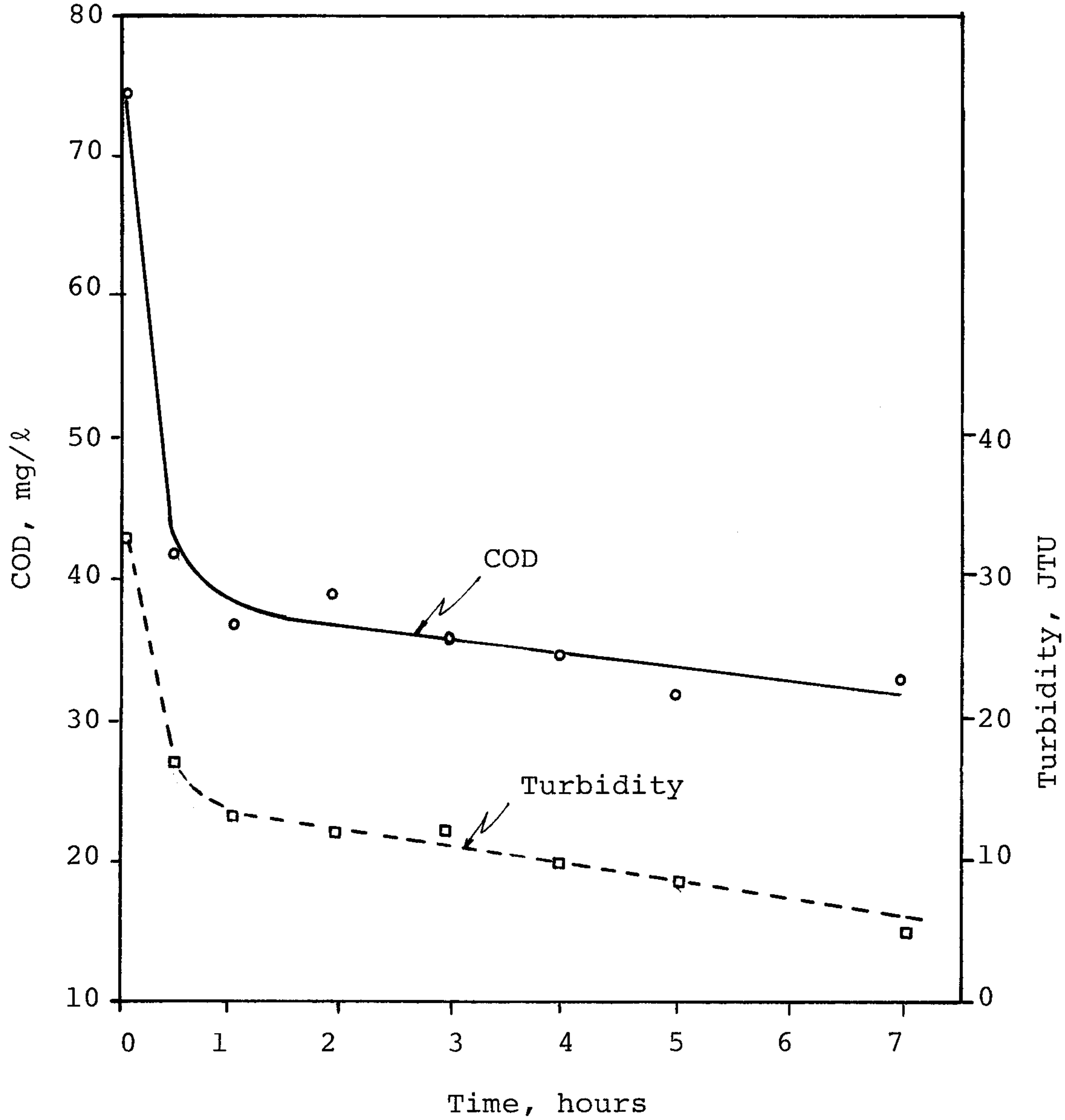


Figure 27. Turbidity and COD vs Time, Batch Settling Test, Rain of 9/15/76.

