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NATIONAL ASSESSMENT OF THE URBAN PARTICULATE PROBLEM
Volume III - Denver

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711

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NATIONAL ASSESSMENT OF THE URBAN PARTICULATE PROBLEM

Volume III

Denver, Colorado

FINAL REPORT

by

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FOREWORD

This document is part of a 16-volume report assessing the urban particulate problem, which was conducted by GCA/Technology Division for EPA.

This particular document is one of the 14 single city volumes that provide working summaries of data gathered in the 14 urban areas during 1974 to support an assessment of the general nature and extent of the TSP problem nationwide. No attempt was made to perform detailed or extensive analyses in each urban area. Rather, the city reports are intended as a collection of pertinent data which collectively form a profile of each urban area. This, in turn contributes to a comparative analysis of data among the 14 areas in an attempt to identify general patterns and factors relating to attainment of the TSP problem nationwide. Such an analysis has been made in Volume I of the study-National Assessment of the Urban Particulate Problem-National Assessment. The reader is referred to this volume as the summary document where the data is collectively analyzed.

This and the other 13 city reports are viewed primarily as working documents; thus, no effort was made to incorporate all the reviewer's comments into the text of the report. The comments were, however, considered during the preparation of Volume I and are included herein in order to alert the reader to different points of view. The 16 volumes comprising the overall study are as follows:

Volume I - National Assessment of the Urban Particulate Problem
Volume II - Particle Characterization
Volume III - Denver
Volume IV - Birmingham
Volume V - Baltimore
Volume VI - Philadelphia
Volume VII - Chattanooga
Volume IX - Oklahoma City
Volume X - Seattle
Volume XI - Cincinnati
Volume XII - Cleveland
Volume XIII - San Francisco
Volume XIV - Miami
Volume XV - St. Louis
Volume XVI - Providence

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ACKNOWLEDGMENTS

GCA/Technology Division wishes to sincerely thank those persons and organizations who made significant contributions to this effort. On-going project supervision was provided by Thompson G. Pace of EPA's Control Programs Development Division. The case study in Denver was greatly assisted by the cooperation and helpfulness of the staff of the Colorado Air Pollution Control Division, particularly Wayne May, Todd Reynolds, Hank Dequasie, and John Clause. In addition, valuable information was provided by Richard Young of the Denver Department of Health and Hospitals, Air Pollution Control Section, and Messrs. Fondi and Herzeberger of the Denver Department of Public Works.

EXECUTIVE SUMMARY

The report summarized herein presents the analyses of the particulate situation in the Metropolitan Denver Air Quality Control Region (AQCR) conducted as part of the study for the national assessment of the problem of attainment or nonattainment of the National Ambient Air Quality Standards for particulates. The Denver AQCR represents a lightly industrialized area, with above average heating requirements and less than average amount of rain, that has had some success in reducing emissions but not particulate concentrations. Sanding for snow control and other fugitive dust sources have been implicated as a major contributing sources to the ambient levels of particulates in Denver so this report provides special emphasis in that area.

In addition to the analyses of sanding activity, analyses of the air quality levels, emissions, regulations, monitoring network, meteorology, and street sweeping are included in this report. The major findings in each of these areas are summarized below in the order in which they appear in the text.

AIR QUALITY

There have been no real trends in TSP levels during the past 6 years in the AQCR though Denver County has shown some improvement in its air quality since 1965. The primary annual air quality standard is being exceeded at most sites around the AQCR and the secondary annual air quality standard is being exceeded at all but one site. The highest annual geometric mean was 131 $\mu g/m^3$, 8 percent higher than that used in the SIP for strategy planning. Violations of the 24-hour standards have also been frequent with the secondary standard exceeded occasionally at most of the monitors in 1974.

The spatial distribution of the air quality is primarily the result of the topography with highest levels near the river bed and the levels decreasing in the suburban and rural areas on higher ground. The county-wide geometric mean of all stations in Denver County was 97 $\mu g/m^3$.

EMISSIONS

The determination of emission levels in the Denver AQCR has been through several iterations, each with the purpose of strategy planning. However, each of these iterations has produced substantially different emission inventories with no consistent trend pattern. Therefore, no correlation can be drawn between changes in emissions and TSP concentration.

The study of fugitive emissions has also produced two different inventories with considerably different values. While the one study that was specific to the State of Colorado is expected to be more accurate, this inventory had serious questions raised about it in the course of this study.

REGULATIONS AND SURVEILLANCE

The Colorado Air Pollution Control Commission (CAPCC) is responsible for the control of particulate matter throughout the State of Colorado. However, in the City of Denver, the sources are controlled by both the city's regulations and the applicable ones of the CAPCC. The two sets of regulations are equivalently stringent. Surveillance of the sources are performed through the use of the permit system, visible emissions, and complaints. Only a small amount of stack testing to determine compliance is done; the majority of sources are determined to be in compliance through theoretical calculations.

The regulations imposed by the CAPCC were compared with other cities reviewed in this study and were found to be more stringent in most cases. Comparison with average regulations in published studies indicated that the city's regulations were at least as stringent as those normally applied.

NETWORK DESIGN

The monitoring network was found to be generally acceptable except in a couple of instances. The most noticeable problem occurred in Denver County where it was felt that monitors should be more centrally located with respect to height and in the monitoring of outlying areas away from population centers. This latter deficiency prevented the provision of valuable information on the air masses entering the city.

METEOROLOGY

Ventilation and precipitation were the two major meteorological elements reviewed and analyzed. The study of ventilation included the consideration of the topography of the area.

Ventilation was found to have a significant impact on the concentration in Denver and is expected to account for much of the observed seasonal pattern in TSP levels. Denver has the lowest average morning mixing heights of the cities studied but also the highest average afternoon mixing heights.

Precipitation appears to have only a minor impact on the ambient concentration where considering annual and monthly means. This was felt to be due to the generally low level and infrequent occurrence of precipitation; i.e., the small impact that occasionally resulted from precipitation was lost in the calculation of geometric means.

URBAN ACTIVITY

The major analysis of urban activity was limited to the impact of sanding operations on the TSP levels. Street sweeping was also considered but insufficient information was available for the determination of any correlation.

The analysis of sanding included a review of the calculation of the total tonnage of emissions due to sanding in Denver County, the results of which indicated that the emission estimates currently being used for planning purposes may over-emphasize the importance of sanding. Seasonal fluctuations in emissions, meteorology, and air quality were also studied and this analysis provided further support to the view that the current fugitive dust inventory was misleading.

Daily fluctuations in TSP levels in response to sanding for snow control provided no firm evidence of the impact of sanding on the TSP levels.

CONCLUSIONS

The results of this study indicated that a major part of understanding the problem of lack of attainment of the NAAQS in the Denver AQCR could be attributed to the lack of sufficiently accurate and detailed information for strategy planning. Recommendations for steps to be taken for the eventual attainment of the standards included further emission inventory studies for both fugitive and traditional sources, expansion of the monitoring network, and the increased consideration of the meteorological and topographical influences.

REVIEWERS' COMMENTS

The draft report for each city was submitted to interested EPA, state, and local officials for comment on the contents and findings. Comments of an editorial nature were reconciled; comments of a substantive nature which reflect differences of opinion were compiled and are presented below.

Page xiii - Network Design - It is impossible to have all samplers at the same height above ground. EPA criteria specify less than 50 ft above ground. The Colorado Department of Health sampler is a bit too high, but has consistently been at the same location since before 1969; therefore, comparison of data with that of previous years should be of value. We disagree with the concept that information on air masses entering Denver can be obtained from 24-hour hi-vol samples. Wind data are available from several sites in the Metro area for use in evaluating flow patterns.

- Meteorology - Seasonal influence of precipitation becomes evident if comparisons are made. The two winter quarters added together are consistently higher than the two summer quarters. Spring and summer rainshower activity plus lawn irrigation tend to "clean" all major traffic lanes.

Page xiv - Conclusion - We doubt that expansion of the network in the Denver AQCR would give us any more useful information. We exceed considerably the EPA requirements for number of samplers for the region.

The many studies already completed on particulates and related micrometeorology over the Denver Region point up the relatively high background level of TSP. The present standards seem to be entirely too low - a point not made in this study. Further study of the problem, better emission inventories, and more detailed sampling will not enable us to design strategies for attainment of unrealistic standards.

Page 11 Figure 3 - In Figure 3, single stations are compared with averages of 4 to 6 stations and are erroneously considered representing trends.

Page 30 - The discrepancy in monitoring data and inventory data may also be due to the apportioning of the emissions done by GCA in the example plan and not only to the magnitude of the total emissions estimated by PEDCo.

Page 38 - The table contains emissions from sanding. The cleaning practices in Denver result in large quantities of sand remaining on the street long after the snow has gone. To estimate emissions, I would use some kind of factor such as 50 percent. Using the figures in the table add 1/2 of the quantity to the next month; i.e.:

	589	895	2,153	1,403
1/2	295	295	595	1,374
	884	1,190	2,748	2,777

Applying such a factor would change the estimate of emissions considerably.

Page 60 P. 3 - The CAMP station and the NASN station are one and the same site.

Page 51 P. 2 - It is felt by many that the monitoring in the Denver area is more than adequate. It may be that some stations should be relocated, however. Any recommendation regarding the addition of stations should be very specific and justified.

Page 62 P. 3 - The correlation noted between precipitation and concentration is tenuous.

Page 67 P. 3 - Here and elsewhere in the report references are made to snow removal which I do not believe generally exists in the city and street sweeping, which is based on averages for the city. There is no indication of what the satellite cities do for each activity. I believe that these considerations need a second look.

Page 76 P. 2 - The statement "In fact the Federal secondary particulate standard ... is exceeded in almost completely undeveloped areas" should be substantiated and qualified. It should be pointed out that while 24-hour values in undeveloped areas are sometimes quite high, annual geometric means are very low - far below standards. This is not true for developed areas.

Page 78 - Network Design - People live and work at varying heights throughout the region. If a sampler shows violation in TSP at 50 feet, control strategies must show improvement at that point as well as at ground level.

General - The conclusions reached in the report are confusing. Specifically, how does climatology and topography affect air quality attainment goals?

The recommendations are not justified. Specifically, recommendations for further air quality and meteorological monitoring in Denver are not responsible since there exists appropriate data.

The analysis techniques used were not explained adequately. For example, it is unclear as to what dispersion models were used in the analysis and what data inputs and model verification should have been done.

A considerable amount of discussion is included relating particulates to precipitation. In cities of the Midwest it may be possible to get a good correlation between particulate and rainfall because much of the rain is in the form of areawide storms and not isolated thundershowers. In Denver the summer rain generally takes the form of isolated storms and they do not affect the general area.

In general, the analysis uses averaging and data smoothing techniques. For Denver, I believe that analysis should go the other direction and become more site and data specific.

SECTION I

STATEMENT OF THE PROBLEM

CHARACTERISTICS OF THE METROPOLITAN DENVER AQCR

The Metropolitan Denver Intrastate Air Quality Control Region (AQCR) encompasses the counties of Adams, Arapahoe, Boulder, Clear Creek, Denver, Douglas, Gilpin, and Jefferson. The AQCR extends eastward from the Continental Divide into the plains, with the major urban centers located along the foothills of the Rockies. The greater Denver area lies within the South Platte River drainage basin with the City of Denver having an elevation in excess of 5,000 feet above sea level. Roughly 20 miles to the west the mountains reach elevations of 10,000 to 14,000 feet; to the southwest, the land rises more gradually along the South Platte River valley. In addition to the City of Denver, the AQCR includes the major urban centers of Boulder, Longmont, and Broomfield in Boulder County, and Brighton in Adams County.

The particulate problem is basically a result of the arid conditions of the region which are conducive to entrainment and re-entrainment of particulares during windy conditions. Fugitive dust, a major component of total particulates, has several man-made sources; unpaved roads, sand on paved roads, agriculture, land development, residential, industrial, and commercial construction, highway construction, aggregate storage, cattle feedlots, and quarrying, mining, and tailings. The pollution problem is exacerbated by the valley effect of the topography and frequent low level inversions in the winter time.

Population

The Denver region's population has grown at a fast pace in the past 3 decades, the rate of growth ranging from 3 to 4.6 percent per year. The Denver Standard Metropolitan Statistical Area (SMSA), encompassing Adams, Arapahoe, Boulder, Denver and Jefferson Counties, had a 1970 population of 1,227,529. Based on population gains through mid-1973, the Denver Regional Council of Governments (DRCOG) estimates the current SMSA population to be approximately 1,416,800. Denver County contained over 50 percent of the total metropolitan Denver population in 1960, but it is estimated that by the year 2000 it will only retain about 25 percent of the total. Population is decreasing in the central city as urban sprawl moves to the north and south along the front range. The suburban communities accounted for approximately 80 percent of the area's population increase between 1950 and 1970.

The major components of population change for the Denver urbanized area include natural increase through increased births, and net migration. Of the two, net migration, or the difference between those coming into the area and those leaving, has been the most important. Both rural-urban migration and the relative stability of Denver's economy are cited as primary contributing factors for the large flux of the residents.

Density of population in the Denver central city, in 1970, was 7,602 per square mile and 198 beyond the central city. In general, this is a low suburban density and is partially because Denver is relatively isolated from other major cities. Additionally, people have shown a preference for open space in the metropolitan area, supported by the high mobility afforded by the automotive-dominant transportation systen and extensive highway network. The overriding characteristic of the region is this low population density and dispersed growth pattern.

The current patterns of sprawling low density suburban areas have contributed to the regional dependence on private automobile travel.

Employment

The Denver AQCR is a relatively light industrialized area with only 21 percent of its work force in the manufacturing sectors. The metropolitan Denver region has shown relatively healthy economic performance in the past decade, with total employment in the region increasing by 30 percent between 1964 and 1970. This represents an annual compound growth rate of 4.5 percent per year. The 1970 labor force for the area was approximately 550,000, with 26,000 employed by the Federal Government. In addition to the large Federal labor force, the Denver region also contains State and local government labor forces (City and County employees) since Denver is the principal governmental and political center in Colorado. Approximately two-thirds of the employment growth between 1964 and 1970 occurred in Denver County, while about 95 percent of the population growth was in surrounding counties.

Based on analysis of industrial groups and employment trends, the Denver Regional Council of Governments (DRCOG) has projected employment growth trends by industry group to the year 2000 for the metropolitan Denver area. Table 1 provides the forecasted annual rates of employment growth for the Denver region by industrial type. These employment growth projections show that higher than average total employment growth will be experienced by three industries: (1) finance, insurance and real estate, (2) services, and (3) government. Approximately average growth will occur in industries: (1) construction, and (2) wholesale and retail trade. Employment growth rates of two industrial groups will be consistently below the rate of growth in total employment: (1) manufacturing, and (2) transportation, communications and utilities. One industry, agriculture, however, is projected to have a negative growth rate.

Table 1. FORECASTED ANNUAL RATES OF EMPLOYMENT GROWTH, METROPOLITAN DENVER 1970 to 2000

Industry category	Forecasted annual rate of growth		
	1970-1980 percent	1980-1990 percent	1990-2000 percent
Agriculture	-0.8	-1.1	-1.6
Mining	0.2	0.4	0.4
Contract construction	3.2	2.4	1.9
Manufacturing	2.8	2.2	1.7
Transportation, communication and public utilities	2.7	2.7	1.6
Wholesale and retail trade	3.0	2.3	1.8
Finance, insurance and real estate	3.8	2.8	2.1
Services	3.4	2.6	2.2
Government	3.6	2.7	2.4
Weighted average growth	3.1	2.4	2.0

Source: The Denver Regional Council of Governments.

Land Use

The Metropolitan Denver AQCR covers a land area of 13,067 square kilometers (5045 square miles), centered around the Denver Metropolitan Area, occupying about 712 square kilometers (275 square miles) and Denver's center city occupying approximately 5 square kilometers including a Central Business District (CBD) of 1.4 square kilometers. General land use trends for the Denver Standard Metropolitan Statistical Area (SMSA) show agricultural and vacant land being transformed to single-family residential use. Major portions of the urbanized areas in the region are characterized by single-family tract housing, strip commercial developments and a substantial freeway network. The recent decades have shown circumferential development in all directions from the Denver Metropolitan Area, served by upgraded arterials and new highways.

The distribution of land uses in the Denver CBD and urbanized regions of the study area reflects the governmental, financial, service, and distribution functions that the urban centers perform for the metropolitan area and the larger Rocky Mountain region. Downtown Denver is not a manufacturing center, but rather the keystone of business and government, devoted to the distribution and exchange of goods, money and ideas. In decreasing order of importance, office space, hotels and motels, retail activity, and governmental facilities are the primary land uses in the Denver CBD, followed by residential, storage, commercial services, and industrial uses. A recent inventory of zoning in the Denver SMSA shows 19 percent or nearly one-fifth of the land zoned for residential use. Although 61 percent of the land in the region is still zoned for agriculture, the trend is for rezoning to higher use (residential, commercial, industrial, and recreational).

For the Denver SMSA, as a whole, commercial and industrial land uses have developed in a dispersion pattern around the urban centers. Commercial growth is mainly attributable to the development of various neighborhood and regional shopping centers. There has been a continued dispersion of new industrial development, while diverse changes are evident in the services, parks and public land uses. New development and growth potential will depend upon available vacant space, transportation accessibility, costs, availability of water resources and related factors. Land use planning and zoning activities have varied in the region's areas. Denver and Aurora, for example, have aggressive annexation policies and promote higher use development of vacant lands through their zoning regulations.

AIR QUALITY SUMMARY

There are currently 23 stations monitoring for total suspended particulates (TSP) in the Denver AQCR, as shown in Figure 1. Over half of these stations are located in or near Denver County and an enlarged view of this area is given in Figure 2. All of these sites are the responsibility of the Colorado Air Pollution Control Division (CAPCD) and have their data reported to NADB. Specific information on the monitoring sites is given in Table 2. The sites are fairly evenly distributed between the suburban and center city areas with two monitors located in rural areas. The stations also have a wide exposure to residential, commercial, and industrial activity. The height above ground ranges from 10 feet to 60 feet with many monitors located in-between and the range of height above mean sea level is even greater due to the topography of the area.

Except for the National Air Sampling Network (NASN) monitor in Denver, consistent information on trends in the AQCR was only available back to 1969 and four of the counties had continuous sampling during this period limited to one monitor. The county-wide annual geometric means

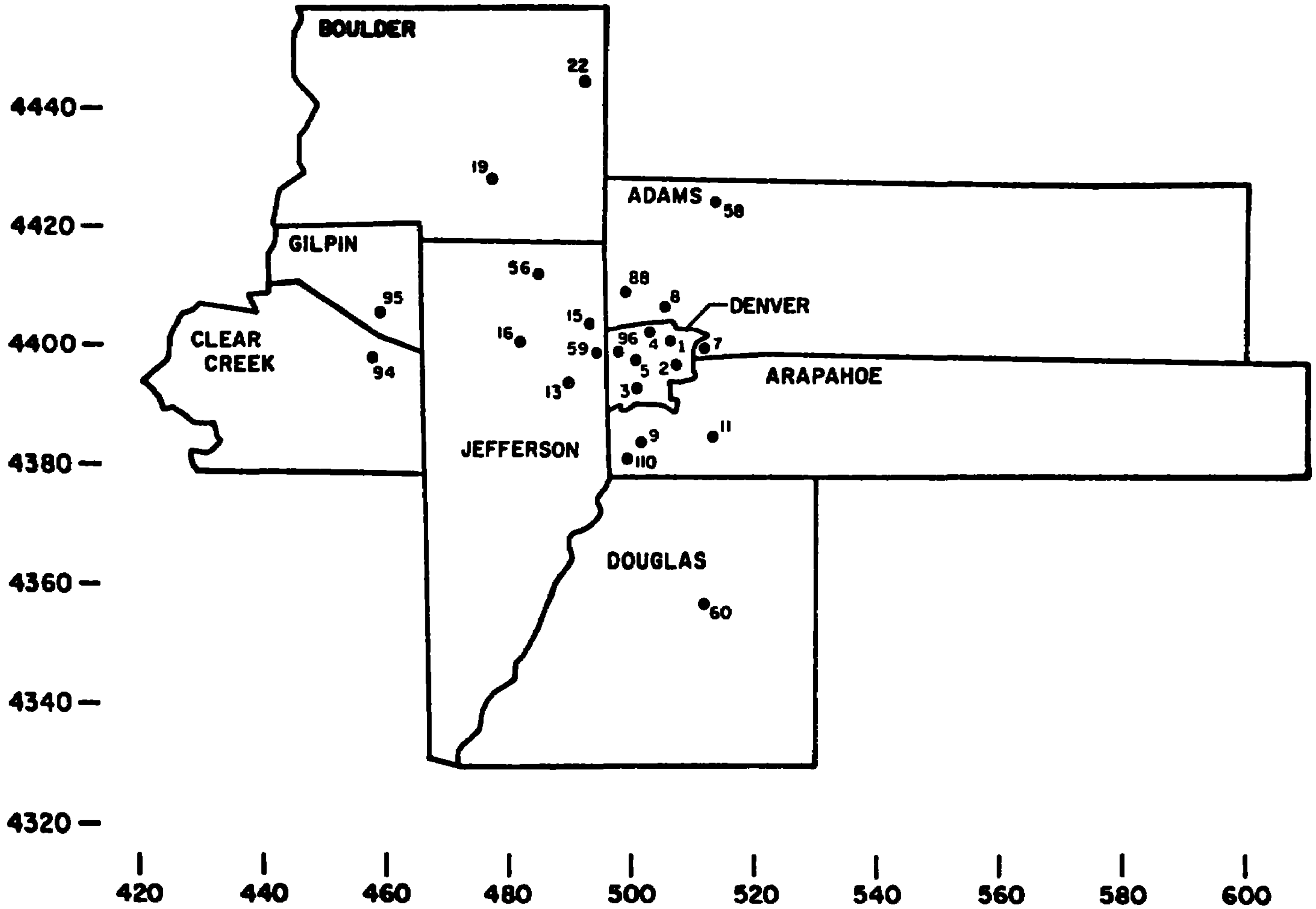

Figure 1. TSP monitoring stations in the Denver AQCR (CAPCD site identification number)