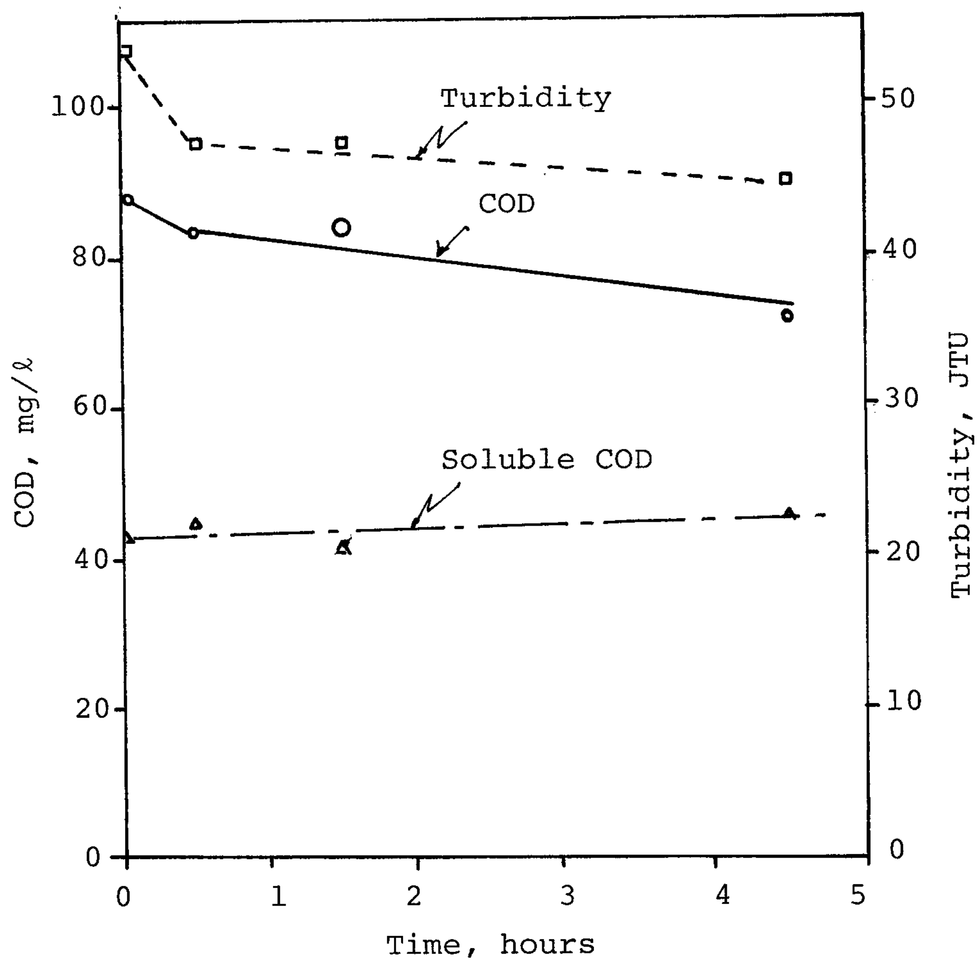


Figure 28. Turbidity and COD vs Time, Batch Settling Test, Snowmelt of 10/16/76.

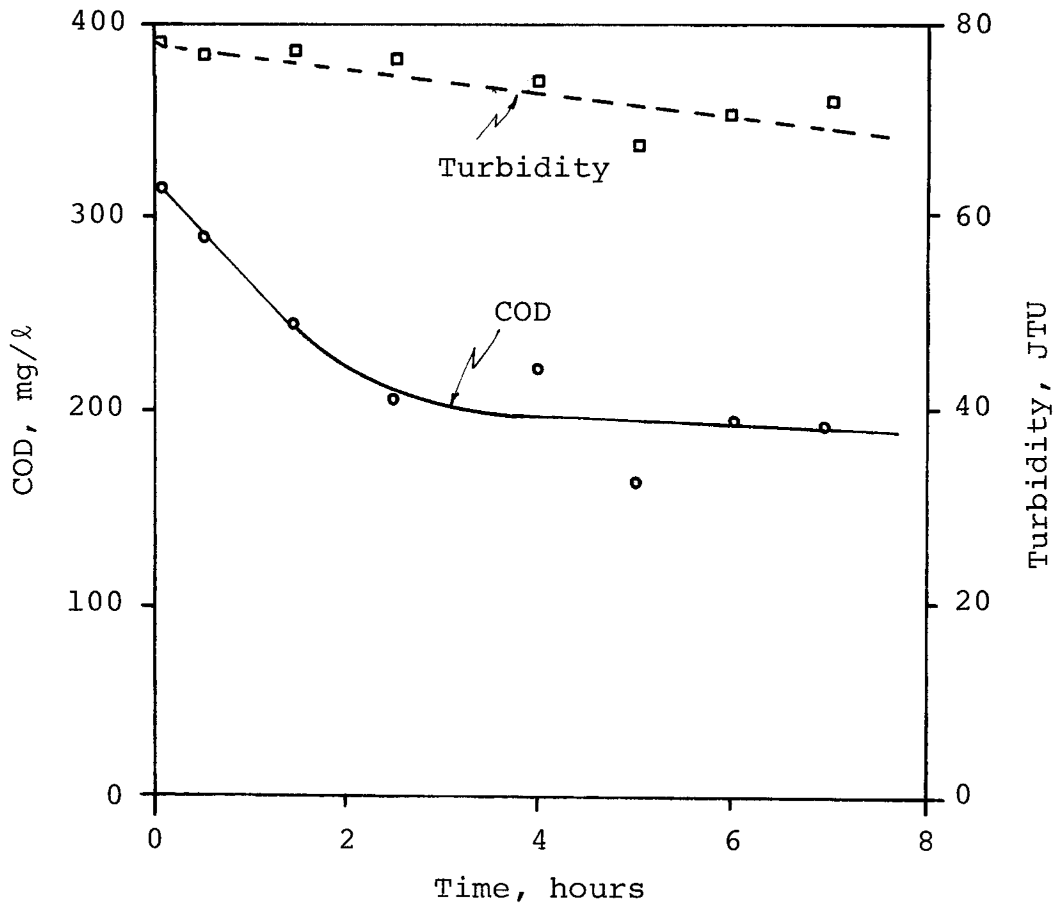


Figure 29. Turbidity and COD *vs* Time, Batch Settling Test, Snowmelt of 2/25/77.

the runoff events investigated. Figure 30 shows a typical COD and turbidity removal curve. Note that a definite optimum dose of 50 mg/ℓ was apparent. For the sample shown, which was taken on 9/15/76, COD, turbidity, and suspended solids removals of 72, 98, and 81 percent were found at the optimum dose.

Table 67 summarizes the results for COD, turbidity, and suspended solids that were found at the optimum dose for all of the samples tested. On the average, 90 percent of the turbidity, 70 percent of the COD, and 88 percent of the suspended solids was removed. It is interesting to note that most of the samples tested resulted in an optimum dose of 50 mg/ℓ, even though the alkalinity varied from 40 to 172 mg/ℓ as $CaCO_3$. The only exception to this was the sample in which 200 mg/ℓ of extra alkalinity was added. In this case, the optimum dose was reduced from 50 mg/ℓ to 25 mg/ℓ. From these results it appears that a reasonably high quality effluent can be produced in terms of COD, turbidity, and suspended solids by utilizing this clarification process.

2. <u>Ferric Chloride</u>

Two snowmelt samples were examined using $FeCl_3$ as the coagulating chemical. The results found were similar to those obtained using alum in that a definite optimum dose was apparent in each sample that was tested. Figures 31 and 32 show the results obtained for the sample taken during the snowmelt of 12/31/76. An optimum dose of 50 mg/ℓ as $FeCl_3$, resulted in 97, 91, and 71 percent removal of turbidity, suspended solids, and COD, respectively.

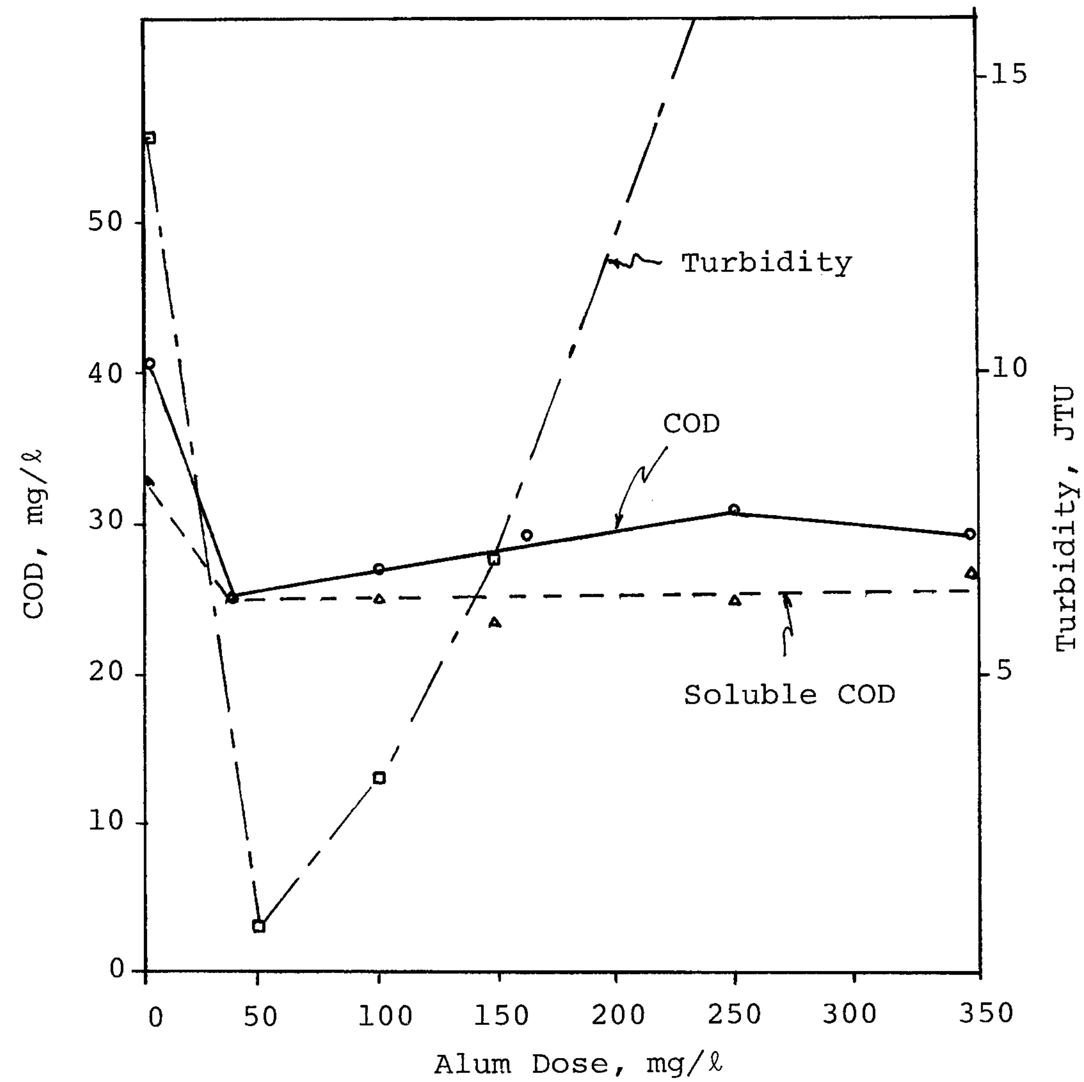


Figure 30. COD and Turbidity vs Alum Dose, Rain of 9/15/76.

TABLE 67

Chemical Clarification Results Using Alum at the Optimum Doses

DATE	TYPE OF RUNOFF	INITIAL ALKALINITY (mg/ℓ as $CaCO_3$)	ALKALINITY ADDED (mg/ℓ as $CaCO_3$)	OPTIMUM DOSE (mg/ℓ)	FINAL pH	INITIAL TURBIDITY (JTU)	FINAL TURBIDITY (JTU)	% REMOVAL	INITIAL COD (mg/ℓ)	FINAL COD (mg/ℓ)	% REMOVAL	INITIAL SS (mg/ℓ)	FINAL SS (mg/ℓ)	% REMOVAL
9/15/76	Rain	50	0	50	6.6	34	.75	98	91.2	25.4	39	91	17	81
10/26/76	Snow	48	0	50	5.9	54	10	81	88.6	31.6	64	93	13.1	86
12/31/76	Snow	172	0	50	7.32	54	1.4	97	120	34.8	71	125.7	6.67	95
2/25/77	Snow	40	0	50	6.4	80	12.0	85	318.8	80.6	75	300	30.0	90
		40	200	25	7.4	66.0	2.6	96	160.9	70.6	56	117.0	8.0	93

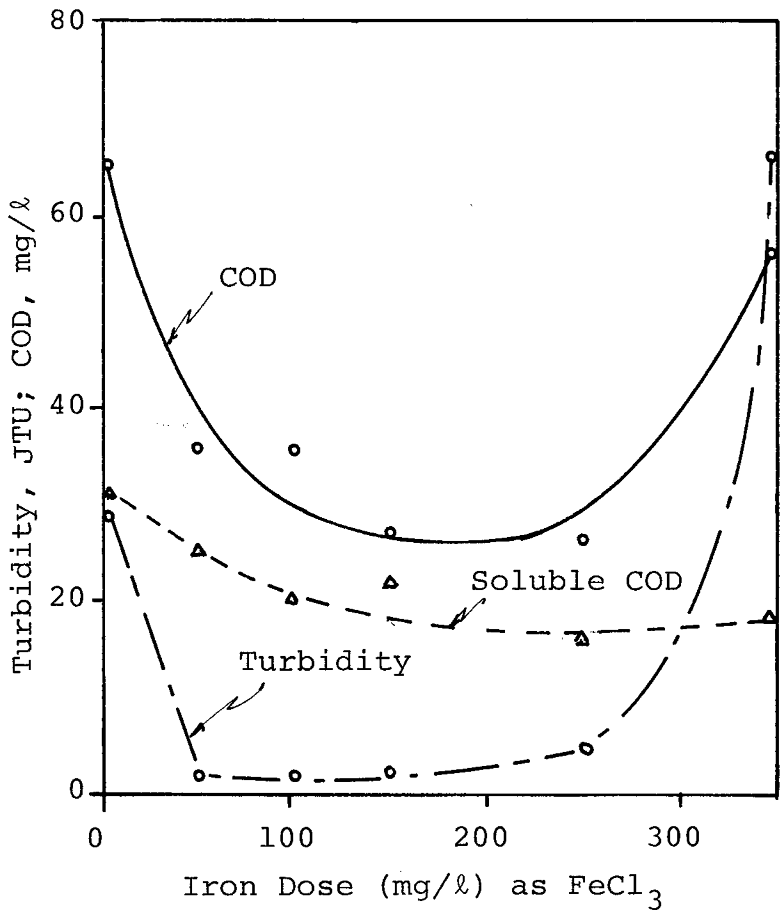


Figure 31. COD and Turbidity vs Ferric Chloride Dose, Snowmelt of 12/31/76.