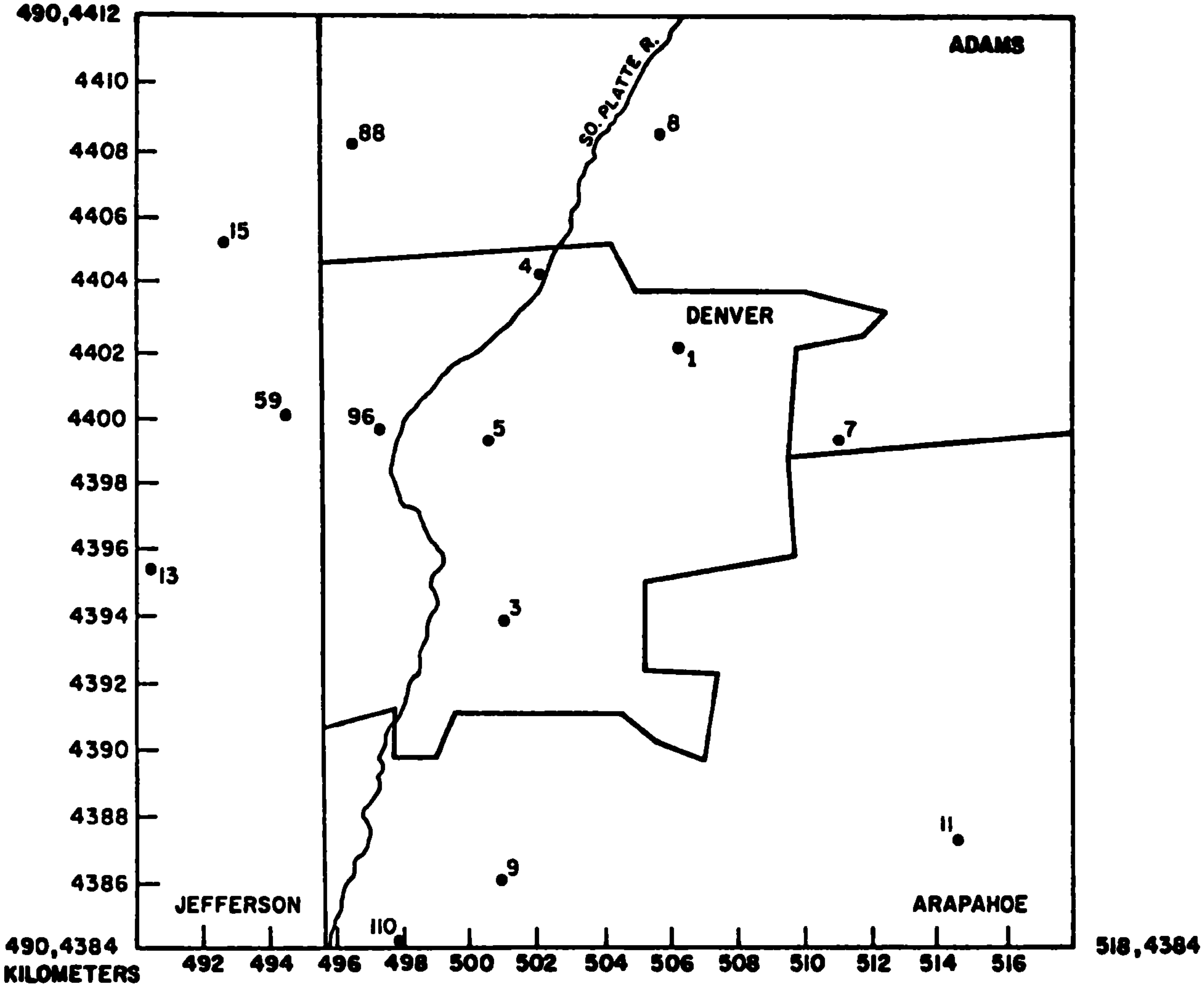

Figure 2. TSP monitoring stations in the Denver County area (CAPCD site identification number)

Table 2. CHARACTERISTICS OF MONITORING SITES IN THE DENVER AQCR

County	CAPCD no.	Location	Height above ground (feet)	Height above mean sea level (feet)	Site characteristic	TSP 1974 geometric mean, ($\mu g/m^3$)	% of observations above the 24-hour standards	
							Primary	Secondary
Adams	88	Westminster	15	5335	Suburban-residential suburban	76	0	10
Adams	7	Aurora	20	5358	Residential/commercial	84	3	20
Adams	8	Adams City	15	5145	Suburban-industrial center city	116	7	34
Adams	58	Brighton	35	5015	Commercial	93	0	10
Arapahoe	11	Cherry Creek Dam	4	5656	Remote to suburban suburban	63	0	1
Arapahoe	9	Englewood	20	5428	Residential/commercial	107	2	27
Arapahoe	110	Centenial Wells	15	5330	Suburban-residential	72	0	6
Boulder	19	Boulder	30	5380	Center city-commercial	66	0	1
	22	Longmont	30	5010	Center city-commercial	94	8	16
Clear Creek	94	Idaho Spring	18	7538	Center city-commercial suburban-residential/	73	0	4
Denver	2	State Health Dept.	60	5380	Light commercial suburban	74	0	4
	1	Hull Photo	25	5293	Light industrial suburban-residential/	73	0	6
	4	Sewer Plant	10	5150	Light commercial suburban	131	14	36
	96	CARIH	15	5325	Heavy industrial	93	2	17
	5	School Administration Bldg.	50	5275	Center city-commercial	107	8	23
	3	Gates Building	25	5288	Center city-industrial	119	6	30
Douglas	60	Castle Rock	15	6210	Center city-commercial	76	1	8
Gilpin	95	Black Hawk	40	8140	Center city-commercial	N.A.	N.A.	N.A.
Jefferson	13	Lakewood	15	5597	Suburban-residential	80	1	10
	59	Edgewater	35	5385	Suburban-commercial	91	2	17
	15	Arvada	15	5353	Suburban-commercial	107	7	27
	16	Golden	20	5670	Suburban-industrial	67	2	4
	56	Rocky Flats	10	5975	Rural-industrial	45	0	2

[a] NASN site omitted because no 1974 data was available.

for each county and the annual geometric means for the NASN station (1957-1973) are plotted in Figure 3. These plots indicate that no significant trend pattern has been established in any county except Douglas, where the TSP concentration has increased steadily, and in Denver where there is approximately a 20 percent decrease in TSP levels noted between the 1964-1965 means and the 1969-1974 means. The primary annual National Ambient Air Quality Standard (NAAQS) of 75 $\mu g/m^3$ is exceeded in all counties except Clear Creek which had an annual geometric mean of 73 $\mu g/m^3$.

The spatial distribution of the TSP levels can be estimated from the plot of the 1974 geometric means given in Figure 4 for the Denver AQCR and in Figure 5 for the Denver County area. As is evident from these figures, the primary and secondary standards are exceeded throughout the AQCR except for Rocky Flats in Jefferson County (CAPCD Number 56) and the area of maximum concentration is centered along the South Platte River. This distribution of concentration is not substantially changed from the time of the submission of the Air Quality Implementation Plan for the State of Colorado. (See Figure 6.)

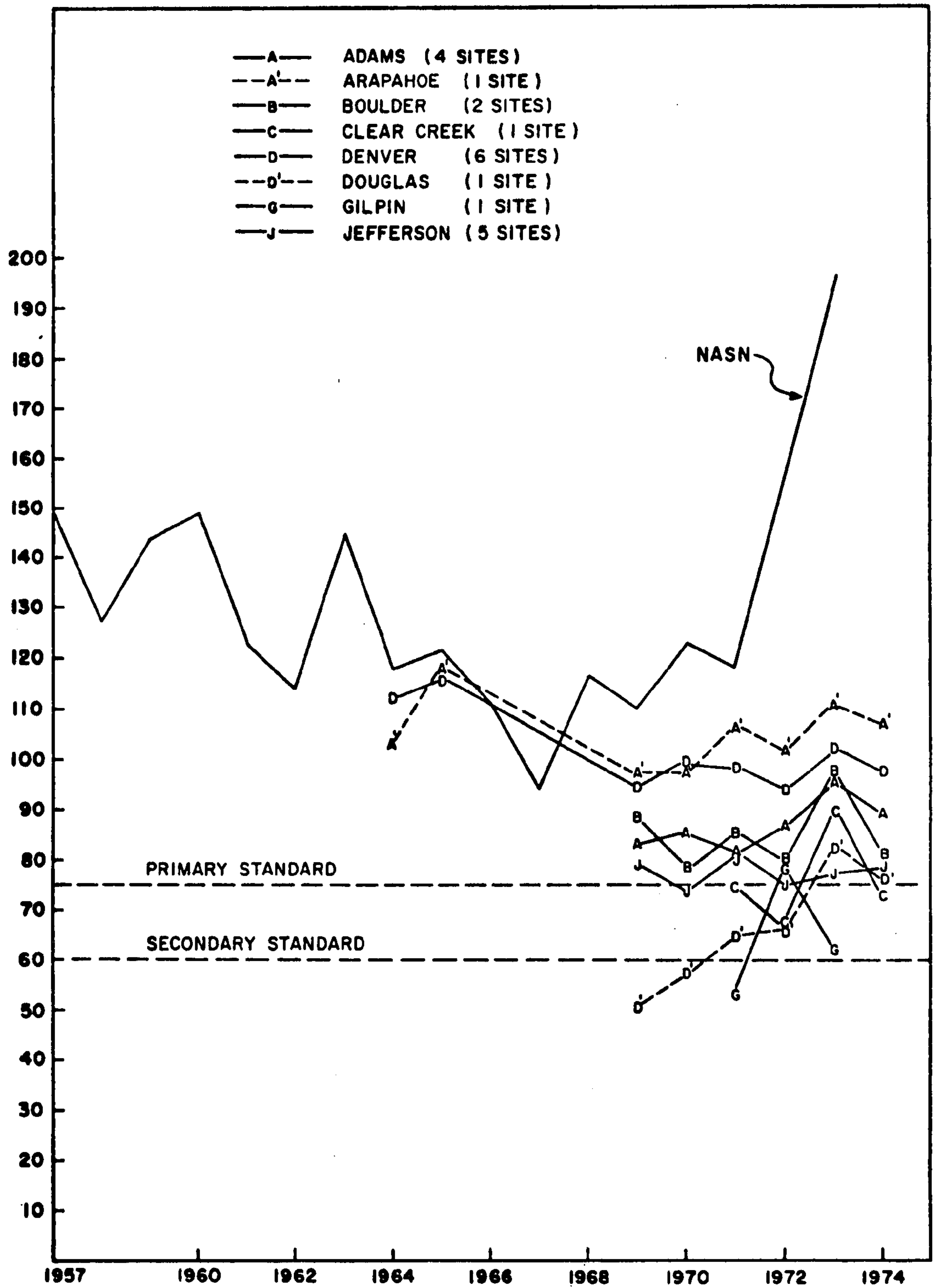

Figure 3. Trends in countywide annual geometric means of TSP

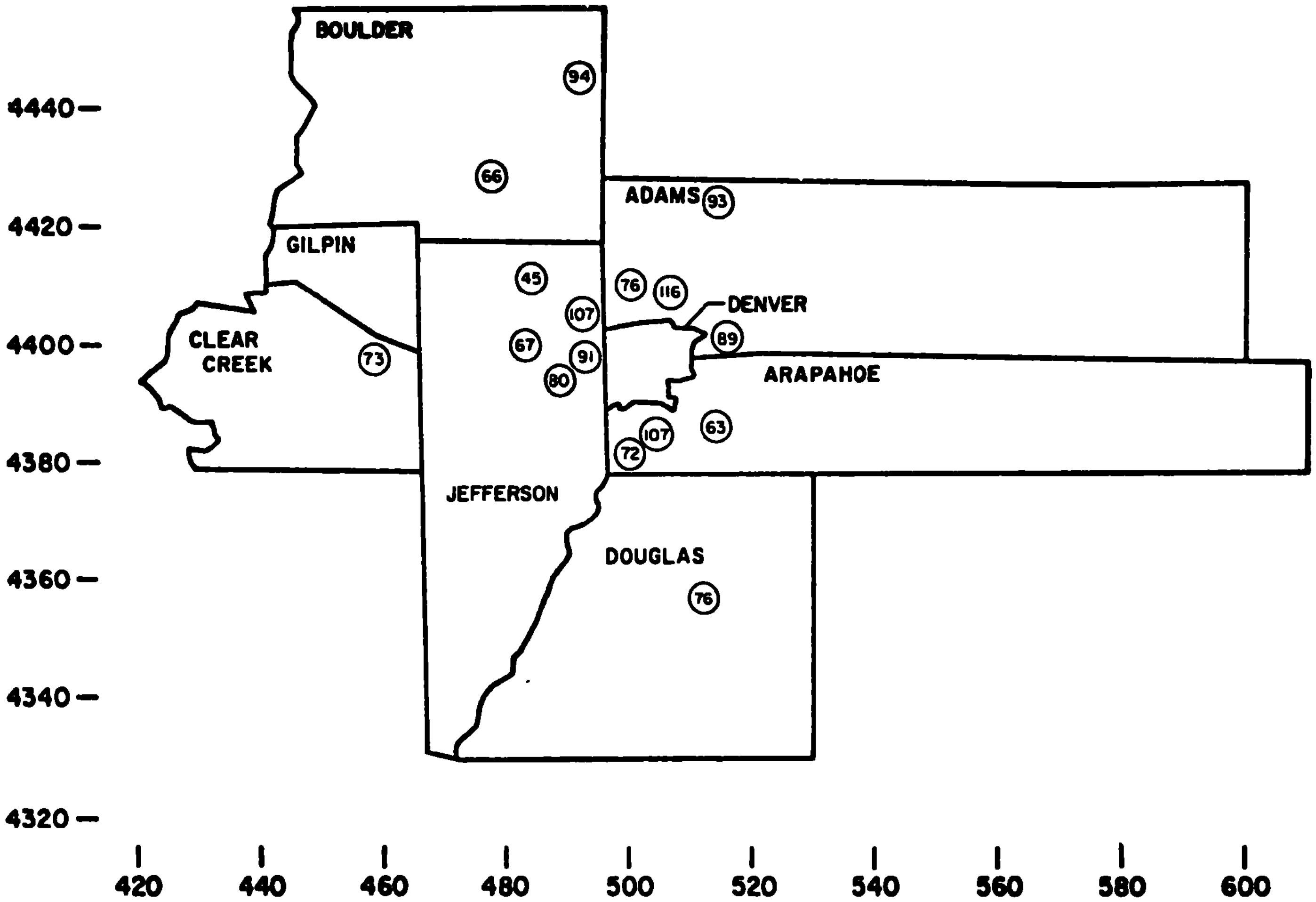

Figure 4. Annual geometric means of TSP in the Denver AQCR ($\mu g/m^3$)

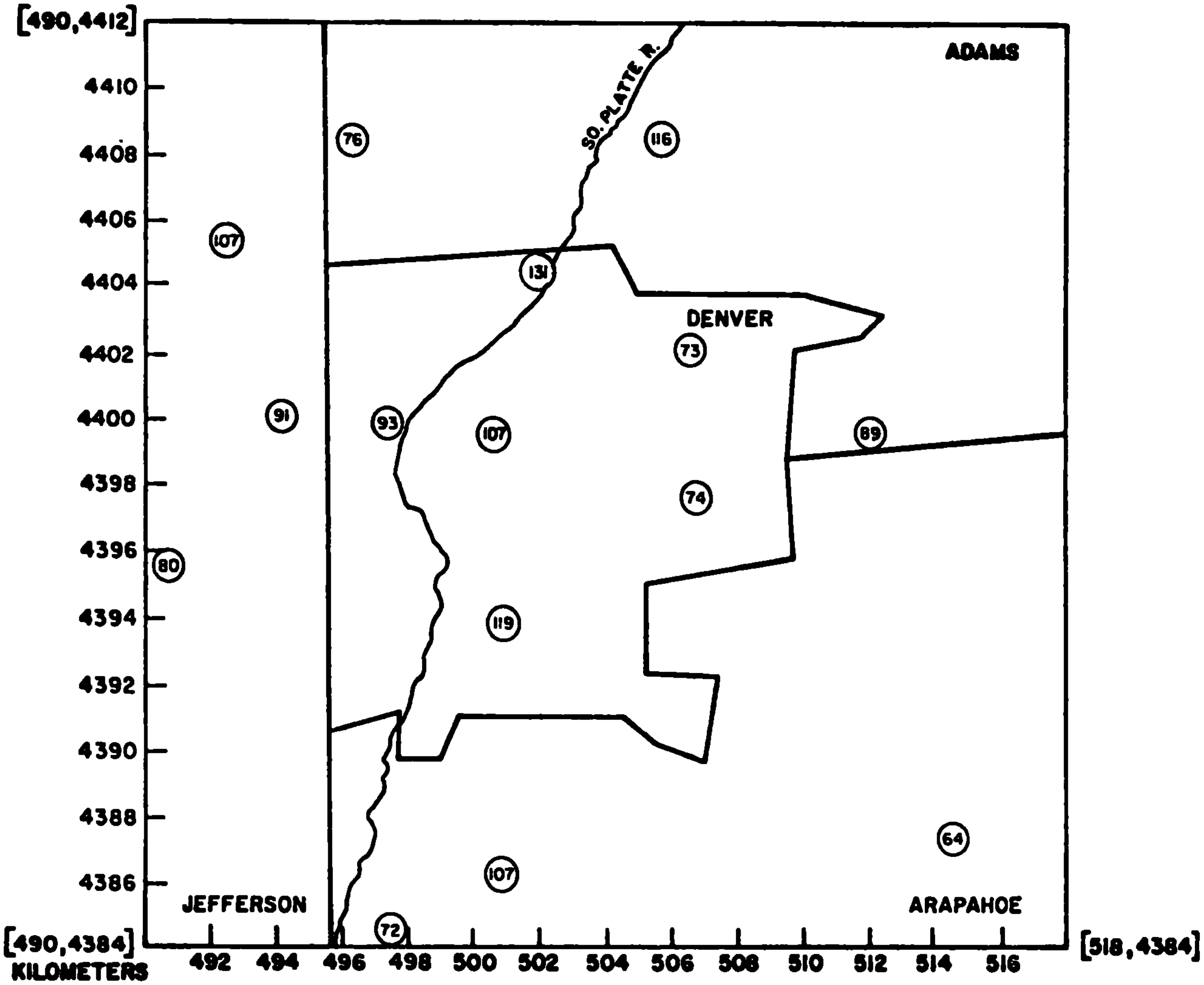

Figure 5. Annual geometric means of TSP in the Denver county area ($\mu g/m^3$)

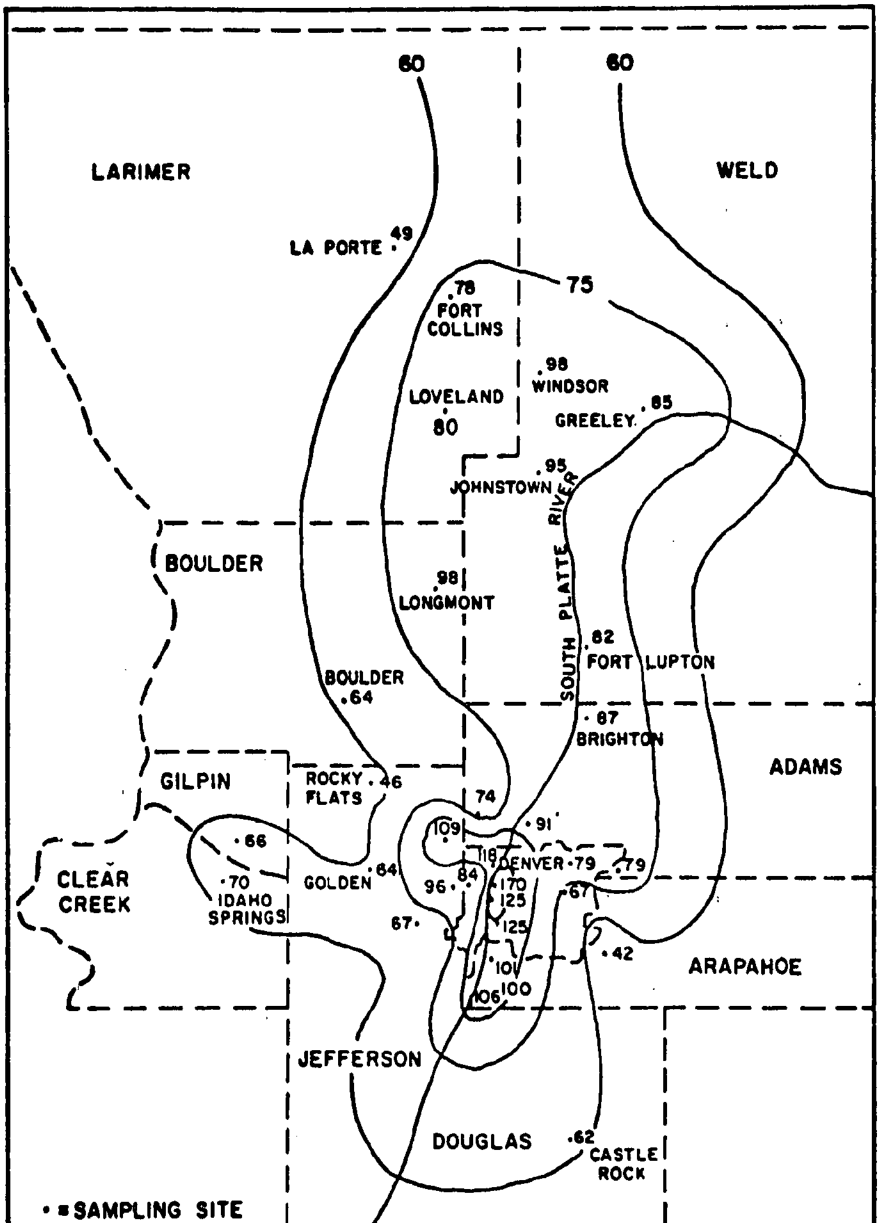

Figure 6. Average annual suspended particulate concentrations measured in Denver and surrounding counties during 1970-1972. Units are μg/m^3

SECTION II

ANALYSES

This section presents the individual analyses that were performed on the data gathered for the study of the particulate problem in Denver. It attempts to correlate various factors which are known to influence air quality with the measured ambient TSP concentrations. These factors include those that most often come under the jurisdiction of the air pollution control agency - emissions, regulations, and monitor siting - and other factors that are not usually or cannot be controlled - urban activity, meteorology, etc.

EMISSIONS

The Metropolitan Denver Intrastate AQCR is a relatively light industrialized area with less than 150 sources coded into the National Emissions Data System (NEDS) for all eight counties. The current NEDS for the area provides the breakdown of the emissions from each source category in the AQCR and the individual counties given in Table 3. The majority of the emissions in the AQCR (82 percent) occur in the three counties, Boulder, Denver, and Jefferson, whereas the counties of Clear Creek, Douglas, and Gilpin each contribute less than 2 percent to the total.

Though the point sources are not numerous, they do contribute slightly over half of the total inventoried emissions in the AQCR. However, the point sources do not contribute evenly to the emissions in each county. While there are no point sources listed in Clear Creek County, its neighboring county, Gilpin, has 98 percent of its particulates attributed to

Table 3. PARTICULATE EMISSIONS IN THE DENVER AQCR, BY COUNTY (CURRENT NEDS (1974))

	Denver AQCR			Adams County				Arapahoe County				Boulder County			
	Total emissions TPY			Total emissions TPY			County % of AQCR	Total emissions TPY			County % of AQCR	Total emissions TPY			County % of AQCR
	Point	Area	Total	Point	Area	Total	Total	Point	Area	Total	Total	Point	Area	Total	Total
Fuel combustion	(10,468)	(13,253)	(23,721)	(803)	(1,084)	(1,887)	(8)	(2)	(1,127)	(1,129)	(5)	(8,481)	(1,518)	(9,999)	(42)
External	10,468	13,253	23,721	803	1,084	1,887	8	2	1,127	1,129	5	8,481	1,518	9,999	42
Residential	-	411	411	-	56	56	14	-	42	42	10	-	56	56	14
Electrical	8,721	-	8,721	748	-	748	9	-	-	-	-	7,579	-	7,579	87
Industrial	1,370	12,206	13,576	47	945	992	7	2	1,030	1,032	6	903	1,381	2,284	17
C-I	378	637	1,015	9	83	92	9	-	55	55	5	-	84	84	8
Internal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industrial process	(13,815)	-	13,815	(1,548)	-	(1,548)	(4)	(151)	-	(151)	(1)	(2,127)	-	(2,127)	(13)
Chemical	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Food/agriculture	248	-	248	221	-	221	89	-	-	-	-	-	-	-	-
Metals	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Mineral	13,409	-	13,409	1,195	-	1,195	9	151	-	151	1	2,127	-	2,127	16
Petroleum	132	-	132	132	-	132	100	-	-	-	-	-	-	-	-
Other	24	-	24	-	-	-	-	-	-	-	-	-	-	-	-
Solid Waste Disposal	(377)	(464)	(841)	-	(82)	(82)	(10)	-	(70)	(70)	(8)	-	(88)	(88)	(10)
Government	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Residential	-	320	320	-	63	63	20	-	53	53	17	-	43	43	13
C-I	377	131	508	-	17	17	3	-	14	14	3	-	44	44	9
Industrial	-	12	12	-	2	2	17	-	2	2	17	-	1	1	8
Transportation	-	(7,119)	(7,119)	-	(963)	(963)	(14)	-	(895)	(895)	(13)	-	(700)	(700)	(10)
Gasoline	-	5,338	5,338	-	755	755	14	-	714	714	13	-	552	552	10
Diesel	-	1,385	1,385	-	208	208	15	-	181	181	13	-	147	147	11
Aircraft	-	395	395	-	-	-	-	-	-	-	-	-	-	-	-
Vessels	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Miscellaneous	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	24,661	20,836	45,497	2,352	2,129	4,480	10	153	2,092	2,245	5	10,615	2,306	12,921	28
% of combined	54.2	45.8	100%	53	47	100%	-	7%	93%	100%	-	82	18	100%	-

Table 3 (continued). PARTICULATE EMISSIONS IN THE DENVER AQCR, BY COUNTY (CURRENT NEDS (1974))

	Clear Creek County				Denver County				Douglas County				Gilpin County				Jefferson County			
	Total emissions TPY			County % of AQCR	Total emissions TPY			County % of AQCR	Total emissions TPY			County % of AQCR	Total emissions TPY			County % of AQCR	Total emissions TPY			County % of AQCR
	Point	Area	Total	Total	Point	Area	Total	Total	Point	Area	Total	Total	Point	Area	Total	Total	Point	Area	Point	Total
Fuel combustion	-	(16)	(16)	-	(451)	(7,160)	(7,611)	(32)	(356)	(55)	(411)	(2)	-	(1)	(1)	-	(375)	(2,292)	(2,667)	(11)
External	-	16	16	-	451	7,160	7,611	32	356	55	411	2	-	1	1	-	375	2,292	2,667	11
Residential	-	6	6	1	-	173	173	42	-	5	5	1	-	-	-	-	-	73	73	18
Electrical	-	-	-	-	394	-	394	5	-	-	-	-	-	-	-	-	-	-	-	-
Industrial	-	-	-	-	12	6,669	6,681	49	356	34	390	3	-	-	-	-	50	2,147	2,197	16
C-I	-	9	9	1	45	318	363	36	-	15	15	1	-	1	1	-	325	72	397	39
Internal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Industrial process	-	-	-	-	(1,901)	-	(1,901)	(14)	(23)	-	(23)	-	(862)	-	(862)	(6)	(7,202)	-	(7,202)	(52)
Chemical	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Food/agricultural	-	-	-	-	27	-	27	11	-	-	-	-	-	-	-	-	-	-	-	-
Metals	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	1	100
Mineral	-	-	-	-	1,850	-	1,850	14	23	-	23	-	862	-	862	6	7,201	-	7,201	54
Petroleum	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Other	-	-	-	-	24	-	24	100	-	-	-	-	-	-	-	-	-	-	-	-
Solid waste disposal	-	(1)	(1)	-	(59)	(119)	(178)	(21)	-	(4)	(4)	-	-	-	-	-	(319)	(100)	(419)	(50)
Government	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Residential	-	1	1	-	-	81	81	25	-	3	3	1	-	-	-	-	-	76	76	24
C-I	-	-	-	-	59	34	93	18	-	1	1	-	-	-	-	-	319	21	340	67
Industrial	-	-	-	-	-	4	4	33	-	-	-	-	-	-	-	-	-	3	3	33
Transportation	-	(44)	(44)	(1)	-	(3,058)	(3,058)	(43)	-	(75)	(75)	(1)	-	(15)	(15)	-	-	(1,369)	(1,369)	(19)
Gasoline	-	41	41	1	-	2,115	2,115	40	-	66	66	1	-	14	14	-	-	1,081	1,081	20
Diesel	-	4	4	-	-	575	575	42	-	9	9	1	-	1	1	-	-	260	260	19
Aircraft	-	-	-	-	-	367	367	93	-	-	-	-	-	-	-	-	-	28	28	7
Vessels	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Miscellaneous	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	-	61	61	-	2,411	10,336	12,747	28	379	134	512	1	862	16	878	2	7,896	3,761	11,657	26
% of combined	-	100	100%	-	23	67	100%	-	74	26	100%	-	98	2	100%	-	67	33	100%	-

point sources. Even in those counties with more emissions - Denver and Boulder - the contribution varies widely with 23 percent and 82 percent, respectively, coming from point sources.

Emission Density

Due to its small size (201 km^2) Denver County has a much higher density of emissions than the other counties in the area even though it has only 28 percent of the total emissions. (Boulder has the same level of total emissions but almost 10 times as much area.) In addition, much of the emissions in the surrounding counties are concentrated near Denver County. Figures 7 and 8 provide emission density isopleths for area and point sources in the AQCR, respectively. The allocated emissions for these figures are the result of a Computer Assisted Area Source Emissions (CAASE) gridding procedure performed for the development of an example maintenance plan for the Denver area[1] utilizing the NEDS inventory at that time. As the immediate Denver County area is the area of highest emission density and similarly highest TSP concentrations, Figures 9 and 10 provide a better resolution of the emission density of area and point sources. (The less than whole numbers in the outlying counties in these figures are a result of different coordinates being used.)

An updated emission inventory of all point sources is just being completed for Colorado by PEDCo Environmental as part of the future maintenance planning activities in the state. As discussed later, this update has provided significantly different emission totals for many of the counties in the AQCR. A point source listing with emission rates was provided to GCA from this effort and the locations of all of these sources in the Denver area are given in Figure 11 and for the rest of the AQCR all sources over 10 tons per year are plotted in Figure 12. From all of these figures it is evident that the Denver County area is the most densely polluted part of the AQCR with major point source activity on the western, southern, and northern boundaries of the county.

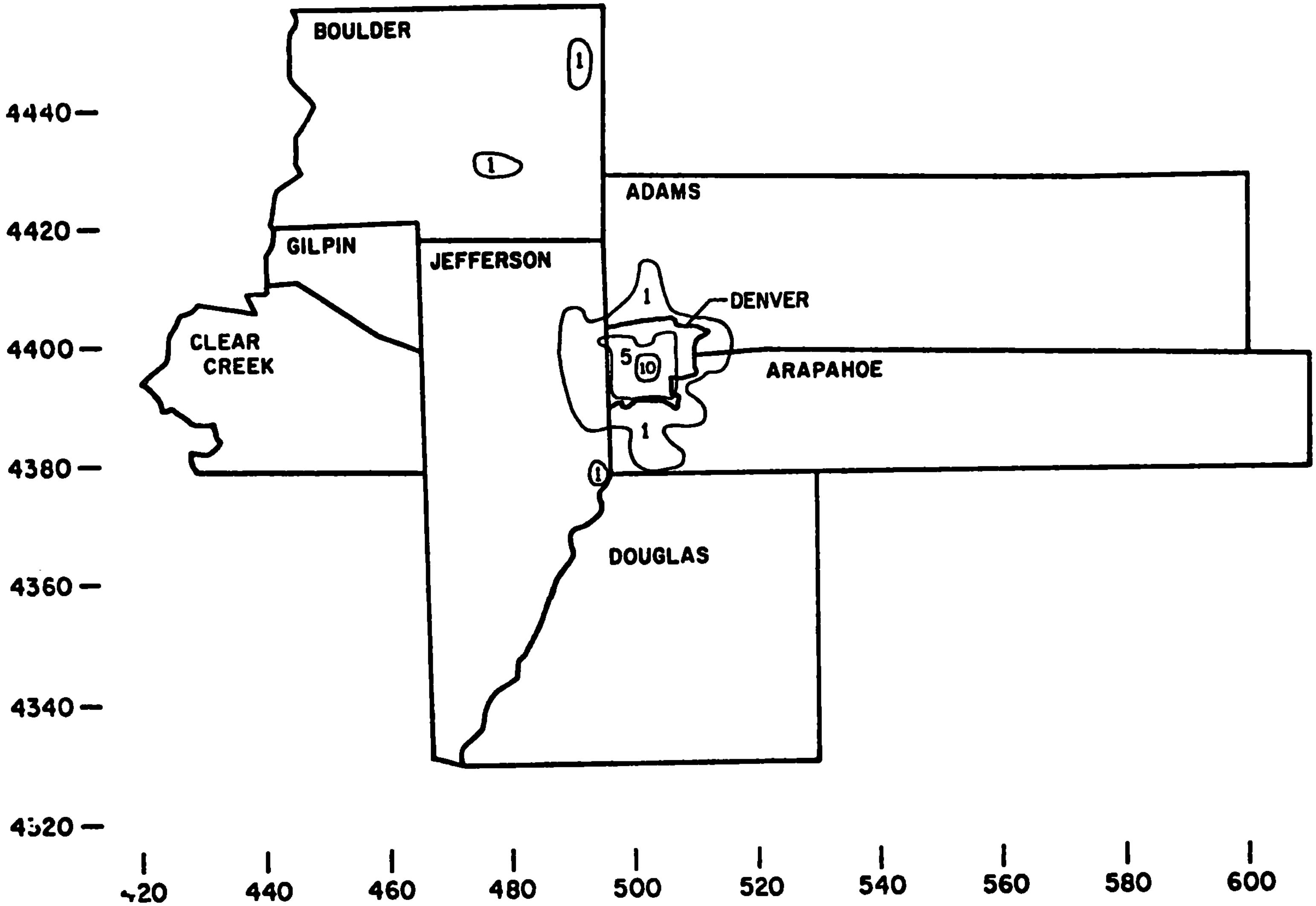

Figure 7. Area source emission density in the Denver AQCR (x 10^2 tons per year per 16 sq km) (Based on CAASE program - NEDS Circa 1973)

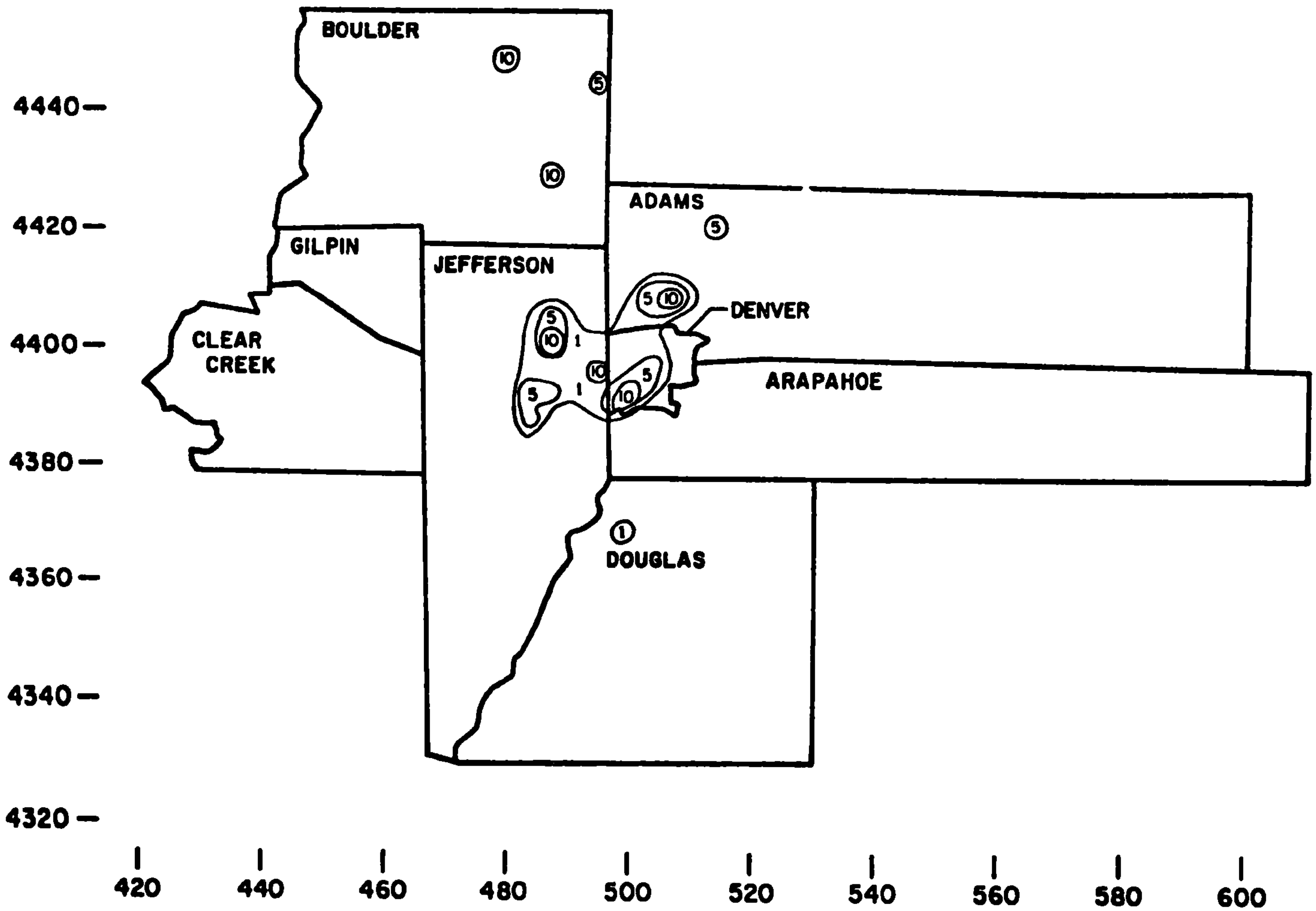

Figure 8. Point source emission density in the Denver AQCR (x 10^2 tons per year per 16 sq km)
(Based on CAASE program - NEDS Circa 1973)

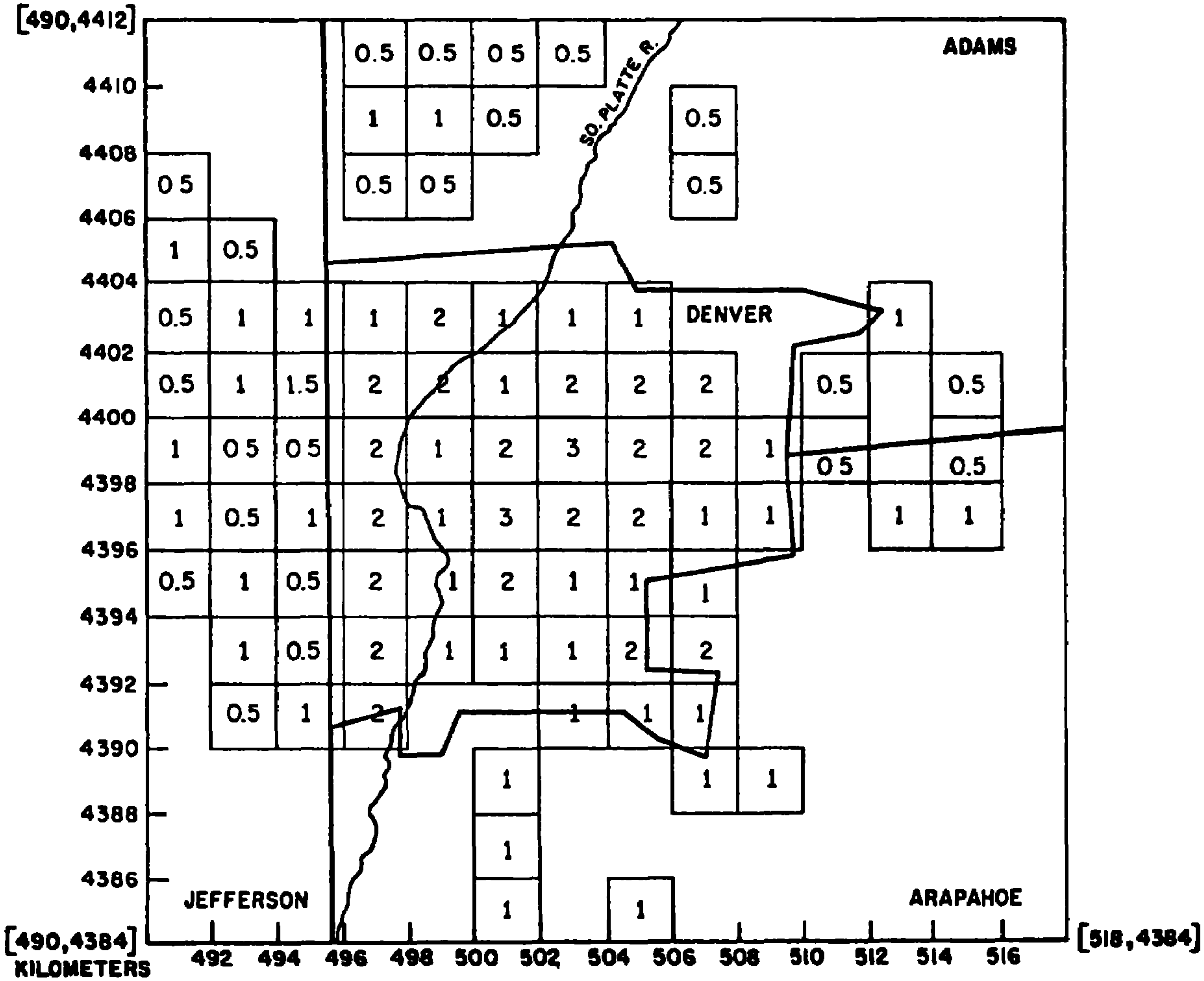

Figure 9. Area source emission density in the Denver County area (x 10^2 tons per year per 16 sq km) (Based on CAASE program - NEDS Circa 1973)

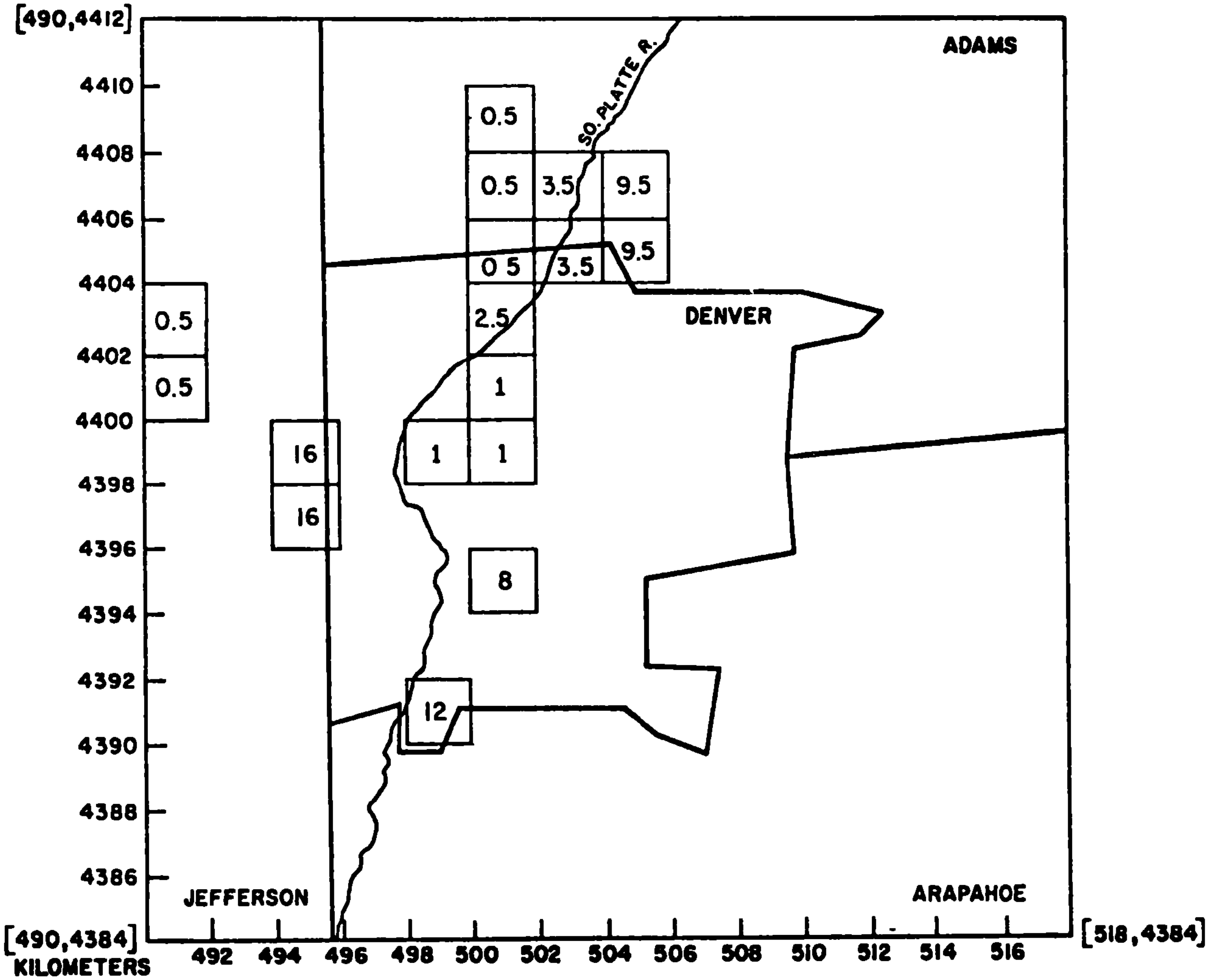

Figure 10. Point source emission density in the Denver County area (x 10^2 tons per year per 4 sq km) (Based on CAASE program - NEDS Circa 1973)