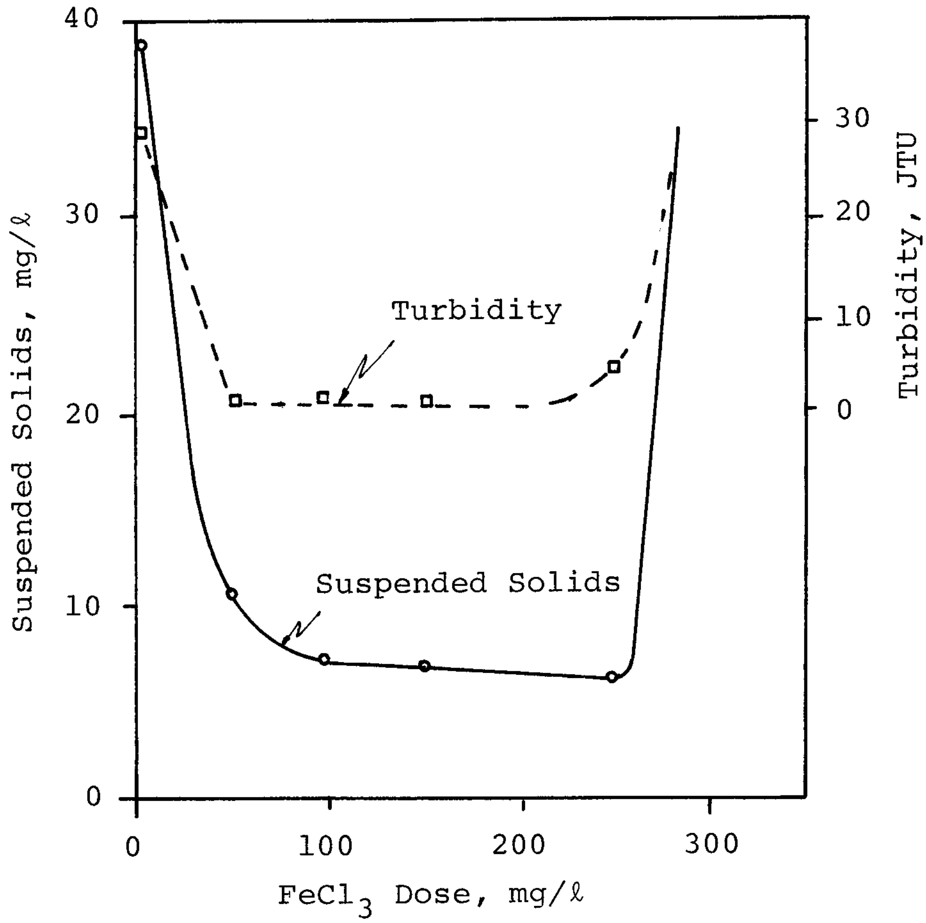


Figure 32. Suspended Solids and Turbidity vs Ferric Chloride Dose, Snowmelt of 12/31/76

During the course of testing, a slight red color was present in the supernatant, indicating that a large iron residual remained. The larger doses typically left higher iron residuals, which was probably a result of the low buffering capacity (alkalinity) of the sample. At the highest dose, 350 mg/ℓ $FeCl_3$, an extreme restabilization occurred resulting in an increase in the turbidity and suspended solids compared to the zero chemical dose.

Lower $FeCl_3$ doses were utilized in the analysis of the second sample, which was taken on 2/25/77. As seen in Figure 33, an optimum dose of 40 mg/ℓ resulted. No residual iron color remained at this dose, although a slight color appeared at the higher doses. Removal efficiencies of 98 and 83 percent were found for turbidity and COD at the optimum dose. As in the previous sample, the removal efficiencies decreased at the highest dose, which in this case was only 75 mg/ℓ as $FeCl_3$.

3. Lime

Lime was evaluated on samples taken during two of the stormwater runoff events that were investigated, and resulted in the lowest removal efficiencies of all of the coagulants examined. Figure 34 shows the results obtained on the sample taken during the rain generated runoff event of 9/15/76. The removal curves shown, indicate that lime was not as effective as a coagulant when compared to ferric chloride and alum. High lime doses were required to achieve significant pollutant removals. At a dose of 350 mg/ℓ, 88 percent of the turbidity