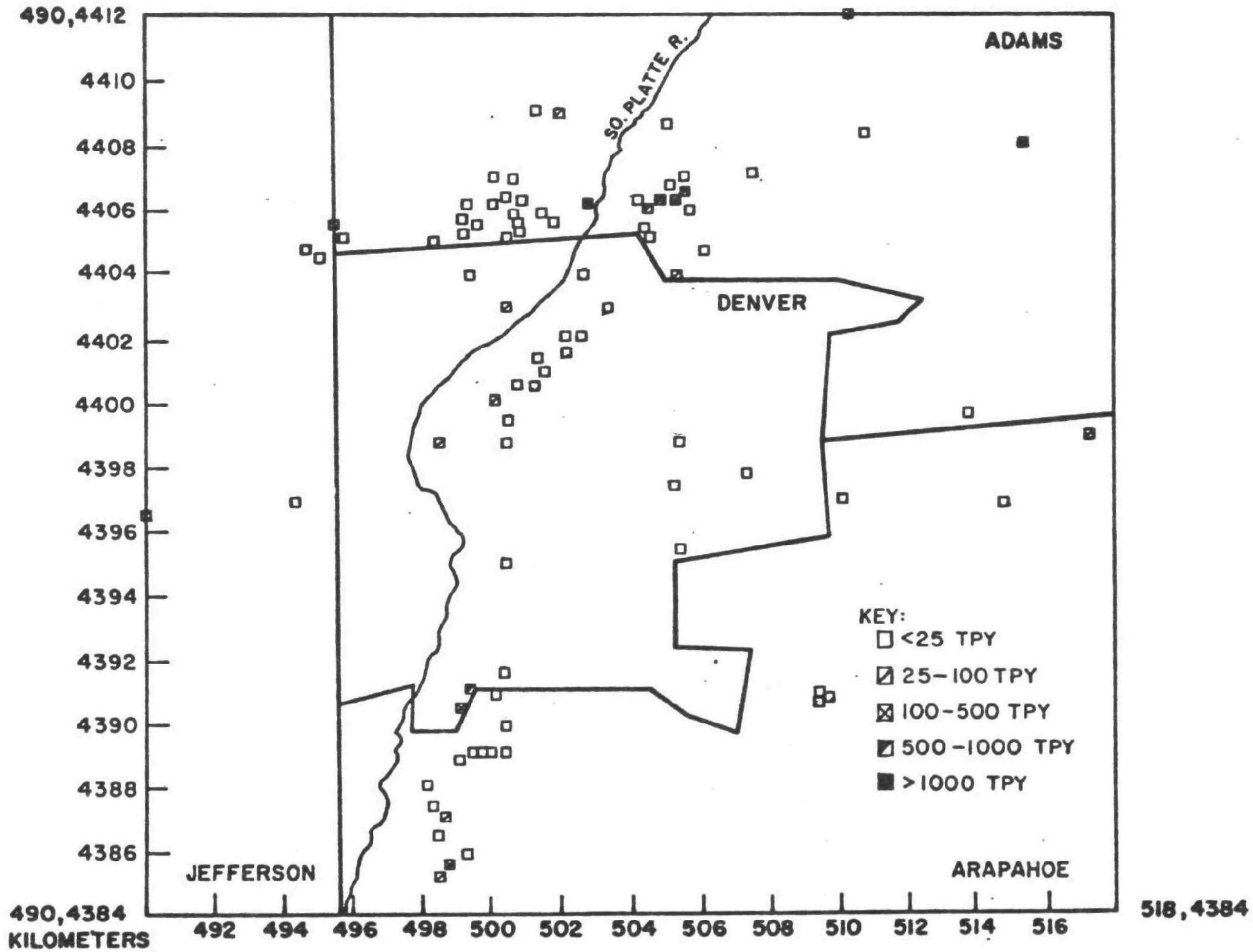

Figure 11. Location of point sources in the Denver County area (Based on recent PEDCo update)

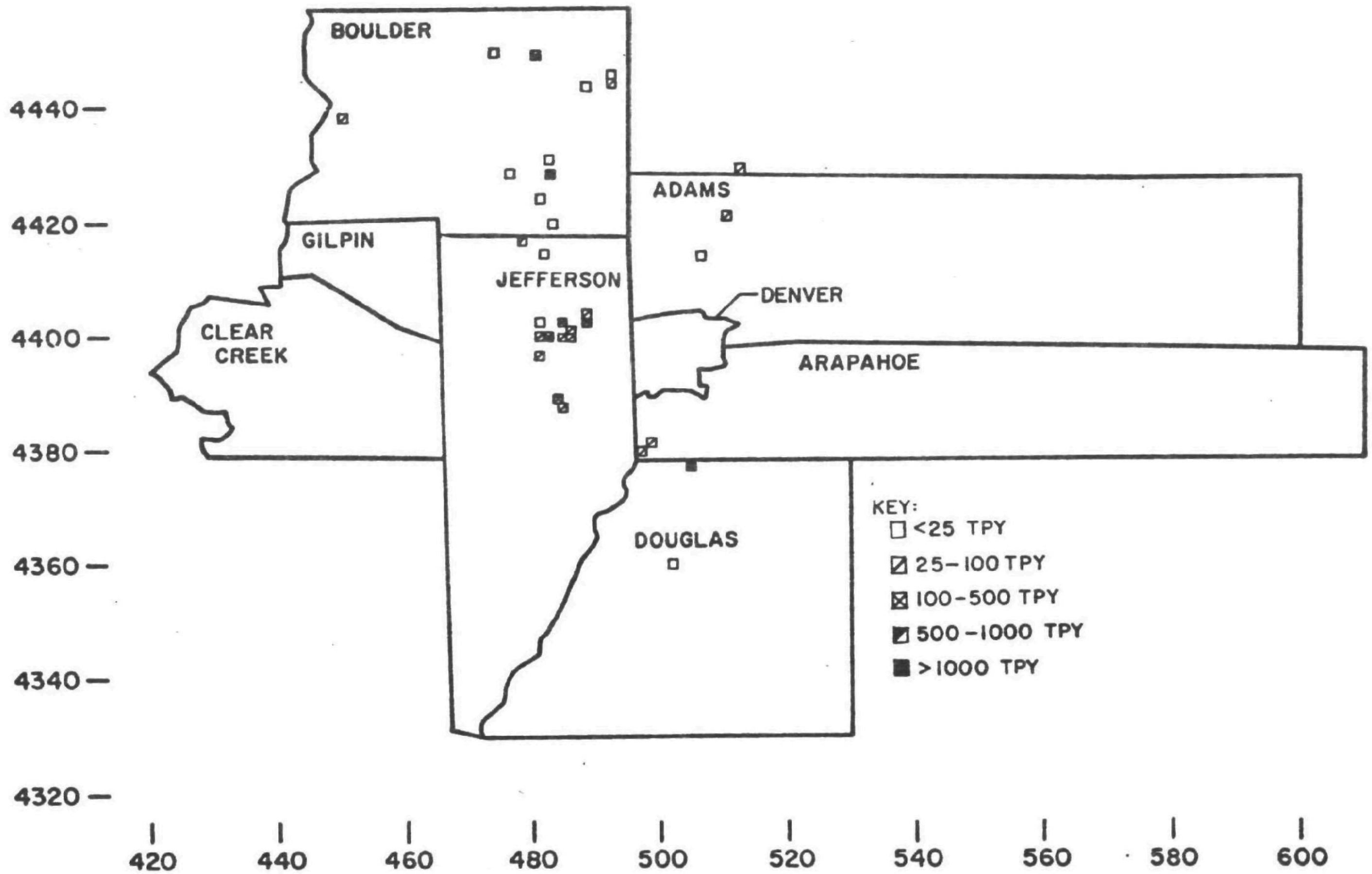

Figure 12. Location of point sources ($\geq$ 10 tons/year) in the Denver AQCR outside of the Denver County area (Based on recent PEDCo update)

The above NEDS data does not include any estimate of the possible fugitive dust emissions that may be occurring in the AQCR. Fugitive dust sources have been considered to contribute significantly to the TSP concentration and several estimates of their possible impact have been made. A calculation of the preliminary data supplied from the MRI study[2] of dirt roads, dirt airstrips, construction, and agricultural tilling indicated that the fugitive dust emissions from these source categories contributes almost 10 times the tonnage as the total inventoried emissions and over 20 times the tonnage of the inventoried area source emissions for the AQCR (see Table 4). The majority of these emissions are from dirt roads (64 percent) and construction (31 percent).

Another study, specific to the State of Colorado, was performed by PEDCo Environmental to establish the levels of fugitive dust.[3] The results of this study, given in Table 5, indicate emissions amounting to more than two and a half times the NEDS emissions. While the accuracy of these emission inventories can not be fully determined in this project, it is assumed that the latter study would be more applicable to the Denver area than the MRI study which indicates more than three times as much fugitive dust as the PEDCo report. The allocation of the fugitive dust emissions to different areas in the counties to determine emission densities, as done for the Denver maintenance study, is given in Figure 13.

From these figures some estimate of the density of the emissions in the vicinity of each sampler may be determined. Table 6 provides a listing of the monitors in order of increasing TSP concentration and with the estimated emission densities from each source sector (point, area, fugitive). Since the emission densities are from 1972 and 1973 inventories, the TSP concentration used in the table is the geometric mean of the 1972 and 1973 annual geometric means for each station. The point and area source emission densities are an average of the respective emission densities within a 2 kilometer radius of the monitor.

Table 4. FUGITIVE EMISSIONS IN THE METROPOLITAN DENVER AQCR (IN TONS PER YEAR)[a]

County	Unpaved roads	Dirt air strips	Construction	Land tilling	Total	County % of AQCR
Adams	56,000	5	22,000	16,000	94,005	22
Arapahoe	26,000	184	16,000	5,000	47,184	11
Boulder	83,000	0	12,000	1,280	96,280	23
Clear Creek	17,000	0	1,460	0	18,460	4
Denver	1,270	0	46,000	0	47,270	11
Douglas	40,000	88	1,640	610	42,338	10
Gilpin	5,000	0	320	0	5,320	1
Jefferson	44,000	0	30,000	370	74,370	17
AQCR total	272,270	277	129,420	23,260	425,227	100%
Percent of total	64	0	31	5	100%	

[a]from MRI study[2]
Not included in any other inventory.

Table 5. DENVER AQCR FUGITIVE DUST INVENTORY[a]

Fugitive dust sources	Adams	Arapahoe	Boulder	Clear Creek	Denver	Douglas	Gilpin	Jefferson	Total	%
Unpaved roads	12,704	8,205	10,403	987	674	1,537	17,732	7,470	59,712	50
Sand on paved roads (snow control)	1,979	1,307	555	Neg.	5,816	Neg.	Neg.	2,581	12,238	10
Agriculture	6,358	821	6,586	Neg.	Neg.	580	Neg.	328	14,673	12
Land development	240	975	278	20	Neg.	2,595	3	473	4,584	4
Residential and commercial construction	2,883	3,005	285	1,920	944	563	480	3,235	13,315	11
Highway construction	1,266	359	490	3,091	524	Neg.	Neg.	2,648	8,378	7
Quarrying, mining, and tailings	320	416	1,351	1,419	Neg.	328	11	1,056	4,901	4
Aggregate storage	164	24	124	Neg.	80	4	2	11	409	0
Cattle feedlots	144	Neg.	105	Neg.	Neg.	22	Neg.	Neg.	271	0
Total fugitive dust	26,058	15,112	20,177	7,437	8,038	5,629	18,228	17,802	118,481	100%
County % of AQCR	22	13	17	6	7	5	15	15	100%	

[a] From PEDCo data.[3]
Done concurrent with PEDCo 1972 inventory.
Not included with area sources in Table 7.

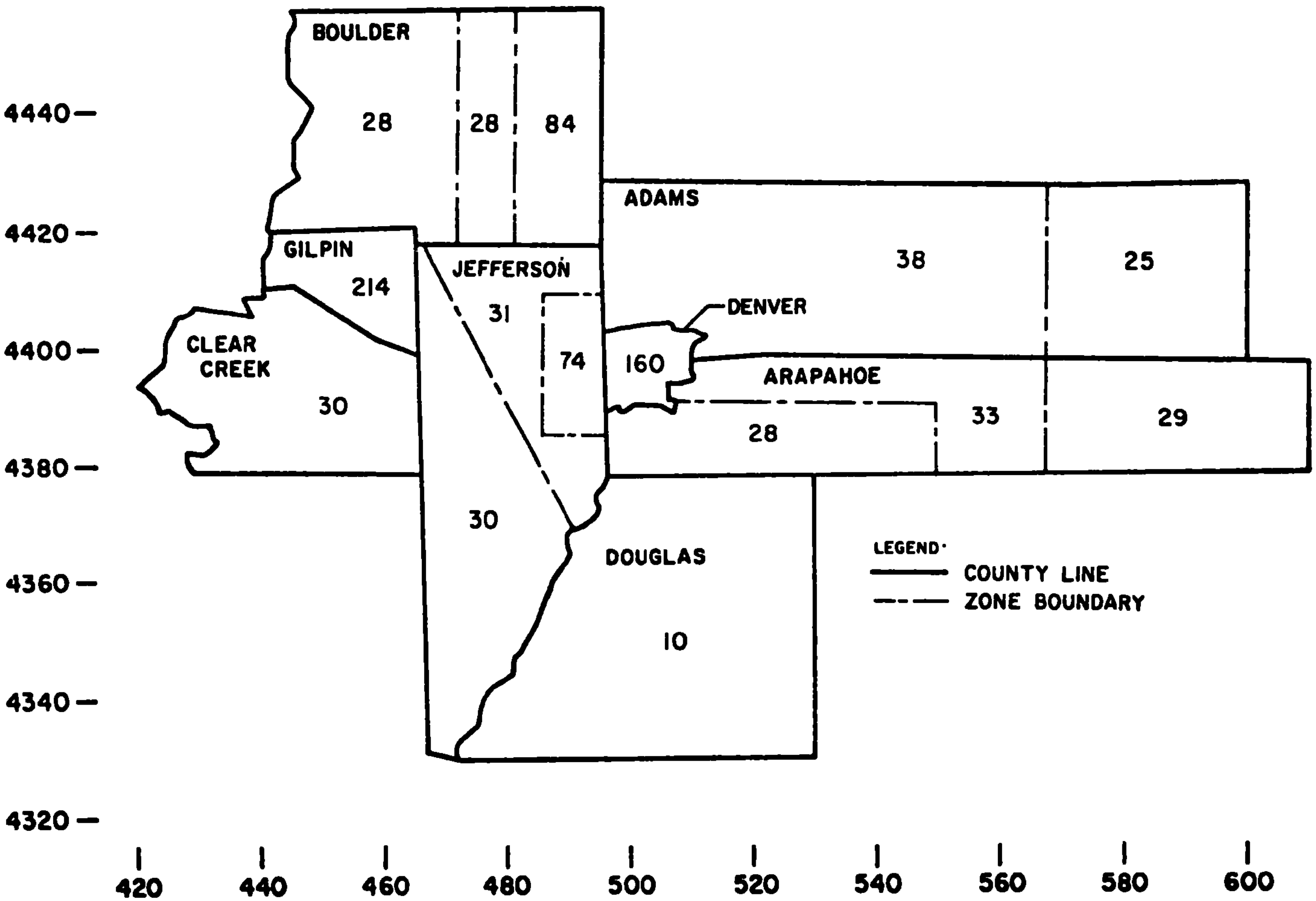

Figure 13. Fugitive dust emission density in the Denver AQCR (tons per year per 4 sq km) (PEDCo 1972 study. Allocated by GCA in Maintenance Study)

Table 6. PARTICULATE EMISSION DENSITIES AND TSP CONCENTRATIONS (1972-1973) AT MONITORING SITES IN THE DENVER AQCR

Station	TSP[a] concentration	Emission density			
		Point[b] 100 tons/year per 4 sq km	Point[b] 100 tons/year per 4 sq km	Fugitive tons/year per 4 sq km	Total tons/ year
Rocky Flats	41	0	0	31	31
Cherry Creek	45	0	0	28	28
Golden	65	1.25	0	31	156
Boulder	66	0	1.25	28	153
State Health	68	0	1.75	160	335
Black Hawk	70	0	0	30	30
Lakewood	73	0	0.75	74	149
Castle Rock	74	0	0	10	10
Hull Photo	77	0	1.25	160	285
Westminster	80	0	0.75	38	113
CARIH	83	0.25	1.75	160	360
Aurora	91	0	0.5	74	88
Edgewater	92	4	1.0	38	574
Brighton	96	1	0	38	138
Adams City	96	2	0.5	28	288
Englewood	106	0	0.75	74	103
Arvada	109	0	0.25	84	99
Longmont	111	1	0.5	160	234
Sewer Plant	120	3	0.25	160	485
Sch. Adm. Bldg.	126	0.75	1.75	160	410
Gates Bldg.	127	4	1.5	160	710

[a]Geometric mean of 1972 and 1973 annual geometric means.

Sources: Point - CAASE
Area - CAASE
Fugitive - PEDCo 1972

With several exceptions, the data in this table indicates that the TSP concentration is generally responsive to the total emission density.

The major exceptions to the trend in rising concentration with increasing emission density are in Denver County (State Health, Hull Photo, CARIH) due to the large density of fugitive emissions and at the Edgewater monitor due to impact of point sources. While the latter case may be due to the positioning of the monitor relative to the sources and also specific errors in the point source emission inventory, the fact that the air quality measured in Denver County does not reflect the emission density due to fugitive sources brings into question the relevance of this inventory. As most of the Denver fugitive emissions are a result of sanding on paved roads, this problem is evaluated further under the discussion of sanding for snow control.

In addition to differences in monitor siting and problems with emission inventories, variations in this table also reflect the topography and air flow in the area. Due to the strong valley effect, monitors which are located in a relatively low emission density area in the valley will often be measuring particulates generated in another part of the valley. This is discussed further under the analysis of the climatology.

Emission Trends

A major problem in the formulation of control strategies in the Denver AQCR has been the determination of an appropriate emission inventory upon which to base the strategies. While the exclusion of the consideration of fugitive dust in the Colorado SIP[6] is a large element in this, the more conventional point and area source inventory in the area has never been completely defined.

Table 7 presents summaries of the point, area, and total emissions for each county in the Denver AQCR as determined from compiled and updated emission inventories from the time of the SIP to the present. The data in this table represents the point and area source emission estimates used in the Colorado SIP for the original formulation of attainment strategies, in the PEDCo study of fugitive dust[3] for the determination of possible measures for the attainment of the secondary standard for particulates, in the GCA formulation of an example maintenance plan for the Denver area[1] (data from 1974 NEDS printout), the current NEDS (1975 printout) provided for this study, and recent updates of the area[7] and point[8] source inventories to be used for maintenance planning by the state. If these were comparable emission inventories, the fact that they each represent different time periods would imply a steady progression to the emission levels projected under the controls of the SIP. Instead, these inventories indicate the widely varied data used for strategy planning which is reflected in the success of the strategies.

As no comparable information was available on long term emission trends for correlation with air quality, the modeling and projection of emissions and air quality that was done for the development of an example maintenance plan in Denver was reviewed. The work done under this study included the modeling of the point, area, and fugitive source emissions using 1972 emissions, the projection of the various source categories in each county based on the regulations for the State of Colorado and the growth rates over this time, and the determination of the impact on air quality of the projected emissions.

In the development of the example plan, it was determined that the regulations imposed by the State of Colorado would have significant impact on the point source emissions and thereby on the levels of TSP contributed by point sources. Table 8 provides particulate concentrations calculated by applying the Climatological Dispersion Model to point source

Table 7. **DIFFERENCES IN POINT AND AREA SOURCE EMISSION INVENTORIES OF PARTICULATES IN THE DENVER AQCR 1970-1975**

AQCR	Jefferson	Gilpin	Douglas	Denver	Clear Creek	Boulder	Arapahoe	Adams		
14,459	152	0	71	2,141	0	1,777	0	10,318	SIP (1970)[6]	Point
42,720	8,652	2,640	44	1,117	-	7,882	8,537	12,448	PEDCo Study (1972)[3]	Point
25,856	7,917	862	379	2,451	-	9,937	154	3,481	Example AQMP[1] (1973)	Point
24,601	7,896	862	379	2,411	0	10,615	153	2,352	Current NEDS (1974)	Point
12,982	2,280	0	51	1,171	8	3,283	3,374	2,815	PEDCo Update (1975)	Point
5,581	152	0	71	1,431	0	936	0	3,261	SIP Projected[a]	Point
8,963	1,018	9	52	4,065	39	795	863	2,122	SIP (1970)[6]	Area
8,739	1,017	9	52	3,887	39	763	863	2,109	PEDCo Study (1972)	Area
13,457	2,205	4	72	7,186	43	1,457	1,224	1,265	Example AQMP[1] (1973)	Area
20,836	3,761	16	134	10,326	61	2,306	2,092	2,129	Current NEDS (1974)	Area
9,000	1,000	-	100	4,100	-	800	900	2,100	TRW Update (973)	Area
5,594	641	1	44	2,646	5	460	594	1,203	SIP Projected[a]	Area
23,422	1,170	9	123	6,206	39	2,572	863	12,440	SIP (1970)[6]	Total
51,459	9,669	649	1,496	5,004	39	8,645	9,400	14,557	PEDC Study (1972)	Total
39,312	10,123	865	451	9,636	43	11,394	1,378	4,746	Example AQMP[1] (1973)	Total
45,497	11,657	818	512	12,747	61	12,921	2,245	4,480	Current NEDS (1974)	Total
21,982	8,296	12,280	151	5,271	8	4,083	4,274	4,915	Recent Update[b] (1974)	Total
11,445	793	1	115	4,077	5	1,396	594	4,464	SIP Projected[a]	Total

[a]Given in the SIP as the projected emissions under the controls stipulated in the SIP.

[b]The recent update is considered 1974 due to its combination of 1973 and 1975 inventories.

Table 8. CALCULATED PARTICULATE CONCENTRATIONS DUE TO POINT SOURCES[a] - 1972 AND 1975[b] ($\mu g/m^3$)

County	Location	Concentration		% reduction
		1972	1975[b]	
Adams	Westminster	9	1	89
	Aurora	3	1	67
	Brighton	7	3	57
	Adams City	17	8	53
Arapahoe	Cherry Creek Dam	2	0	100
	Englewood	8	1	88
Boulder	Boulder	1	0	100
	Longmont	2	1	50
Clear Creek	Idaho Springs	1	0	100
Denver	State Health Department	5	1	80
	Hull Photo	6	2	67
	CARIH	12	2	83
	Sewer Plant	14	6	57
	Sch. Admin. Bldg. (State)	22	4	82
	Gates Building	22	3	86
Douglas	Castle Rock	1	0	100
Gilpin	Black Hawk	1	0	100
Jefferson	Rocky Flats	4	2	50
	Golden	5	2	60
	Lakewood	9	1	89
	Edgewater	56	4	93
	Arvada	6	1	83

[a]Calculated with the Climatological Dispersion Model.

[b]1972 NEDS data with Colorado regulations applied to all point sources over 100 tons/year.

emissions in 1972 and 1975. The 1975 emission levels were determined by applying the Colorado regulations to all NEDS sources greater than 100 tons/year. The concentrations are for the specific monitoring sites in the AQCR. Reductions in the concentration attributable to point sources ranged from 50 to 100 percent at the different sites with countywide average reductions around 70 percent or greater.

Because of the large contributions from area and fugitive sources, when these emissions were included in the modeling effort (using the Hanna-Gifford Area Source Model), the improvement in the air quality was much less than that due only to point sources. At the same time, since area source emissions were increasing with the growing population and fugitive source emissions could not be controlled to the same extent as point sources, the importance of these sources was projected to increase between 1972 and 1975. Table 9 presents the results of the modeling of all three source sectors. It includes the calculated concentration, adjusted for background, at each of the monitoring sites in 1972 and 1975 and the percent contribution of each of the source sectors to the above background concentration. The contribution of point sources to the modeled TSP concentration was projected to decrease significantly between 1972 and 1975 while the percent contribution from the area and fugitive source categories would rise. Area sources show the biggest rise as these emissions are increasing with the growth of the area while the fugitive dust sources are being controlled by the fugitive dust regulations. The projected decrease in above background TSP concentration between 1972 and 1974 varies between 0 and 56 percent with Denver County having 10 to 20 percent reductions.

While Table 9 indicates that those monitors which were most influenced by point sources in 1972 generally are expected to show the greatest improvement by 1975, the trends in air quality to date do not parallel these results. Table 10 allows for a comparison between the ratio of modeled TSP concentration (above background levels) in 1972 and 1975

Table 9. PERCENTAGE CONTRIBUTION OF PARTICULATE SOURCE SECTORS IN THE DENVER AQCR (1972 AND 1975)

County	Location	1972[d]				1975[a]				% reduction in TSP concentration[c]
		% contribution			Adj. AQ[b]	% contribution			Adj. AQ[b]	
		Point	Area	Fug.		Point	Area	Fug.		
Adams	Westminster	19	45	36	70	3	60	37	63	18
	Aurora	15	-	85	47	6	-	94	43	24
	Brighton	29	-	71	51	12	-	88	45	29
	Adams City	39	22	39	68	19	35	46	57	29
Arapahoe	Cherry Creek Dam	15	-	85	41	-	-	100	37	36
	Englewood	20	53	27	64	3	71	26	58	18
Boulder	Boulder	2	79	19	75	-	87	13	75	0
	Longmont	4	38	58	77	2	44	54	75	4
Clear Creek	Idaho Springs	8	-	92	41	-	-	100	39	18
Denver	State Health Dept.	6	26	68	98	1	32	67	92	9
	Hull Photo	7	34	59	108	2	40	58	101	9
	CARIH	10	40	50	122	2	47	51	110	13
	Sewer Plant	18	13	69	97	8	17	75	85	18
	Sch. Admin. Bldg. (State)	19	35	46	131	4	47	49	114	17
	Gates Building	21	29	50	122	3	40	57	102	22
Douglas	Castle Rock	17	-	83	35	-	-	100	34	20
Gilpin	Black Hawk	1	-	99	98	-	-	100	97	1
Jefferson	Rocky Flats	25	-	75	44	12	-	88	37	50
	Golden	29	-	71	45	11	-	89	38	47
	Lakewood	26	-	74	60	4	-	96	50	33
	Edgewater	54	20	25	118	4	48	48	69	56
	Arvada	14	24	62	66	3	33	64	59	19

[a]Emission rates determined by assuming all sources under compliance and appropriate growth rates in activity.

[b]Adj. AQ is the fitted TSP Concentration adjusted for background contribution in $\mu g/m^3$.

[c]Assuming a background of 30 $\mu g/m^3$.

[d]Based on Circa 1973 NEDS Printout (assumed 1972 data).

Table 10. COMPARISON OF ACTUAL AND PROJECTED CHANGES IN TSP CONCENTRATIONS IN THE DENVER AQCR

Monitor	Ratio of actual annual geometric means, 1972 to 1972	Ratio of projected annual geometric means[a] 1974 to 1972
School Administration	0.79	0.83
Edgewater	0.90	0.44
Gates Building	0.94	0.78
Westminster	0.94	0.82
Longmont	0.97	0.96
Hull Photo	0.98	0.91
Arvada	1.00	0.81
Aurora	1.00	0.76
Boulder	1.06	1.00
Englewood	1.07	0.82
Brighton	1.11	0.71
CARIH	1.17	0.87
Golden	1.19	0.53
Idaho Springs	1.19	0.82
Lakewood	1.22	0.67
Castle Rock	1.28	0.80
Sewer Plant	1.29	0.82
State Health	1.29	0.91
Adams City	1.46	0.71
Rocky Flats	1.88	0.50

[a]From example maintenance plan for Denver.[1]

and the similar ratio for actual measured concentration in 1972 and 1974. This table has been arranged to present the monitors in order of decreasing actual improvement in air quality (increasing ratio) to provide some understanding of what has occurred since the time of the SIP. The order of the monitors in Table 10 indicates that no pattern of trends is evident during this short time frame. While about half of the monitors in Denver have shown some decreases in TSP concentration (School Administration, Gates Building, Hull Photo), the other monitors (CARIH, Sewer Plant, State Health) have all noted increases in TSP levels between 1972 and 1974; similar differences may be noted in the other counties. In general, more monitors showed increasing values in TSP than decreasing values.

In addition to the review of long-term trends in emissions and TSP concentrations, some further understanding of the relationship between these two parameters may be derived from an analysis of the seasonal fluctuations. In Denver, the seasonal differences in emissions would be due not only to the space heating emissions that occur in the winter but also to the fugitive emissions from the street sanding in winter and the construction activity primarily in the summer. Table 11 presents these emissions apportioned to each month. The space heating emissions, estimated to be equal to the sum of the current NEDS area source emissions from residential and commercial/institutional use and one-third of the industrial area source emissions (a similar ratio as found in Philadelphia), are apportioned by heating degree days for 1974. The fugitive emissions from sanding on paved roads were apportioned by the amount of cubic yards of sand used each month and the construction activity emissions were evenly divided among those months when no sanding activity occurred as it was expected that little ground breaking activity would occur during snow cover.

From the estimated monthly emissions in Table 11 it would appear that in Denver County there are two to three times the emissions in the winter

Table 11. ESTIMATED MONTHLY EMISSIONS OF PARTICULATES IN DENVER COUNTY[a]

Month	Space heating emissions	Emissions from sanding[b]	Emissions from construction	Total monthly emissions	Ratio[c]
January	597	2,153	0	3,649	2.11
February	380	1,403	0	2,682	1.55
March	299	535	0	1,733	1.00
April	244	241	0	1,384	0.80
May	54	0	244	1,197	0.69
June	27	0	245	1,171	0.68
July	0	0	245	1,144	0.66
August	0	0	245	1,144	0.66
September	81	0	245	1,225	0.71
October	163	0	244	1,306	0.75
November	380	589	0	1,868	1.08
December	489	895	0	2,283	1.32
Total	2,714	5,816	1,468	20,786	

[a]Based on space heating emissions from current NEDS and sanding and construction emissions from PEDCo 1972.

[b]The annual emissions from sanding were apportioned relative to the monthly variations in sand used for snow control.

[c]Monthly emissions ÷ average monthly emissions.

months than in the summer months due to space heating and fugitive emissions from sanding activities. If this is the case, it would be expected that the TSP levels above background would be similarly higher in the winter months, assuming comparable meteorology. Figure 14 provides a plot of the ratio of the monthly emissions to the average monthly emissions and also the ratio of the above background levels of the county-wide monthly geometric means to the county-wide annual geometric mean. This figure indicates a fairly good correlation between the seasonal trends in emissions and TSP concentration given the assumptions about emissions stated above. Discrepancies in the trends, especially during May, are partially explanable through the analysis of meteorology given later. The emission ratios are fairly sensitive to the emission inventory inputs and, while the general shape of the graph remains the same, the magnitude of the difference between the seasons varies widely with the inputs. For example, if it is assumed that the emissions from sanding are half of those assumed by PEDCo, the extremes of the ratios - summer and winter - are much closer to the above background ratios of TSP levels; i.e. emission ratios ranging from 0.77 to 1.85 corresponding to TSP ratios of 0.80 and 1.95 for July and January respectively.

LEGAL AUTHORITY, REGULATIONS, AND SURVEILLANCE

The Colorado Air Pollution Control Act of 1970 created the nine-member Colorado Air Pollution Control Commission to develop an air pollution control program and promulgate such regulations as may be necessary or desirable to "achieve the maximum practical degree of air purity in every portion of the state." Eight members of the Commission are appointed by the governor with the consent of the Senate for a term of 3 years and the other member is from the State Board of Health.

The duties of the Air Pollution Control Commission include the development and maintenance of a comprehensive program for prevention, control,

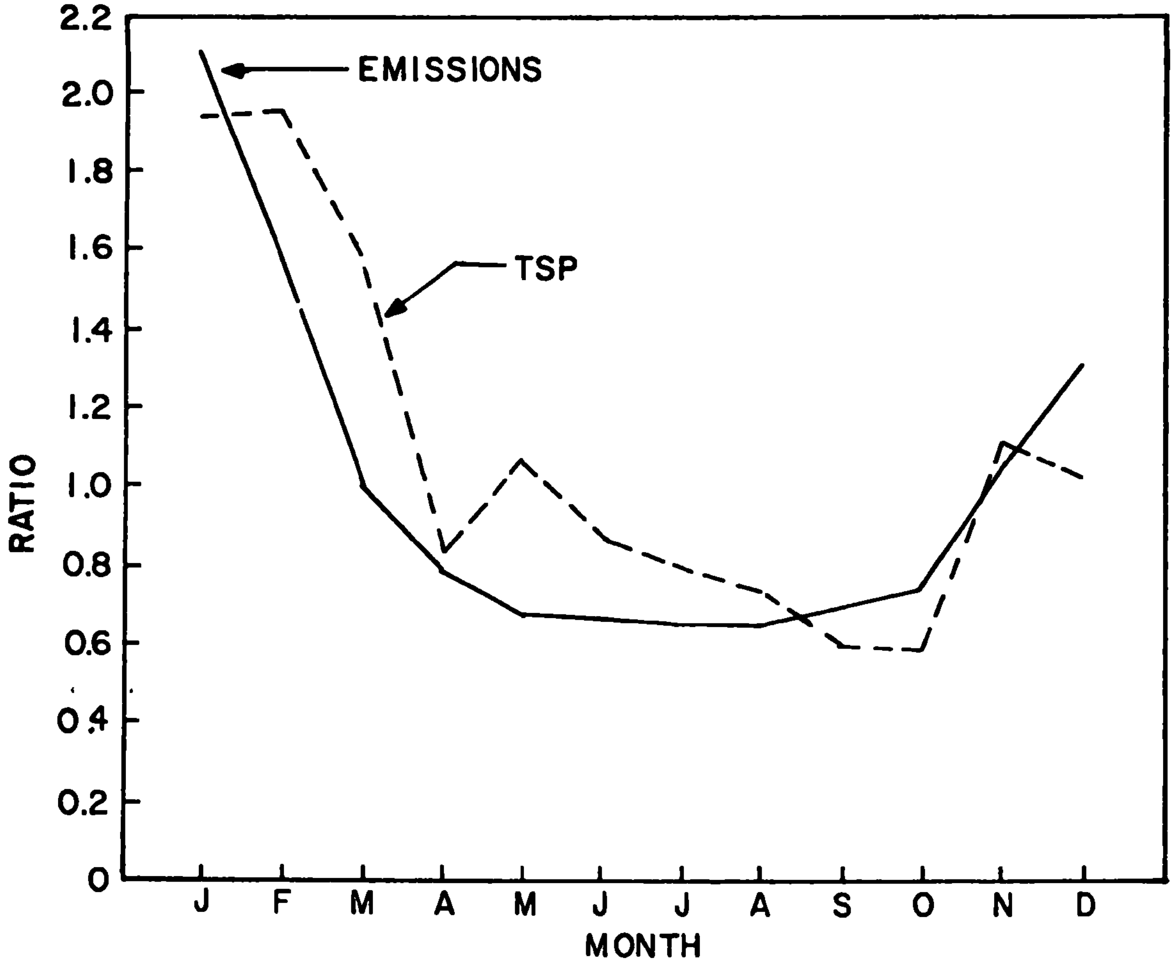

Figure 14. Monthly emission and above background TSP ratios in Denver (1974).

and abatement of air pollution throughout the entire state, including a program for control of emissions from all significant sources of air pollution; the promulgation of ambient air goals for every portion of the state; the adoption and promulgation of ambient air quality standards and emission control regulations; the receipt and, at its discretion, the hearing and determination of violations and applications for the granting of variances; and, at its discretion, the review of any variance order or determination of the variance board to which such applications may have been transmitted.

The Colorado Air Pollution Control Act of 1970 also established a division within the Department of Health to administer and enforce the air pollution control programs adopted by the Commission. Specifically, the Division is empowered to conduct studies and research with respect to air pollution, including the control, abatement, or prevention thereof; determine if the ambient air standards are being violated in any area of the state; enter and inspect any property, premise, or place for the purpose of investigating any actual, suspected, or potential source of air pollution; furnish technical advice and services; notify any affected jurisdiction of standards which are not being met; and to issue contaminant emission notices. The Division also has the authority to enforce compliance with the promulgated emission control regulations.

The Department of Health, within which the Air Pollution Control Division was established, is designated as the "state agency" for all purposes of the Federal Clean Air Act, as amended, and regulations promulgated under that act. The Department of Health accepts and supervises the administration of loans and grants from the Federal government (and from other sources, public or private) which are received by the state for air pollution control purposes.

As required by Section 66-31-8 of the Colorado Air Pollution Control Act of 1970, the Colorado Air Pollution Control Commission has adopted a number of regulations which stipulate control measures for emissions and other measures which help provide for the attainment of the NAAQS. In addition, the Commission has also adopted ambient air standards for suspended particulate matter and sulfur dioxide for the Metropolitan Denver AQCR and the State of Colorado which are more stringent than those promulgated by EPA. The standards for particulate matter outside of the Denver AQCR and other designated areas is 150 $\mu g/m^3$ on a 24-hour basis and 45 $\mu g/m^3$ for the annual arithmetic average. These standards are also to be attained in the Denver AQCR by 1980 with intermediate short-term and long-term standards of 200 $\mu g/m^3$ and 70 $\mu g/m^3$ in 1973 and 180 $\mu g/m^3$ and 55 $\mu g/m^3$ in 1976.

The regulations on emissions of contaminants to the air vary as to their level of technicality. The control stipulations range from banning of emissions (e.g., open burning) and opacity to process rates. Some of the regulations apply generally to control of specific pollutants (particulates, sulfur oxides, odor, hydrocarbons, and chemical substances) from many sources while other apply to individual processes (wigwam waste burners, alfalfa dehydration plants, new sources as controlled by New Source Performance Standards, and motor vehicles). In addition, a permit system, requiring a permit to construct and operate, exists.

The basic control of particulates is through Regulation 1 from which the summary for each source type is given below.

- Visible Emissions - The emission from stationary sources of any pollutant in excess of 20 percent opacity is forbidden. From mobile sources, this section prohibits the emission of any visible emissions for more than 5 seconds from any four-cycle gasoline vehicles, of any emissions greater than 20 percent opacity for more than 10 seconds from a two-cycle gasoline vehicle, and of any emissions greater than 30 percent opacity at less that 8,000 feet or 40 percent opacity at more than 8,000 feet for more than 10 seconds for diesel-powered vehicles.

- Open Burning - Open burning is allowed by permit only, contingent on location, potential contribution to air pollution, climatic conditions, and the existence of alternative disposal methods.

- Fuel Burning Equipment - The emissions from fuel burning are limited to a maximum of 0.5 pounds per million Btu for sources generating less than 1 million Btu, and 0.10 pounds per million Btu input for units larger than 500 million Btu. Intermediate values can be determined from the graph in Figure 15.

- Incinerators - All incinerators in the state must not emit more than 0.15 grains per standard cubic foot and in designated areas of the state, including the Denver AQCR, a limit of 0.10 grains per standard cubic foot is set for all new incinerators and also for existing incinerators effective 1977. In addition, in the designated control areas of the state, incinerators on property devoted to residential use are prohibited effective 1977. Permits are required for all incinerators.

- Manufacturing Processes - Maximum hourly emission rates from any process are determined by the graph in Figure 16 Each process unit is considered a separate entity regardless of how many units are vented through the same opening.

- Fugitive Dust - The regulation of fugitive dust includes a general statewide requirement that no fugitive dust be emitted which exceeds 20 percent visible opacity or which is visible after it leaves the property of the owner of the emission source. Certain activities, such as agriculture, are exempted. Within the Priority I portions of Air Quality Control Regions only, which includes the Metropolitan area but not the whole AQCR, specific requirements are established for control of dust from:

    a. All new unpaved roads and parking areas with traffic volumes of 165 vehicles per day (vpd) or more.

    b. Existing privately owned roads and parking areas with 165 vpd or more.

    c. Existing publicly owned roads and parking areas with 165 vpd or more, but with controls only to the extent allowed by financial resources.

    d. Land development, construction, demolition, and related activities.

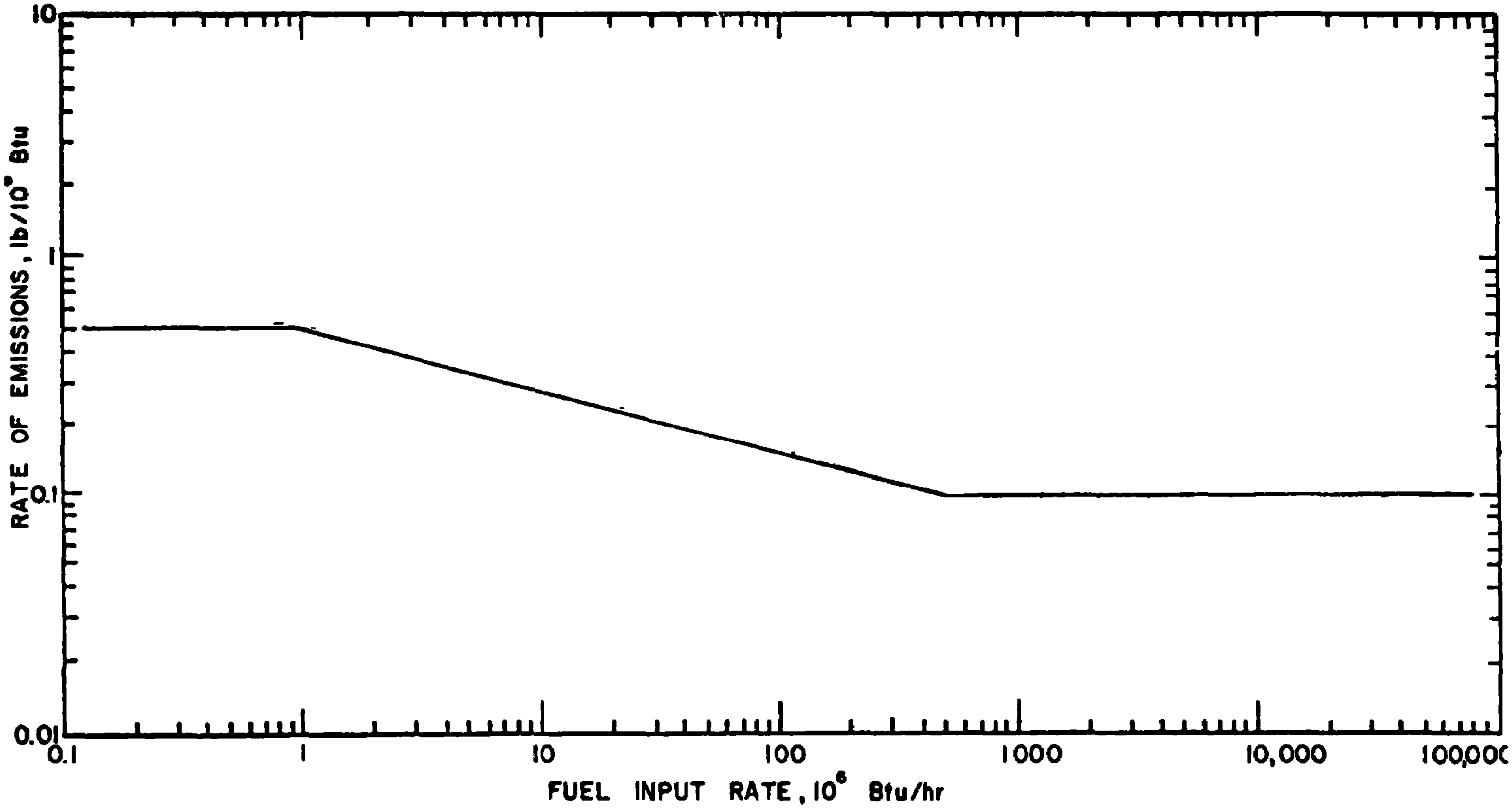

Figure 15. Fuel combustion - emission rate curve for Colorado

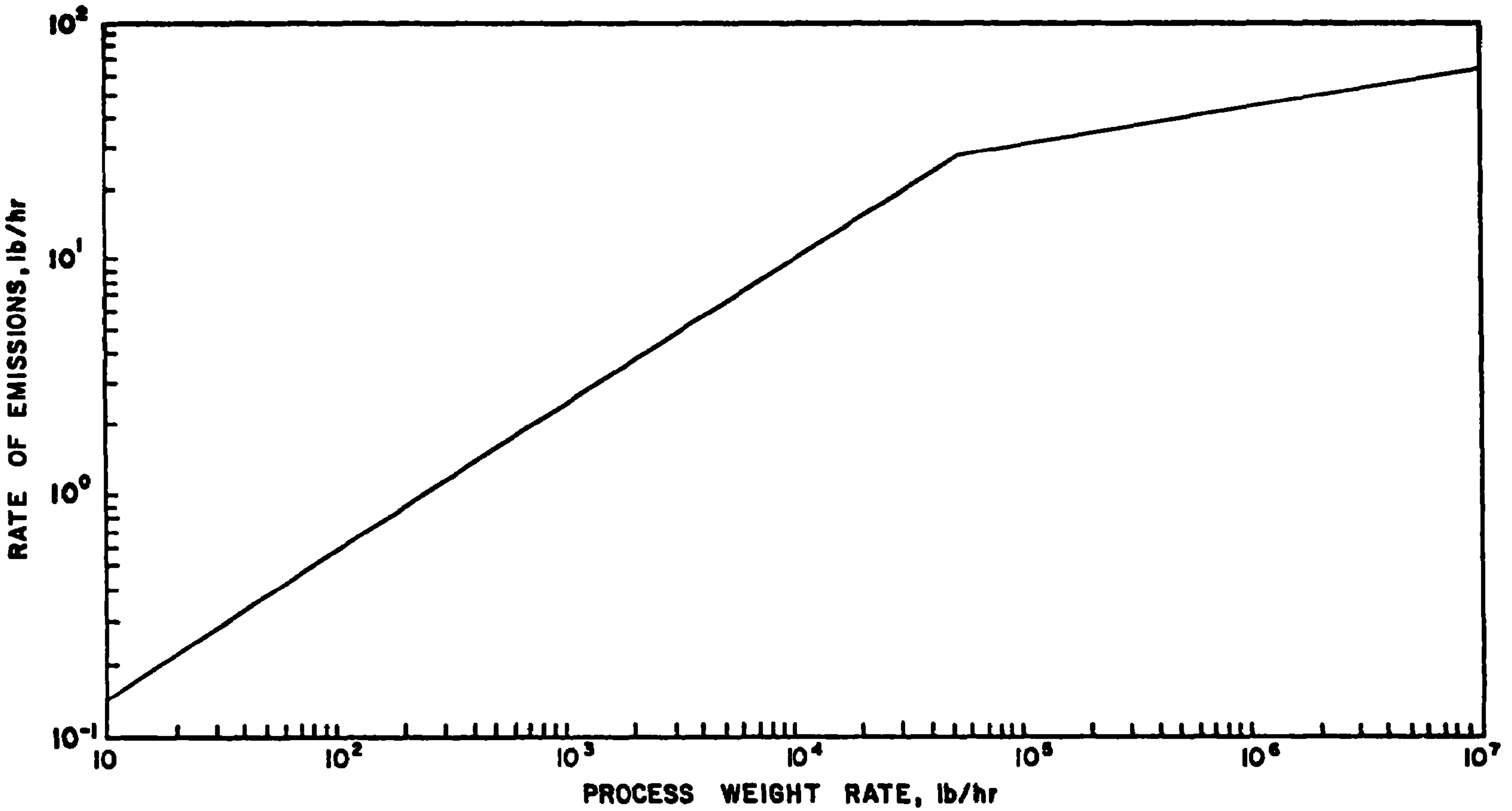

Figure 16. Process weight rate curve for Colorado

In addition, there are control requirements, statewide, on open mining activities. Wherever requirements for controls are provided, permits must be obtained and specified types of abatement and preventive measures identified in the permit must be utilized.