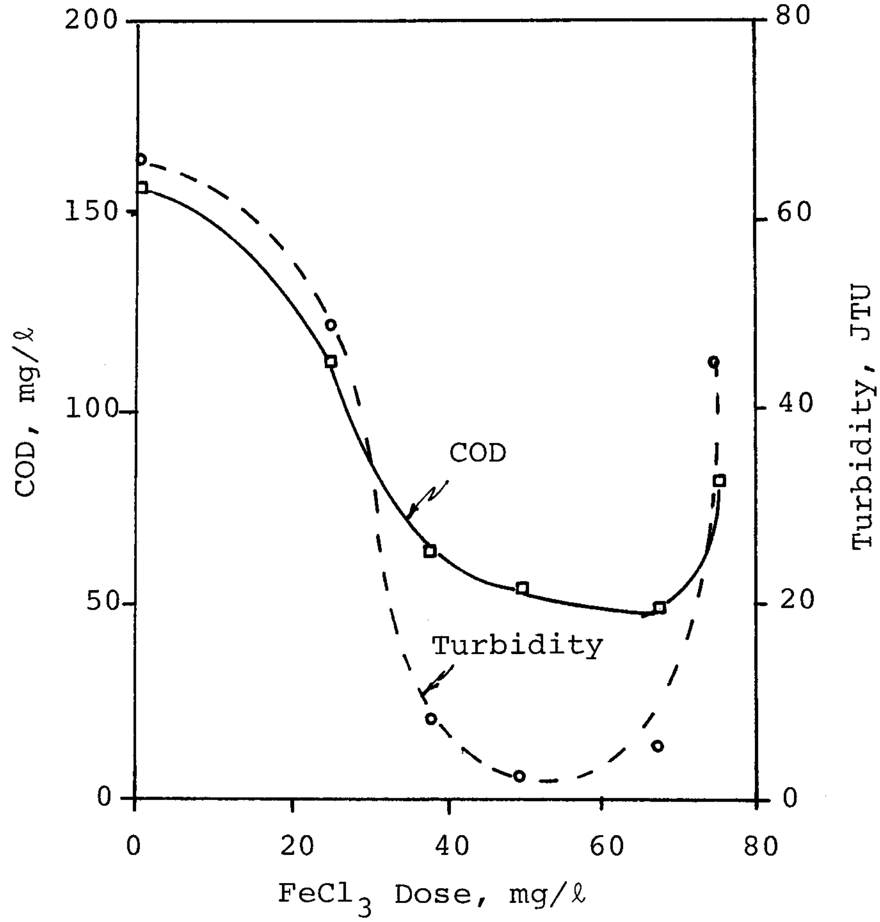


Figure 33. COD and Turbidity vs Ferric Chloride Dose, Snowmelt of 2/25/77.

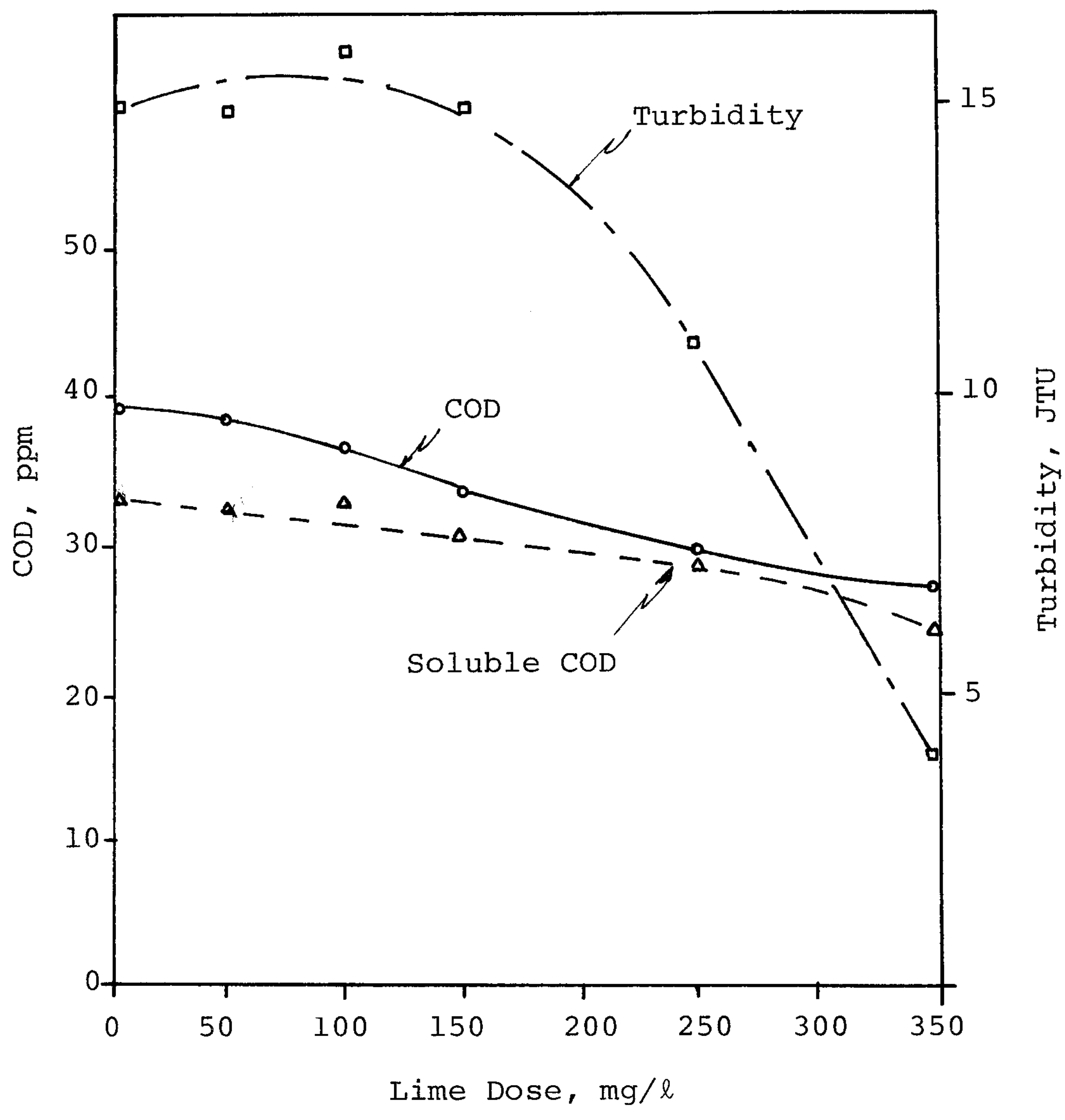


Figure 34. COD and Turbidity <u>vs</u> Lime Dose, Rain of 9/15/76.

and 70 percent of the COD was removed. These are slightly lower than the 98 percent turbidity and 72 percent COD removals experienced using alum on the same stormwater sample at an optimum dose of 50 mg/ℓ.