In addition to the control program operated by the State, the City and County of Denver maintains an Air Pollution Control Section in its Department of Health and Hospitals: Environmental Health Service. Control measures required by the City are essentially identical to those of the State except for incinerators. The City has the additional restriction that incinerators must be multiple chamber or auxiliary fuel-fired and that all incinerators with a changing rate of more than 200 pounds of solid waste per hour must not emit particulate matter in excess of 0.10 grains per standard cubic foot.

The particulate regulations in the Denver AQCR are among the most stringent of those cities reviewed in the course of this study and as compared with published summaries of other states.[4] While Colorado's control of large fuel-burning sources (greater than 500×10^6 Btu) is no more stringent than the most stringent of the other cities (with the exception of Washington, D.C.), it is much more restrictive than most of the cities for the smaller sources and imposes the maximum control of 0.1 pounds/10^6 Btu/hr on sources an order of magnitude smaller than in most other areas. Similarly with incinerators, when considering the controls imposed by the City, the restrictions are on sources an order of magnitude smaller than in many other areas. The general process weight rate regulation is more stringent than those in other areas reviewed (with the exception of Illinois) and slightly more stringent than the average of all state regulations applicable to general process sources.[5]

The regulation promulgated for the control of fugitive dust, which became effective August 1, 1974, is the most comprehensive and detailed of those reviewed to-date. The controls under this regulation were the maximum feasible controls recommended for the area in a separate study[3] except for the lack of a control strategy for removing sand after sanding operations due to snow and the control of dust from cattle feedlots. While the control of this latter source was determined to be of little significance, the removal of sand on paved roads was projected to help prevent the future growth in fugitive dust emissions.[1]

The enforcement of regulations is undertaken by both the Colorado Air Pollution Control Division (CAPCD) and the Denver Air Pollution Control Section with the latter agency working only within the City limits. Almost all sources have been determined to be in final compliance with the regulations with only one major source, a unit of the power company, being out of compliance frequently due to operating difficulties. This is expected to be solved shortly. Determination of compliance and enforcement relies primarily on the opacity regulation though sources also must meet the other standards. Many sources have done actual stack sampling either on their own or at the request of the CAPCD and, if compliance is questionable, testing may be required. A reduction of 90 percent in point source emissions due to the regulations was estimated.

The fugitive dust regulation is too recently promulgated to make an evaluation as to its enforcement or effectiveness. The CAPCD is just beginning to have the ability to do the necessary vehicle counts and is informing the various political subdivisions what needs to be done. The requirement for a permit for construction and demolition activity and the requisite controls, are apparently being accepted. Even though prior to this thus, only minimal control was exercised.

The Air Pollution Control Section in the Department of Health and Hospitals has undertaken an active program to control smoking vehicles and has a visible emissions testing program to inspect the cars. Owners of cars on the road found not to be in compliance are normally mailed a notice of violation and are requested to comply with the law. If two sitings are made for the same car, the owner may be called into court to determine why compliance was not met. In April of 1975, the police became part of the program increasing the number of sitings almost threefold. In June 1975, there were almost 1000 vehicle emission sitings, 84 cars tested at the inspection station with 11 of them failing, and 5 owners ordered to comply by the court.

In reviewing the control programs in the Denver AQCR, it was felt that insufficient information was available for an accurate determination of their effectiveness. The regulations are reasonably stringent but the surveillance of the sources does not appear strict. Much appears to rely upon the Air Contaminant Emission Notices that are filed by the sources and many of these are several years old, some as old as 5 years. If stationary sources are actually in compliance, than the relative importance of fugitive emissions would justify more of the effort being shifted to the education of fugitive dust sources as to the requirements they must meet and the enforcement of the fugitive emission regulations.

NETWORK DESIGN

The monitoring network for the AQCR (Figure 1) is designed to define the spatial distribution of TSP concentrations within the Denver metropolitan area, where emissions are concentrated, and to monitor the outlying smaller population centers which are subject principally to fugitive dust emissions at single in-town locations. Because of the widespread nature of the AQCR and the fact that the TSP problem is centered in the Denver metropolitan area, no analysis of the sites of these outlying monitors was carried out.

Within the Denver metropolitan area (Figure 2), the area of greatest concern lies along the Platte River Valley. This is a result of the concentration of industrial, commercial and residential sources along the valley and the prevalence of a daily wind regime during light-windspeed, high-pollution days under which the local air mass drifts down the valley during the night and returns during the day. Details are given elsewhere in the section of this report covering meteorology. The requirement for monitoring concentrations along the valley appears to be satisfactorily met by six monitors distributed roughly along a NNE to SSW line and extending for a distance of 13 kilometers from Littleton in the south through the central business district (CBD) to Adams City in the north. Of these six monitors, one is located in the CBD, one is located on the outskirts of the CBD in a mixed commercial-industrial area, one is centered within the principal industrial area of Denver at an open exposure location, one is slightly removed from a major north-south commercial street which passes through a residential area, and the remaining two are located at the southern and northern ends of the sampling line. The monitoring network also covers areas of recent and projected growth from Arvada and Lakewood west of Denver, to Aurora in the east. These areas, being at elevations of the order of 100 to 200 feet above the valley floor and somewhat removed from the areas of maximum emissions, experience lower concentrations than those within the valley proper. The 15 monitoring sites used in this study which were operating within the Denver metropolitan area in 1974 have been grouped in Table 12, according to the predominant neighborhood characteristic of each. In addition, Table 12 provides the annual 1974 geometric means, monitor heights and, for sites visited by GCA personnel in the course of this study, special siting comments.

With few exceptions, the hi-vols are on the roofs of one- and two-story buildings and well exposed to the general air flow. The monitor on the roof of the State Health Department Building is at a height of 60 feet and somewhat sheltered from air flow from the southeast. Very limited information on the vertical gradient of TSP concentration in urban areas suggests that concentrations at the more standard Denver monitoring height of 15 to 25 feet in this area would exceed those measured at 60 feet by 10 to 15 percent. The principal CBD monitoring site is at a height of 50 feet on the roof of the School Administration Building. The hi-vol at this site is well exposed, not being subjected to any street-canyon effect as a result of neighboring high-rise building. It should

Table 12. ANALYSIS OF 1974 TSP MONITORING SITES IN DENVER

Neighborhood	State identification number	Location	1974 annual geometric mean (μg/m^3)	Height of monitor (ft)	Siting comments
Residential/commercial	2	State Health Dept., Denver	74	60	Highest monitor site. Heavy traffic on Colorado Blvd. one and a half blocks to west. Predominantly residential except for light commercial along boulevard.
	7	Aurora	89	20	
	9	Englewood	107	20	100 feet west by heavily traveled So. Broadway. Largely residential except for light commerical along Broadway. Some unpaved alleys and partially bare lots.
	13	Lakewood	80	15	
	88	Westminster	76	15	
	96	CARIH, Denver	93	15	
	110	Centenial Wells, Littleton	86 Ave (86)	?	
Center City	3	Gates Bldg, Denver	119	25	Mixed industrial/commercial area. Approximately 200 feet east of heavily traveled So. Broadway and 1000 feet southwest of the valley highway.
	5	School Admin. Bldg., Denver	107 Ave (113)	50	Second highest monitor site. Not far from urban renewal. During the past few years blocks to west and north of site have been demolished and replaced with new buildings and paved parking lots.
Commercial	15	Arvada	107	15	
	59	Edgewater	91 Ave (99)	35	
Industrial	1	Hull Photo, Denver	73	25	
	4	Sewer Plant, Denver	131	10	Centrally located in principal industrial area of Denver, north of CBD and on west bank of Platte River. Stockyards and other sources of fugitive dust nearby.
	8	Adams City	116 Ave (107)	15	Open area, 90 feet from street, adjacent to paved parking lot. General area semi-developed with vacant lots and unpaved roads.
Remote	11	Cherry Creek Dam, Arapahoe County	63	4	

be recognized, however, that concentrations measured at this site are not representative of street-level concentrations within the CBD. For example, the average concentration at the School Administration Building for the 3 years from 1970 to 1972 was 120 $\mu g/m^3$, while that measured at a height of 9 feet at the CAMP station at 2105 Broadway was 170 $\mu g/m^3$.

A general conclusion is that the TSP monitoring network is well designed and properly run. Because of the important part apparently played by fugitive emissions in the Denver area and the need for a substantial reduction in total emissions in order to meet the primary standards, however, an increased monitoring program designed to provide better estimates of incoming and city-generated particulates and of the relative contributions of major sources of fugitive dust within the city - such as street sanding and salting - would be helpful. Specific changes in the monitoring network would include the establishment of a more uniform height for all monitors and the location of several monitors arranged in outlying areas to the west and southwest of Denver to provide a better understanding of the background concentration entering the Denver area; i.e., away from the outlying centers of population. Reductions in the monitoring heights of the several higher monitors to a more uniform height of around 15 feet should only be done after running current samples for a reasonable period of time (at least 1 year) so that previous data can be adjusted for final analyses. The concurrent operation of monitors at different levels would also provide data on the contribution of local fugitive dust sources.

METEOROLOGY AND CLIMATOLOGY

The general meteorology and climatology in the Denver AQCR is strongly influenced by the topography of the area and, in turn, has a significant effect on the ambient levels of TSP. Because of Denver's location on the eastern slope of the Rocky Mountains in the belt of prevailing westerlies, the climate is generally mild and dry. The greatest amount of precipitation occurs in spring when moist air currents from the Gulf of Mexico meet weak polar outbreaks from the north. Wide local variations in wind regimes along the foothills are introduced by mountain and valley winds. Air drainage is generally good in the canyons, but as these canyons emerge onto the plains the slope is much less, and the air circulation may become very sluggish along the wider river and creek valleys, resulting in a drastically increased pollution potential. Other climatic effects of the mountains on this area are reduced temperature variations and increased precipitation as compared to those of the plains proper.

Due to the limits of time and data availability, the analysis of the impact of meteorology on the pollution levels in the AQCR was limited to the Denver County area and the data recorded at Stapleton International Airport. The following discussion centers upon the two major meteorological factors known to have a significant impact on Denver air quality levels — ventilation and precipitation. Supporting data on meteorological parameters considered below is presented graphically in the appendix.

Ventilation

With a given set of emission sources, the degree of air pollution experienced within an urban area, including its spatial distribution and the frequency and duration of its occurrence, depends largely upon existing meteorological conditions. The principal controlling meteorological parameters are the wind speed and direction and the vertical stability of the atmosphere within the first few hundred feet above the ground. To a large extent the wind speed governs the rate of dilution experienced by the pollutants upon emission, and the stability controls the rate at which pollutants can be mixed vertically and the thickness of the atmospheric layer through which this mixing occurs. It follows that the pollution potential for a region is greatest during periods of light winds and strong surface temperature inversions.

The maximum vertical depth of the atmosphere available in any day for the mixing of polluted air usually occurs in the afternoon following the period of maximum surface heating and is known as the maximum mixing height. The minimum mixing height is associated with minimum surface temperatures and usually occurs at or around sunrise. For any given wind speed, the greater the mixing height, the greater the volume of air available to dilute the pollutants and therefore to lower their concentrations. During a typical 24-hour cycle, the depth of the mixing layer in Denver varies by nearly one order of magnitude as a result of radiational cooling of the earth's surface at night and solar heating of the earth's surface during the day. The generally clear skies and low humidity of the area contributes markedly to the amplitude of this diurnal cycle. Afternoon mixing heights are least in the fall and winter and greatest in the spring and summer, ranging from a low of about 1300 meters in December to a high of about 3600 meters in May. The mean morning mixing heights range from about 175 to 450 meters, with the greatest heights again occurring in the spring and early summer.

Since a greater mixing height generally implies a lower concentration, Figure 17 presents the ratio of the average mixing height to the monthly mixing height for both morning and afternoon and also the ratio of the county-wide 1974 monthly geometric means to the 1974 annual geometric mean in Denver. Though the data from which the mixing height graphs were constructed is not specific to 1974 but rather an 8-year mean, the seasonal pattern in the data is a recurring phenomenon and is felt to be representative of the general pattern in 1974. While both

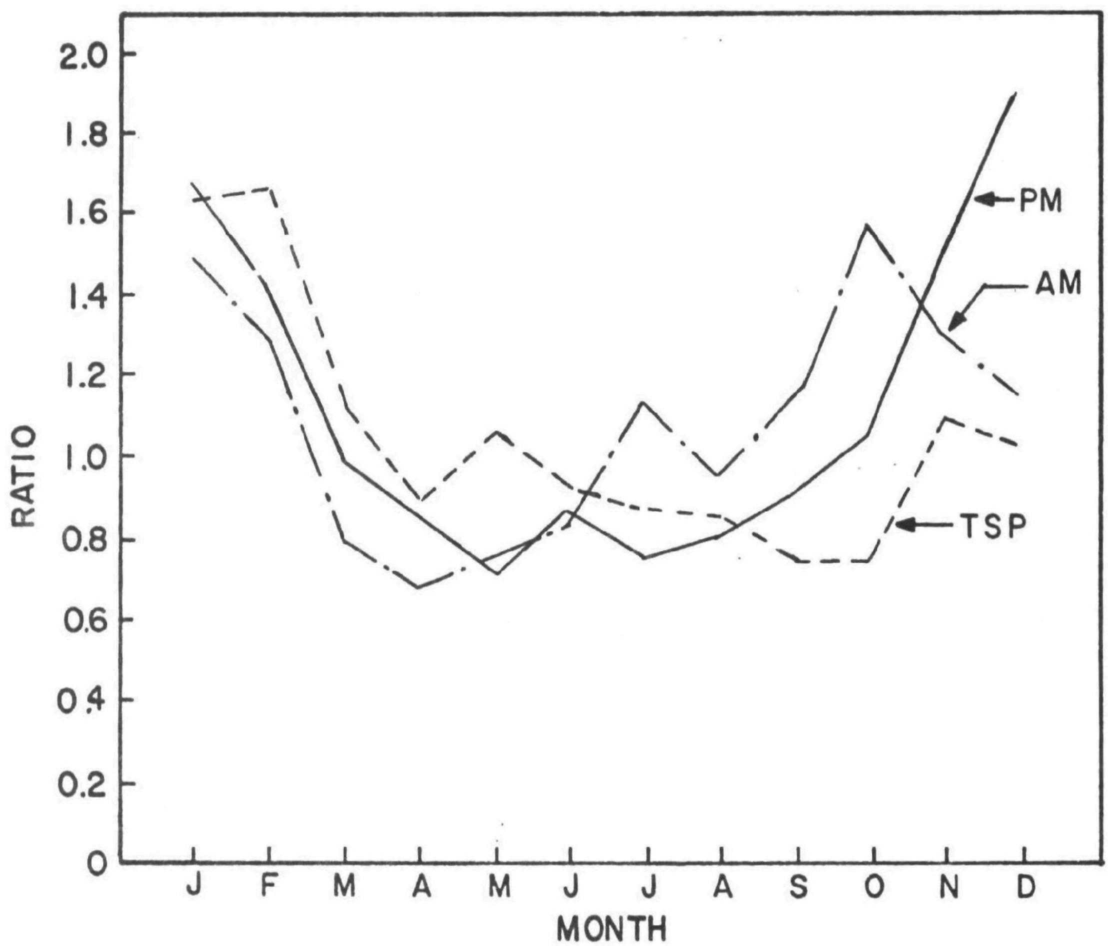

Figure 17. Average/monthly mean morning and afternoon mixing heights and county-wide monthly/annual geometric means of TSP in Denver.

mixing heights demonstrate the overall ventilations in the region, the morning mixing height is of more interest as it is the lowest of the cities studied. At the same time, the afternoon mixing height is the highest of the fourteen cities and indicates relatively good mixing even in the winter months.

The seasonal pattern in morning mixing heights indicates that concentrations would normally be higher in the winter and fall than during the spring and summer. The pattern of higher winter than summer is paralleled in the TSP ratio curve but the spring and fall differences are reversed for TSP. This could be due to numerous factors including other meteorological factors and emission rates (e.g., more agricultural tilling and ground breaking for construction in the spring).

A similar fall and winter versus spring and summer pattern is evident from the frequency of low level inversions observed during these seasons. On most nights of the year in the Denver area, temperature inversions form at or near the surface; these inversions range from a few degrees to 30°F or more in extreme cases. While the frequency of low-level inversions are comparable in the early morning hours throughout the year (see Table 13), the daytime heating rapidly breaks up the inversion

Table 13. PERCENTAGE OF FREQUENCY OF LOW-LEVEL INVERSION[a] (STAPLETON INTERNATIONAL AIRPORT)

Season	5 p.m.	8 p.m.	5 a.m.	8 a.m.
Fall	22	78	80	49
Winter	54	82	83	75
Spring	5	58	65	22
Summer	8	54	84	15

[a]Hosler, Charles R., 1961: Low-level inversion frequency in the Contiguous United States. Monthly Weather Review, vol. 89, Sept., 1961, 319-339

in the spring and summer months, as shown by the 8 a.m. values. The impact of the ceiling effect of inversions in Denver is compounded by the topography which further limits the ventilation. Figure 16 presents a cross-section profile of pollution layer depths over Denver on days when temperature inversions are not eliminated.

The major topographical influence on the wind regime in the area is related to this trapping of air masses in the valley of the South Platte River. As was shown in Figure 18, the South Platte River passes through the City of Denver, flowing from southwest to northeast. Under light nighttime wind conditions surface air, made relatively more dense by radiational cooling, drains down the river valley toward the northeast and lower elevations. This cold air drainage apparently stops just beyond the suburbs and the shallow air mass, which has accumulated pollutants from city sources, is frequently brought back by a sudden wind reversal around noon. Although this change in wind direction probably reflects, in part, upslope winds produced by surface heating during the morning, the driving mechanism for the reversal is not fully understood. Under a light wind regime, crossing and re-crossing of the pollutant sources by the same air mass may continue for several days, thus leading to an excessive local accumulation of pollutants. The sketches in Figure 19, taken from Riehl and Crow,[9] show composite wind fields prior to, during, and following such a wind reversal, and the southerly drift of the returning edge of the polluted air mass on one such day.

An estimate of the impact that the topography had on the wind regime during the monitoring in 1974 may be determined from the graph of the frequency of wind direction during sampling periods in Figure 20. This graph indicates that the greatest frequency of wind direction while the monitors were operating was from the southerly direction with 35 percent of the wind from a sixty degree sector centered just west of south. Almost another 20 percent of the observations occurred in the 60 degree sector centered around north-northwest.

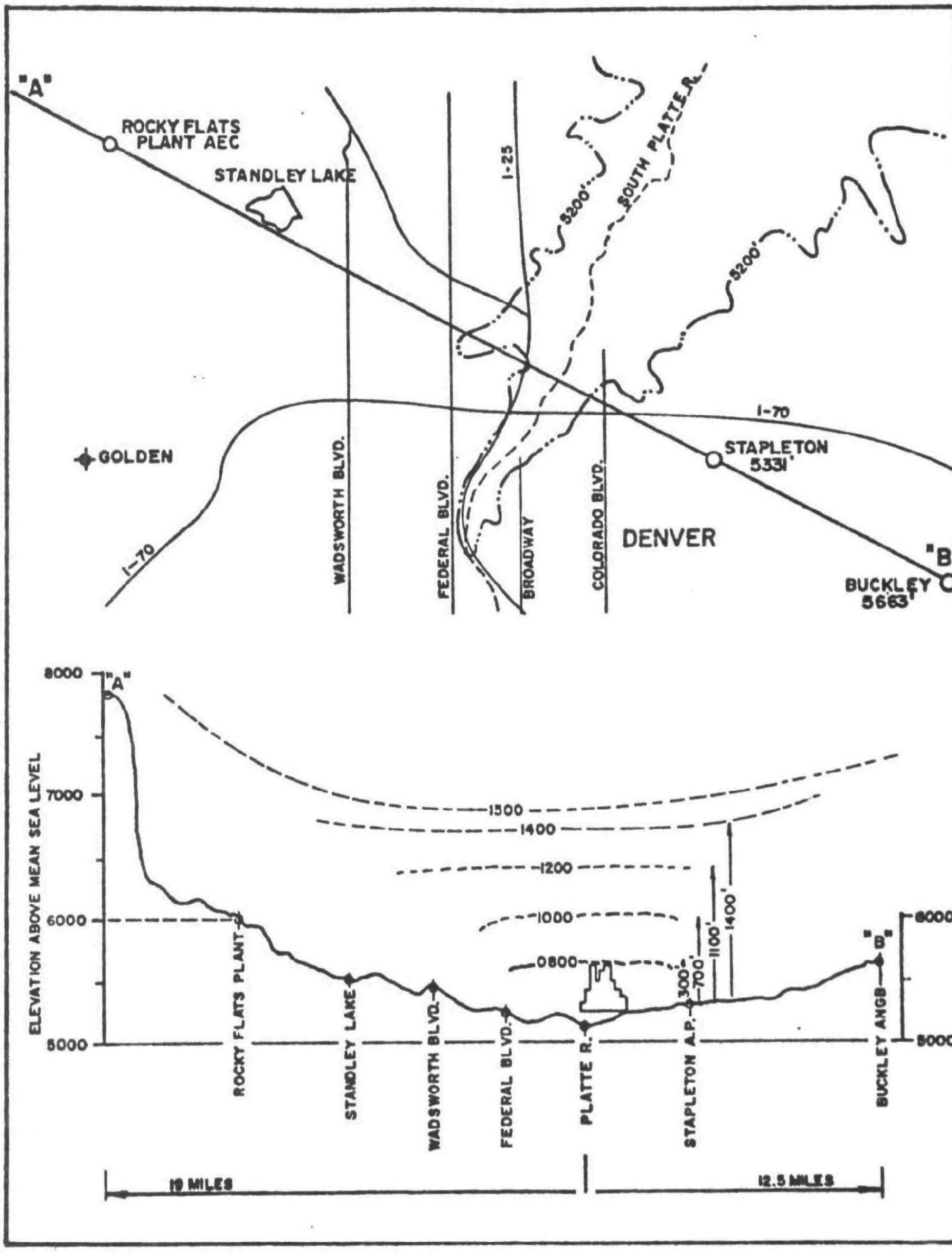

Figure 18. Typical WNW-ESE profile of pollution layer depths over metropolitan Denver between 0800 and 1500 on days when temperature inversions are not eliminated