Figure 35 shows the results obtained on the sample taken during the snowmelt of 2/25/77. Again, low turbidity and COD removals (43 and 66 percent, respectively) were experienced at the high dose relative to those obtained using alum and ferric chloride. Although the supernatant pH due to the addition of the lime coagulant ranged between 9.8 and 11.4, floc formation was low. The addition of alkalinity did not improve removals for either the lime or ferric chloride coagulant.

C. Filtration

Overall, filtration proved to be one of the most effective treatment processes that was examined. The results obtained are shown in Table 68. Turbidity, COD, and suspended solids removals averaged 93, 82, and 85 percent, respectively. During the course of testing, it was found that much of the suspended material in the samples was removed within the top one inch of the soil matrix. This created a loose mat of material which tended to plug the column. If an "in-situ" filtration system were to be developed, provisions would have to be made to remove this material in order to prevent serious plugging.

In this preliminary study, loading rates were very low (around 1 BV per six hours) due to the nature of the filter media. It is probable that, through the proper selection of

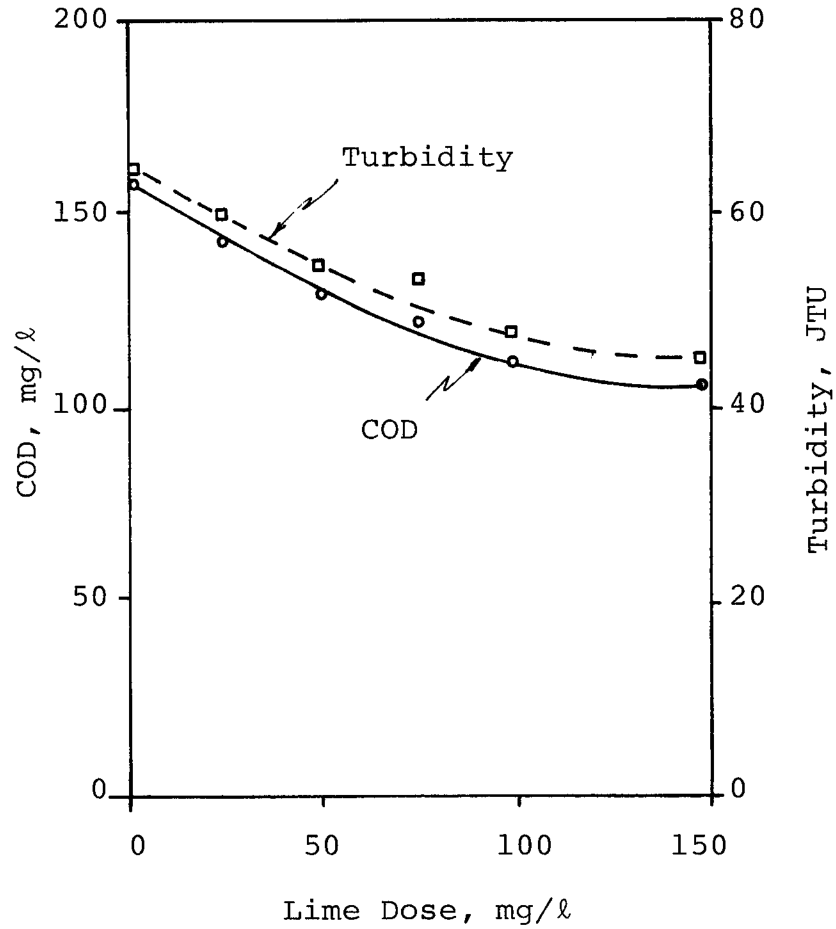


Figure 35. COD and Turbidity vs Lime Dose, Snowmelt of 2/25/77.