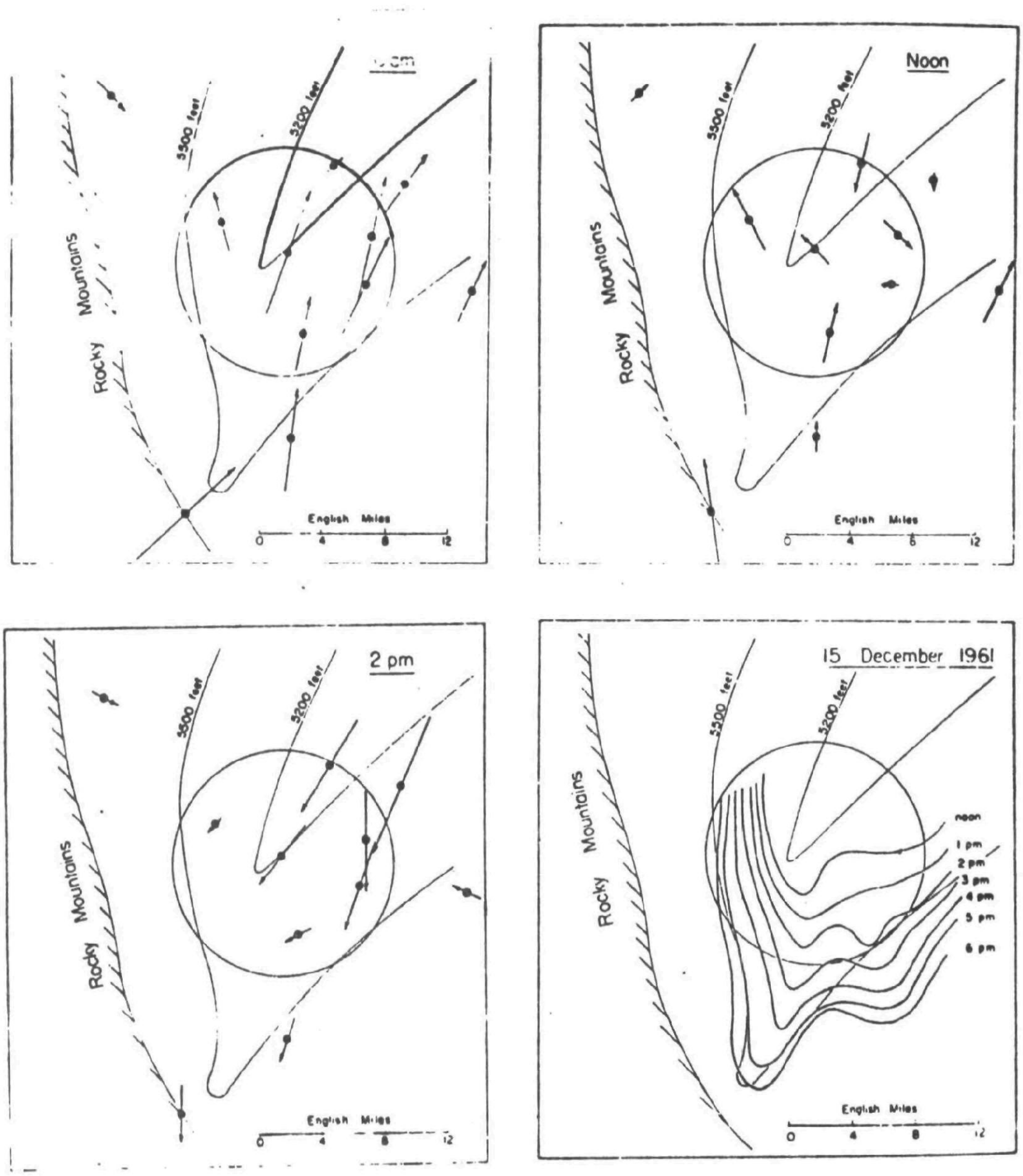

Figure 19. Average wind during pollution episodes from 10 a.m. to 2 p.m. (a, b, c). Length of arrow indicates one-hour air movement. Curves in "d" indicate forward edge of polluted mass at indicated times during southward advance of polluted mass. (From Riehl and Crow, 1962)

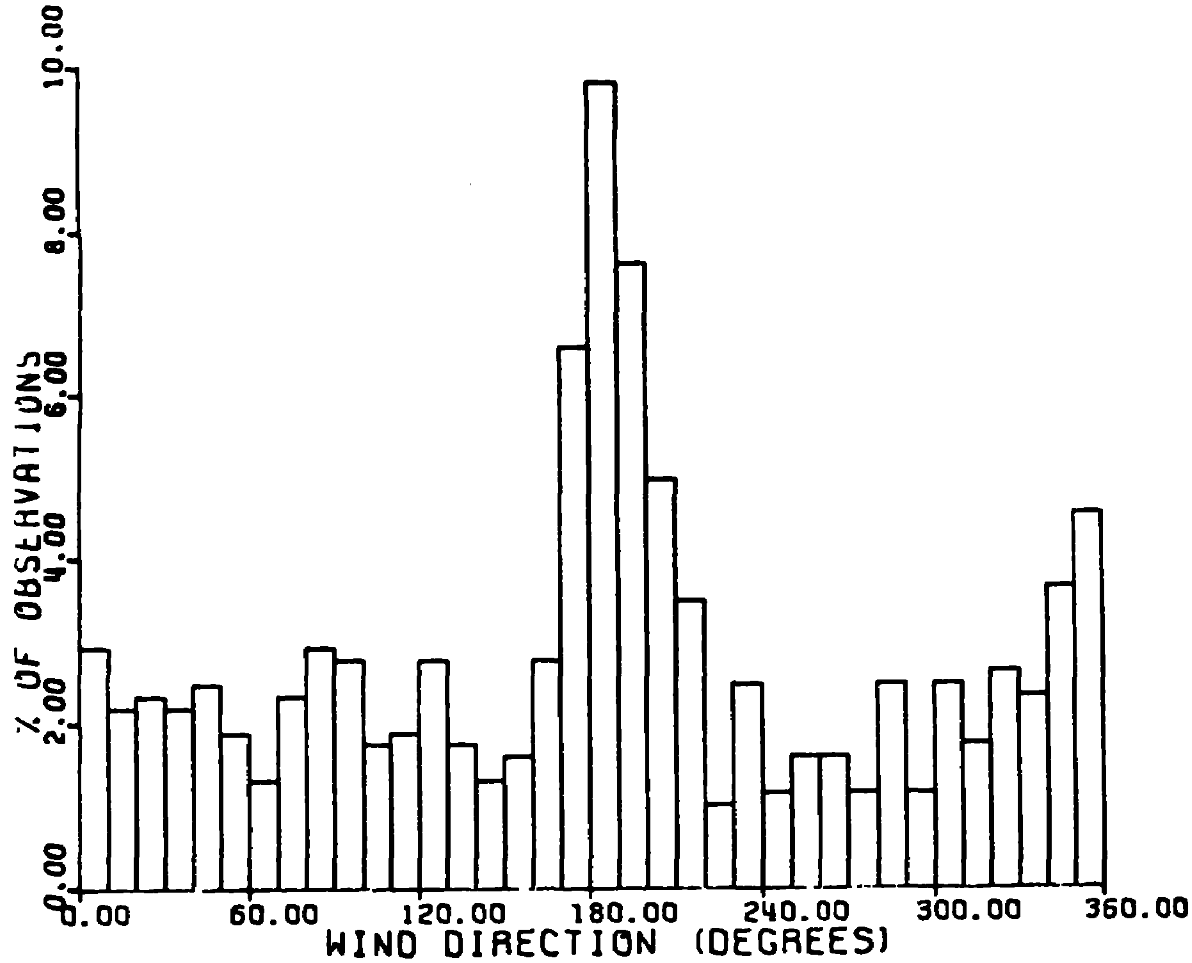

Figure 20. Percent of observations versus wind direction in Denver

Another meteorological parameter related to the ventilation in the area, and for which 1974 data is available, is the windspeed. This data (see Appendix) indicates only a minor range of average monthly windspeeds (7.1 mph in September to 10.1 mph in April), with the winter and summer windspeeds being fairly comparable. The pattern in windspeed of higher values in the spring and lower in the fall would tend to support the mixing height argument that TSP concentrations should be lower in the spring than in the summer.

Precipitation

Aside from ventilation, precipitation is normally considered to be the meteorological parameter which has the maximum impact on air quality levels. It helps to clean the air of particulates through washout and rainout and can suppress the rise of pollution levels by wetting down particulates that would be resuspended if dry or even washing particulates off the streets into sewer systems if the rain is heavy enough. The expected relationship is one of inverse correlation with the pollutant concentration.

Denver is an arid region with a normal annual precipitation level of 15.5 inches spread over 88 days. In 1974 the annual precipitation was slightly over 14 inches and precipitation greater than or equal to 0.01 inch occured on 83 days. From the small amount of data available for analysis, precipitation does not appear to have the same degree of impact that has been observed elsewhere. Figure 21 provides an inverse graph of the precipitation over the past 18 years by dividing the normal (1947-70) precipitation level by that which occured in each of the years. Overlayed on this figure are the annual geometric means for particulates measured at the NASN station at 2105 Broadway in Denver. The graphs in this figure indicate a relatively weak correlation between precipitation and the TSP levels sampled at this station and therefore other circumstances and conditions at this site must be overriding any impact that precipitation is having on the annual levels.

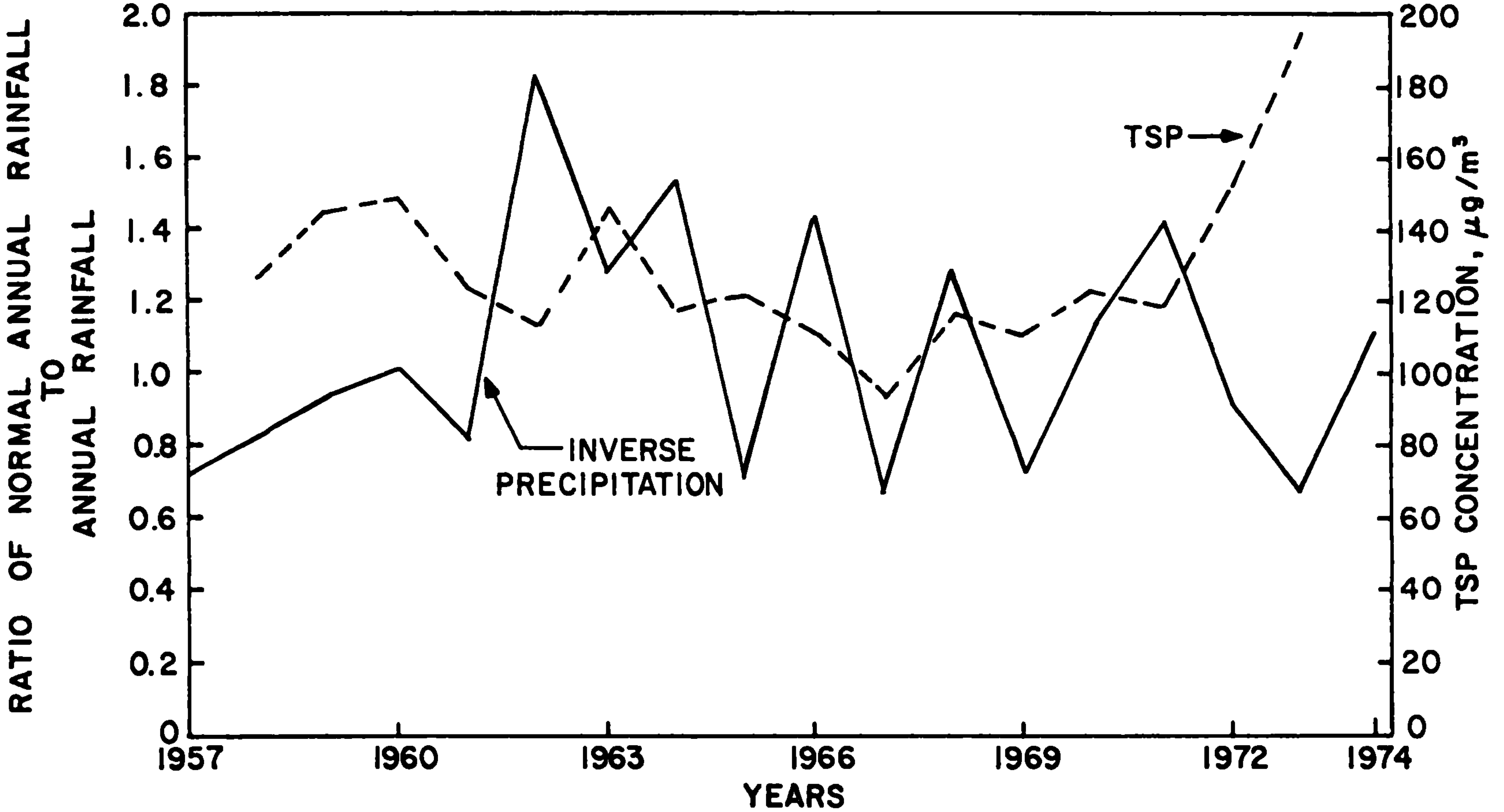

Figure 21. Normal/yearly precipitation and TSP concentration at Denver NASN station, 1957 to 1974

To discount the impact of conditions at an individual site, mean county-wide concentrations were compared with the precipitation levels from 1969 through 1974. For the determination of the relative impact of changes in precipitation on the changes in air quality, both the inverse ratio of precipitation and the ratio of the county-wide annual geometric mean to the county-wide 6-year geometric mean were plotted in Figure 22. This graph also indicates minor correlation between annual precipitation levels and TSP concentration in Denver County.

A better way of determining the relationship between precipitation and air quality levels is to consider a citywide average of air quality, thereby discounting major influences that certain activities may have on an individual site, and precipitation during 1 year. Such an analysis was performed utilizing 1974 data and monthly fluctuations over the year. A major advantage of this 1-year analysis is that wider fluctuations in the meteorology are expected on the smaller time scale and these wider fluctuations should be reflected in the air quality levels if there is a correlation. While one problem of changes in emissions over long time scales is eliminated, the additional problem of seasonal fluctuations in the emissions levels is present.

Again in the interest of normalizing the rainfall levels and wanting to show comparable changes in precipitation and air quality, Figure 23 provides a graph of the average monthly geometric mean divided by the annual geometric mean for all monitors in Denver County along with the normalized inverse of monthly precipitation (average monthly/monthly). From this graph it is evident that there is some correlation between precipitation and concentration but that it is not a very strong one and that while above normal periods of rain (April, June, July, October) tend to decrease the ambient concentration of particulates, below normal amounts (May, August, December) have little if any impact on the monthly TSP levels.

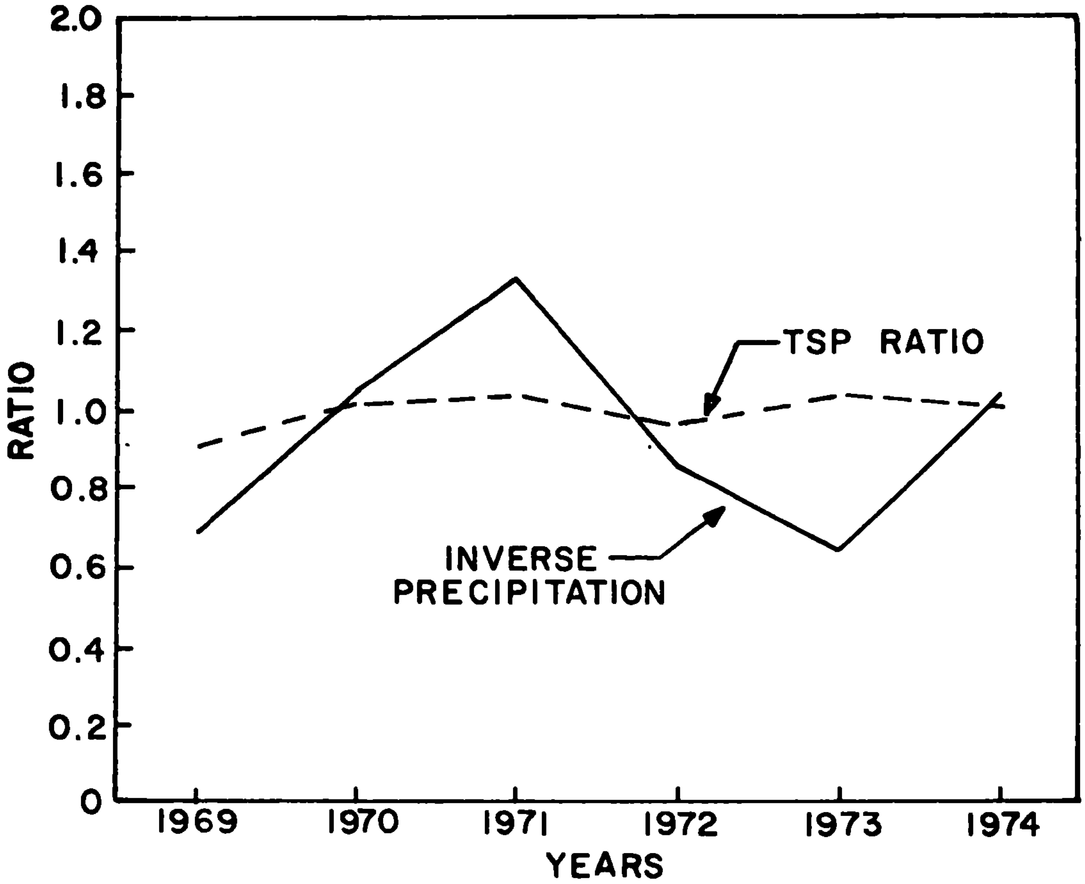

Figure 22. Normal/yearly precipitation and county-wide annual geometric mean/6-year mean, 1969-1974.

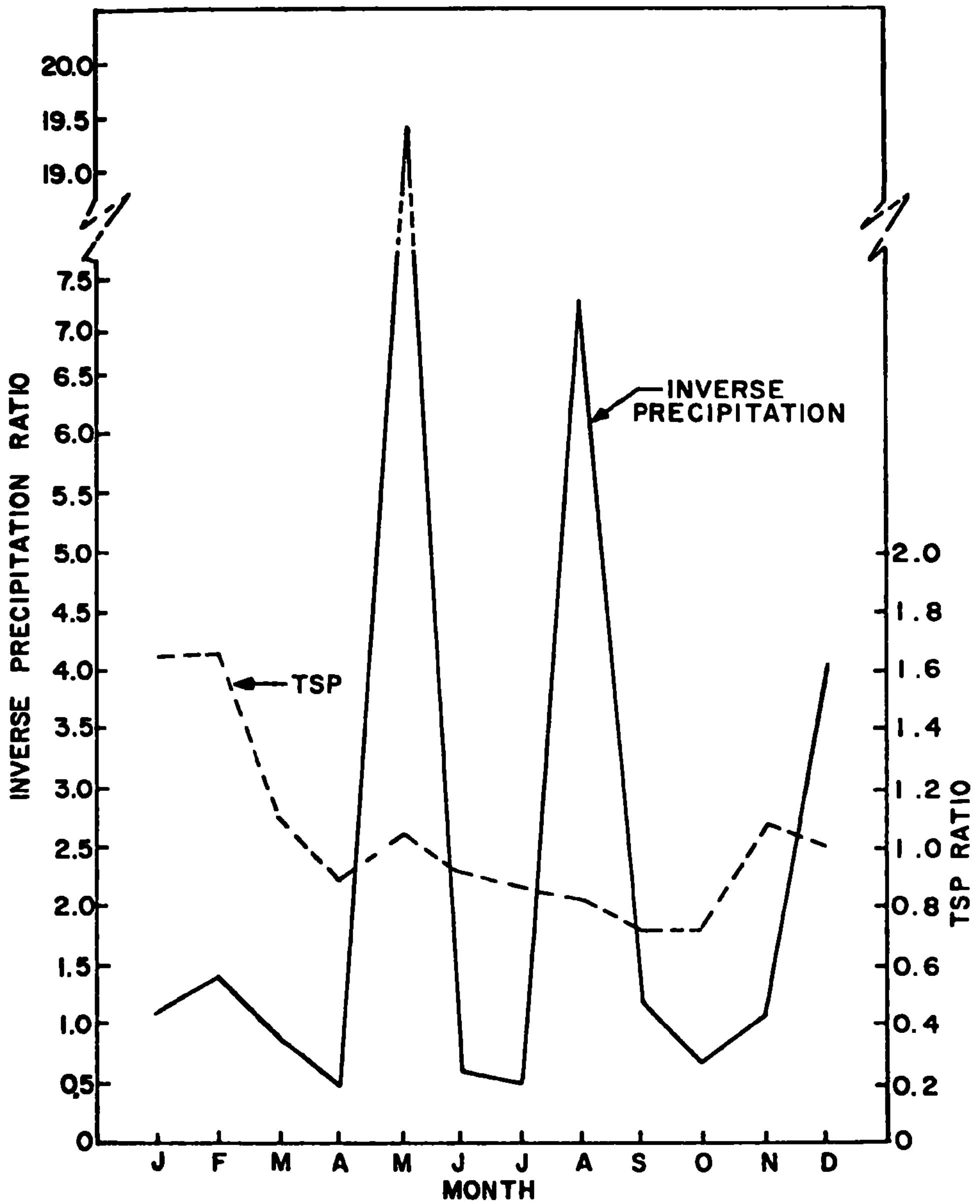

Figure 23. Average monthly/monthly precipitation and countywide monthly geometric mean/annual geometric mean for TSP in Denver, 1974

One possible explanation for the lack of a strong relationship is the relatively small amount of precipitation and the infrequency of occurrence. It is not unreasonable to assume that the more frequent the precipitation, and the greater the amount, the more impact it would have on the annual and monthly levels; i.e., if only a few samples are reduced during the year or month, the geometric mean would not be noticeably changed. Analysis of the TSP concentrations on the day of or the day after precipitation, both rainfall and snowfall, is presented in the discussion of sanding activities.

URBAN ACTIVITY

Several areas of urban activity were investigated in the course of this study to determine how these activities impacted on the measured ambient air quality. Principal among these were sanding for snow control, street sweeping and construction. A cursory analysis of this latter area indicated that it was not a citywide phenomenon of interest having any correlation with citywide TSP levels and more detailed analysis was felt to be beyond the current scope of effort. Therefore, the following discussion centers on the analyses conducted on sanding and sweeping activities.

Sanding and Salting

The City and County of Denver, Department of Public Works, spread over 13,000 cubic yards of sand and salt on the roads of Denver in 1974 and this sanding activity has been implicated in several studies[3,10] as contributing a large amount of particulates to the air through the grinding and resuspension by vehicles on the paved surfaces. The possibility that sanding has a major impact on the countywide levels of TSP was considered in several analyses.

Total Tonnage Calculations - The figures given in the PEDCo study of fugitive dust in Colorado[3] indicate that 5,816 tons per year of particulates were added to the air in Denver County in 1972. This tonnage figure was calculated in part by assuming an average of about twelve heavy snowfalls during the year, a reasonable assumption given 1974 data, and also that the sand remained on the road after the snow melted until sweeping operations removed the sand. This latter assumption yielded approximately 18 days of dusty paved roads per year (36 hours before street sweeping operations). The actual calculation of the tonnage emissions was based on a study of emissions from dusty paved roads in the Duwamish Valley of Seattle, Washington, which gave an emission rate of 0.17 pounds per vehicle mile (VM). The vehicle miles traveled in Denver were assumed to be 80 percent of normal after the snowfall had melted.

As the calculation of emissions from sanding was not directly related to the sanding activity itself, an analysis of the assumptions used in the calculations was conducted. From this analysis the following points were raised.