TABLE 68

Filtration Results

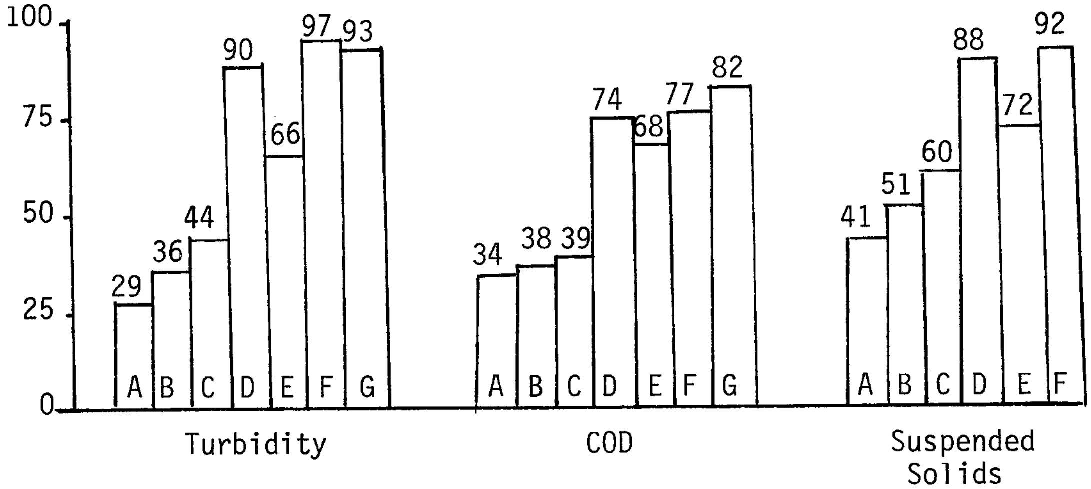
DATE	RUNOFF TYPE	INITIAL COD (mg/ℓ)	FINAL COD (mg/ℓ)	% REMOVAL	INITIAL TURBIDITY (JTU)	FINAL TURBIDITY (JTU)	% REMOVAL	INITIAL SS	FINAL SS	% REMOVAL
9/15/76	Rain	91.2	23	75	34	2.7	92	91	18.5	80
10/26/76	Snow	88.6	8.0	91	54	4.8	91	93	26	72
12/31/76	Snow	120	20.8	83	-	-	-	125.7	11	91
2/25/77	Snow	318.8	62.2	80	66	2	97	300	12	96
August Removals				82			93			85

filter media materials, comparable removal efficiencies can be attained at loading rates many times those evaluated here.

D. Process Comparison

In order to compare the various treatment processes that were examined, the results that have been obtained are presented in a slightly different form. Figure 36 shows the average removals that were found in all of the tests conducted. Using these figures, the relative effectiveness of each process can be determined.

Overall, coagulation with ferric chloride was found to be the most effective process, yielding a pollutant removal efficiency of 89 percent (average of turbidity, COD, and suspended solids removal efficiencies). Filtration proved to be the next most effective process with an overall efficiency of 87 percent. Coagulation with alum and lime yielded 84 and 69 percent removals, respectively. One of the interesting results was the ineffectiveness of plain sedimentation for the removal of pollutants.



A - 2 hr Sedimentation

B - 4 hr Sedimentation

C - Flocculation-Sedimentation

D - Alum Coagulation-Sedimentation

E - Lime Coagulation-Sedimentation

F - Ferric Chloride Coagulation-Sedimentation

G - Filtration

Figure 36. Average Removals for Each Treatment Process

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

A summary of the runoff pollution studies has been presented in a previous chapter. The following is a very brief statement of the most significant conclusions.

1. Stormwater runoff is an important source of pollution in many stream assessment problems. The annual loadings of suspended solids, COD, coliform bacteria and lead are greater than, or in the same range as, those for secondary treated sewage effluent from an equivalent sized area.

2. Stormwater pollutant loadings are highly variable from place to place and are affected by land use type and traffic densities. Different intensity storms can produce rather large variations in pollutant concentrations at the same location.

3. Snowmelt runoff occurs over a long period of time during the sunshine hours of the day. As a result, the concentrations of pollutant loadings were found to be slightly lower than those of rainfall for some of the major pollutants (COD, total solids and suspended solids), but significantly lower for the nutrients, nitrogen and phosphorus.

4. A first flush effect was found for the concentration of pollutants from a storm sewer. When the mass flow of pollutants was examined for the same conditions, no first flush effect occurred.

5. Treatment techniques for stormwaters were evaluated. It was found that a large portion of the organic pollutants

were associated with very fine or colloidal solids. For this reason, chemical coagulation or filtration was found to be effective. Plain sedimentation was rather ineffective and produced variable removals.

6. The stormwater pollution assessment is very complex and will require extensive field measurements for each location where it is applied.

The recommendations include a need for an extensive study of stormwater characteristics involving a large sampling and analysis network. This will involve the use of many automatic samplers and a large analysis facility.

The nonpoint or multi-point source nature of stormwater discharges introduces a difficult problem to the analysis of stream pollution. This source can no longer be ignored as an important consideration but it cannot be thought of in the same way as municipal sanitary waste streams. It is not economically possible or justified to provide treatment for all stormwater streams. Extensive analysis must be made on an individual stream assessment basis to establish those stormwater flows that significantly impact the pollutional loading of a receiving stream.

The treatment alternatives for stormwaters requires more study. Economic methods for the treatment of very large but intermittent flows needs to be examined. Retention equalization and treatment in a municipal treatment plant must be weighed against separate treatment of individual stormwater discharges. Treatment of stormwater involves the removal of colloidal matter and plain sedimentation has not been found to be very effective. More research is needed into treatment methods that are economical and effective for the unique flows and pollutants associated with stormwater discharges.

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