- While there were approximately 12 "major" snowfalls in 1974, there were about 18 major periods of sanding activity due to the need to respond to small snowfalls also.
- Sanding activity actually occurred on 50 different days in 1974.
- Streets are swept on the average of five times per year so it is not likely that sand would be removed from the street within 36 hours.
- While traffic may be less than normal during the snowfall and while the snow is on the streets, once the snow has melted the average daily traffic should return to normal, especially considering the length of time that the sand must remain on the road.
- The emission rates were based on a study[11] which calculated the rates from isokinetically sampling the air behind a moving car.

The first four of the items listed above tend to indicate that the tonnage calculation by PEDCo may have grossly underestimated the total tonnage that should be calculated using that methodology. At the same time, the

Duwamish Valley study tends to give an emission rate that is too high. While the emissions directly behind an automobile on a dusty road may be 0.17 lb/VM, the resulting emissions that actually remain airborne and transported more than a few feet of the ground and away from the road can be expected to be much less. In addition, the Duwamish Valley study was concerned with the carryout of mud and dirt from unpaved roads and parking lots. The very nature of this carryout material would imply that it is selectively more adhesive to the tires and more readily picked up in transit; i.e., mud and sand would not have the same emission rate.

The fact that the tonnage calculations performed by PEDCo could be larger or smaller than the actual emissions from sanding provides no resolution as to the final accuracy of this figure. One approach that does provide at least a ceiling on the emissions possible from sanding operations is the determination of the total tonnage applied to the roads in Denver.

Data provided by the Department of Public Works for the City and County of Denver gave a total volume of salt and sand mixture spread in Denver roads in 1974 as 13,638 cubic yards. Since the salt to sand ratio used in Denver is 1 to 5 and 1 cubic yard of the samd (actually three-eights inch aggregate) weighs 1.4 tons, the total tonnage of sand added to the roads in 1974 was 15,911 tons. A comparison of this tonnage with the PEDCo emission rate of 5,816 tons would imply that over 35 percent of the sand added to the road ends up as air contaminant. Under the assumptions that: (1) some of this three-eights inch aggregate is bounced into the gutters by passing cars, as would be some of the sand ground from passing cars; (2) some of the sand and gravel would be collected by street plowing and snow removal operations and thereby disposed of elsewhere; (3) the sand would be evenly dispersed over the road with more tendency to accumulate on sections of the road other than where the tires are most frequently traveling; and, (4) some street sweeping operations do occur, this percentage emission rate would appear to be extremely high.

This analysis brings into question the appropriateness of the emission estimate given in the PEDCo study for strategy planning purposes. While 5,800 tons or much more may actually be temporarily reentrained due to the traffic on sanded paved roads, the duration of this reentrainment and the distance of transport of these emissions must be considered in the analysis for strategy planning.

Seasonal Fluctuations - One method of determining the "equivalent" emission rate for sand on paved roads would be through modeling the emissions and correlating the modeled TSP levels with actual air quality measurements. As this approach was beyond the scope of this effort, an alternative analysis was conducted by comparing the estimated monthly emissions from sanding operations with the countywide monthly geometric means of TSP concentration. The mechanics and direct results of this analysis were presented above in the section on emissions. In that discussion it was shown that a correlation did exist between the monthly emissions of fugitive dust and the monthly TSP levels. However, it was also suggested that the correlation might be much closer if an emission rate of one-half that calculated by PEDCo was assumed.

Further analysis that was conducted under the discussion of meteorology indicated that the seasonal patterns in TSP levels may be just as well correlated with seasonal changes in mixing heights and the frequency of low level inversions. As these latter parameters are much less susceptible to errors in their determination than the calculation of seasonal emissions, it must be assumed that, regardless of whether street sanding is practiced, the TSP levels in the winter would be higher than those in the summer.

Therefore, the fact that the ratio of monthly emissions to the average monthly emissions is comparable to the ratio of above background monthly levels of TSP to the annual emissions does not immediately mean that a correct apportionment of emissions has been made. Rather, given the seasonal meteorological influence, lower emission ratio than TSP concentration ratio would be the expected norm. In the case of the Denver emissions, one method of obtaining a lower ratio in the winter months would be to assume a much lower value of emissions from sanding activity.

Daily Fluctuations - The City and County of Denver, Department of Public Works provided information regarding the quantity of sand and salt mixture spread in Denver for each day in 1974. This data, along with snowfall records from the U.S. Department of Commerce and TSP levels for six monitoring sites from the Colorado Department of Health, were compared for those months when sand and salt mixture was spread (January through April, November and December).

Several observations were made from this analyses:

- Several days after sand is spread, TSP levels increase to an apparent peak and then decline to pre-storm levels. The lag time between sanding activity and peaking TSP levels varies between 1 and 11 days with 2 to 4 days being the most common range.

- It is not known precisely when TSP levels peaked and what the magnitude of that peak was because readings are recorded every 4th day. Hence, the actual peak and the apparent peak may be offset by as much as 3 days. Accordingly, the actual peak TSP level will exceed the apparent peak TSP level in those cases where the actual and apparent peaks do no coincide.

- For specific storms the lag time between sanding operations and the apparent peak TSP levels appears to decrease as the quantity of sand and salt mixture spread increases. There is no apparent relationship between the lag time between sanding activity and peak TSP levels and the magnitude of the peak level.

- The magnitude of the increase in TSP levels varies from a high of 309 $\mu g/m^3$ above the monthly average at the lowest monitor (Sewer Plant) on Friday, January 25th after 1,570 cu. yd. of sand was spread between January 21 and 23, to a low of 70 $\mu g/m^3$ below the monthly average at the same monitor on Thursday, April 11th after 335 cu. yd. of sand was spread on April 3rd.

- For the 13 storms considered, an average of 945 cu. yd. of sand was spread and an average increase in TSP levels of 54 $\mu g/m^3$ was observed at the apparent peak. It is difficult to quantify the extent to which sanding operations were responsible for this increase. At least part of the increase could be due to the normal variation in TSP levels.

- There is no apparent quantifiable relationship between increases in TSP levels and the amount of sand spread. It appears that meteorological factors (temperature, wind and precipitation) may also have a strong influence on the magnitude of the increase.

- TSP levels during periods of snowfall are usually lower than the monthly average. The magnitude of the difference varies from a high of 217 $\mu g/m^3$ below the monthly average at the Sewer Plant on Wednesday, January 9th to a low of 96 $\mu g/m^3$ above the monthly average at Gates on the same day.

- For the 13 storms considered, the average difference in TSP levels during periods of snowfall was 49 $\mu g/m^3$ below the monthly average. This is not to say that snowfall is responsible for the entire decrease. At least part of the decrease could be due to the normal variation in TSP levels, the cumulative effects of snowcover on the ground and inswept sand.

This preliminary review did not lead to any direct relationship between snowfall and the amount of sand spread. Other meteorological factors such as temperature, wind speed, and snowcover are also important. In addition, it could be considered equally likely that the snowfall is depressing <u>normally high</u> values as that the sanding operations are increasingly <u>normally low</u> levels.

In an attempt to separate out the effect of the storm systems and the precipitation itself, a comparison of the daily TSP levels before and after precipitation was made between the winter storms (snowfall) and summer storms (rainfall). This analysis was based on the differences between the ambient particulate concentration on the sampling days around the time of the precipitation with the geometric mean for the sampler for the month in which the precipitation occurred. In the case of rainfall, this was a straight comparison of the sample immediately before the rainfall with the monthly mean and of the sample closest to after the rainfall had ended. For snowfall however, the problem of snowcover lasting for several days precluded the use of the sampling date immediately following the snowfall. Instead, the peak value after the snowfall was used. Table 14 presents the total difference found by comparing the daily with the monthly, the number of samples that were taken, and the average difference in samples for each day.

The data in this table indicates that before periods of snowfall, the air quality would appear to get increasingly better as the storm approaches, but for rainfall the only consistent improvement is on the actual day of rain and the day after. The difference may lie in the fact that snowfall is normally associated with a storm system while rainfall may occur with less associated activity. While the rainfall appears to suppress particulate levels for 1 day, TSP levels rise quickly after a snowfall with perhaps a peak on the second day after snowfall. This phenomenon may be attributable to the sanding activity but may also be a result of the impact of the passing storm system.

Street Sweeping

If sanding were found to be having an impact on the monitored levels of TSP due to resuspension caused by vehicle traffic, then it might be expected that the removal of excess dirt from the paved roads would bring about a reduction in the ambient levels. In the course of this study, data on street sweeping activities in Denver was gathered and compared with the daily TSP readings at the monitors in the vicinity of the sweeping. For maximum impact on the monitors, sweeping activity was only considered in the analysis if it occurred within an approximately one-half kilometer (about 6 blocks) radius of the monitor and within 2 days prior to sampling.

Table 14. COMPARISON OF TSP CONCENTRATIONS BEFORE AND AFTER SNOWFALL AND RAINFALL STORMS

Days	Snowfall			Rainfall		
	Total difference: daily TSP-monthly TSP (μg/m³)	Number of samples	Average difference (μg/m³)	Total difference: daily TSP-monthly TSP (μg/m³)	Number of samples	Average difference (μg/m³)
Before						
3	-116	11	-15	-24	6	-4
2	-130	4	-33	141	10	14
1	-179	5	-36	162	20	8
0	-2734	53	-52	-892	33	-27
After						
1	217	6	36	-173	21	-8
2	1115	13	86	325	19	17
3	656	15	44	188	12	16
4	849	14	61	11	16	1
5	194	3	65			
6	158	9	18			
7	263	2	132			
8	284	8	36			
9	260	3	87			
10	—	—	—			
11	18	1	18			

Since street sweeping does not occur in Denver on any definite schedule and the blocks are swept an average of only five times per year, very few pairs of ambient monitoring and street sweeping activity were found. To further hinder the analysis, only one of the pairs was at a sampler 10 feet off the ground and one pair was at a sampler 25 feet off the ground. The other paired activities were all near monitors at heights of 50 to 60 feet.

The analyses conducted on these paired observations included a comparison of the ambient concentration measured after street sweeping with the corresponding monthly and annual geometric means for that monitor and also a review of the pattern of increases and decreases in TSP levels measured at other monitors in the city on that day. These analyses provided no correlation at all between street sweeping activity and ambient levels. The TSP concentrations after sweeping were both higher and lower than the monthly and annual geometric means and no deviation from the 4-day pattern of TSP at all monitors in the city was observed.

Despite the finding of no correlation, the conclusion that no correlation exists can not be made due to the inadequate data base. More paired observations and samples closer to the ground would be appropriate for further study.

SECTION III

SUMMARY AND CONCLUSIONS

The analyses presented in Section II of this report indicate that many factors have contributed to the lack of attainment of the NAAQS for total suspended particulate in the Denver AQCR. These factors have ranged from the problems in developing an appropriate emission inventory to the influence of topography and climatology. This section attempts to review the circumstances that brought about the current conditions and make recommendations where possible on measures necessary for the attainment of the particulate standards.

PRIOR ATTAINMENT STRATEGY APPROACH

The Air Quality Implementation Plan for the State of Colorado based its control strategy development for suspended particulates on the highest reported annual geometric mean of 122 $\mu g/m^3$, which occurred in Denver. This value determined required emission reductions of 51 percent and 67 percent to meet the primary and secondary standards, respectively. The reduction of 51 percent was to be achieved in part by the application of Regulation No. 1 with the balance being met by the application of Federal particulate emission control regulations on automobiles and aircraft. (Federal regulations directed at controlling particulate emissions from automobiles were never promulgated.) The reduction of 67 percent to attain the secondary standard was assumed to require emission reductions exceeding those which can be achieved through the application of reasonably available control technology (RACT) so an 18-month extension was requested, and granted by EPA, in order to formulate and submit that portion of the SIP.

Regulation No. 1, as presented in the SIP, was projected to decrease stationary source particulate emissions in the Metropolitan Denver AQCR from 18,096 tons/year in 1970 to 8,425 tons/year in 1975, or a reduction of 46 percent. The control measures imposed to receive this reduction included a general requirement that emissions could not obscure vision to a degree greater than 20 percent opacity, a ban on open burning without a permit, and process rate based regulations for major fuel-burning equipment, refuse-burning equipment, and manufacturing processes. Control of fugitive dust, at the time of the SIP, was based on the 20 percent opacity regulation and the need for five or more complaints.

In searching for particulate emission sources where additional emission reductions could be demonstrated as part of the plan to achieve the secondary standard, the Colorado Air Pollution Control Commission identified fugitive dust from unpaved roads and other sources as contributors to particulate pollution which were amenable to control. The agency next drafted regulations designed to provide the best control feasible for the fugitive dust sources that they had identified. However, due to lack of available data on (1) emission rates from these sources and (2) the effectiveness of the proposed regulations in reducing particulate emissions, the Commission was unable to quantitatively demonstrate that the fugitive dust controls would result in the necessary reduction in emissions.

To compound this problem of presentation, measured particulate levels at some sampling sites were increasing with time, rather than decreasing according to the projections of the initial implementation plan. This divergence of actual measurements from projections indicated that the emission inventory on which the control strategy was based did not account for all emission sources affecting the samplers.

A study was thus undertaken to quantify the reduction in fugitive dust emissions that can be expected from enforcement of the proposed regulations and to estimate the resulting air quality in three Colorado Air

Quality Control Regions with these regulations in addition to existing control regulations. The resulting emission inventory showed that, in the Denver AQCR, unpaved roads were the largest source of particulate, accounting for 35 percent of the particulate emissions inventoried. The other eight fugitive dust categories - sanded paved roads (for snow control), land development, agriculture, building construction, highway construction, quarrying/mining, aggregate storage, and cattle feedlots - also contributed significant emissions on a regional basis, so that fugitive dust was responsible for 70 percent of particulate emissions in the Metro-Denver AQCR. In Denver County, 62 percent of the particulates were estimated to be from fugitive dust and 73 percent of this was determined to be the result of sanding activities for snow control. In response to this emission inventory, the Colorado Air Pollution Control Commission has recently promulgated a new regulation for the control of fugitive dust.

However, even with these additional provisions, it is unlikely that even the primary standards will be achieved in the AQCR. The major problems in achieving the standards are the large contribution of fugitive dust to total particulate emissions in the regions and the low control efficiencies attainable for most fugitive dust sources. In fact the Federal secondary particulate standard of 150 $\mu g/m^3$ (24 hour) is exceeded in almost completely undeveloped areas. The high winds in these semiarid areas of sparse vegetation are the cause of the violation of standards due to their uplifting action on the dusty ground cover.

A major problem in formulating appropriate control strategies for the attainment of particulate standards in the Denver AQCR has been the establishment of a complete and accurate emission inventory. Aside from the original exclusion of fugitive dust in the SIP's emission inventory, there have been several emission inventories generated and used for planning purposes. These inventories have most often had wide discrepancies in the total emissions as well as other emission levels attributed to different source categories. Inconsistent, and therefore inaccurate, data must be one of the principal causes of the lack of success of the attainment strategies.

In addition to the exclusion of fugitive dust and the continuing inconsistencies of emission inventories, planning activities in the AQCR, especially under the SIP, have failed to take into account the significant impact of the topography and ventilation characteristics of the region. Common air quality models cannot accurately represent these outside parameters which are so important in Denver. The roll-back calculations utilized in the SIP are even less appropriate.

RECOMMENDATIONS

Much of the problem with the attainment of the particulate standard in the Denver AQCR lies in the exact definition of the situation with respect to particulates. If the standards are to be attained, more intensive study will have to be conducted than has been done in the past. Specific areas which, in the course of this effort, have been identified as needing further study prior to another attempt at planning are listed below:

- Conventional Emission Inventory - More updating of the current emission inventory is needed than has recently been done utilizing the CAPCD's air contaminant emission notices, many of which are 5 years old. Due to the strong seasonal influence of meteorology, this update should have detailed information on the seasonal emission patterns. At the same time, trends information should be compiled to serve as a guide in strategy planning.

- Fugitive Dust Inventory - Further study of the emission rates from possible fugitive dust sources is needed if fugitive emissions are to be considered in strategy planning. These emission rates must be better defined than they are currently and should reflect an effective emission rate rather than an actual emission rate to include only those particulates that remain airborne sufficiently long to be considered air contaminants.

- Network Design - Pending future requirements for a fixed monitoring height, CAPCD should reconsider its location of monitors at varying heights within the city. The inconsistency of heights hinders the determination of a uniform control strategy for fugitive dust as the higher samplers will not show the improvement that may be found at a lower monitor.

- Meteorology and Topography - Further attention must be given to these factors in the future development of control strategies. As strong seasonal patterns are likely to result solely due to changes in the meteorology, annual and average 24-hour modeling cannot be expected to provide control measures that have comparable impacts throughout the year.

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APPENDIX A

METEOROLOGICAL DATA

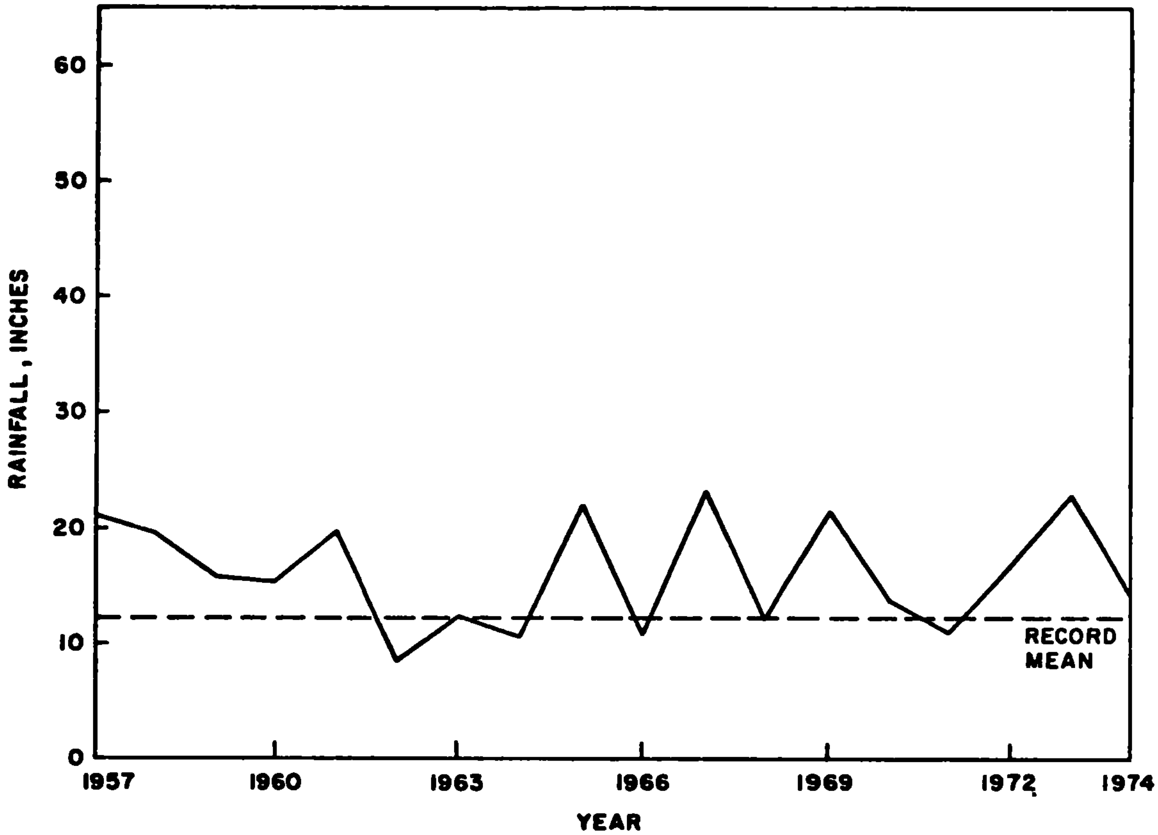

Figure 24. Yearly rainfall in Denver

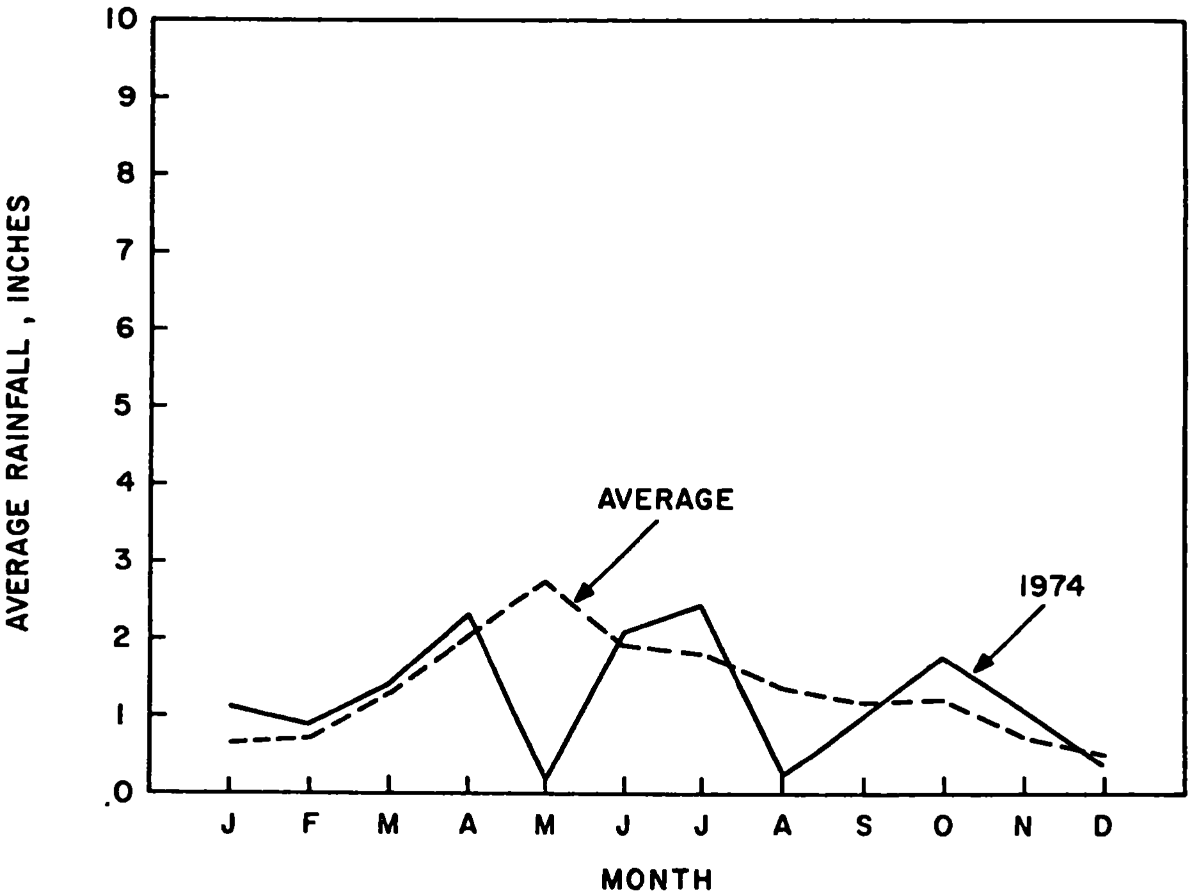

Figure 25. Monthly rainfall in Denver

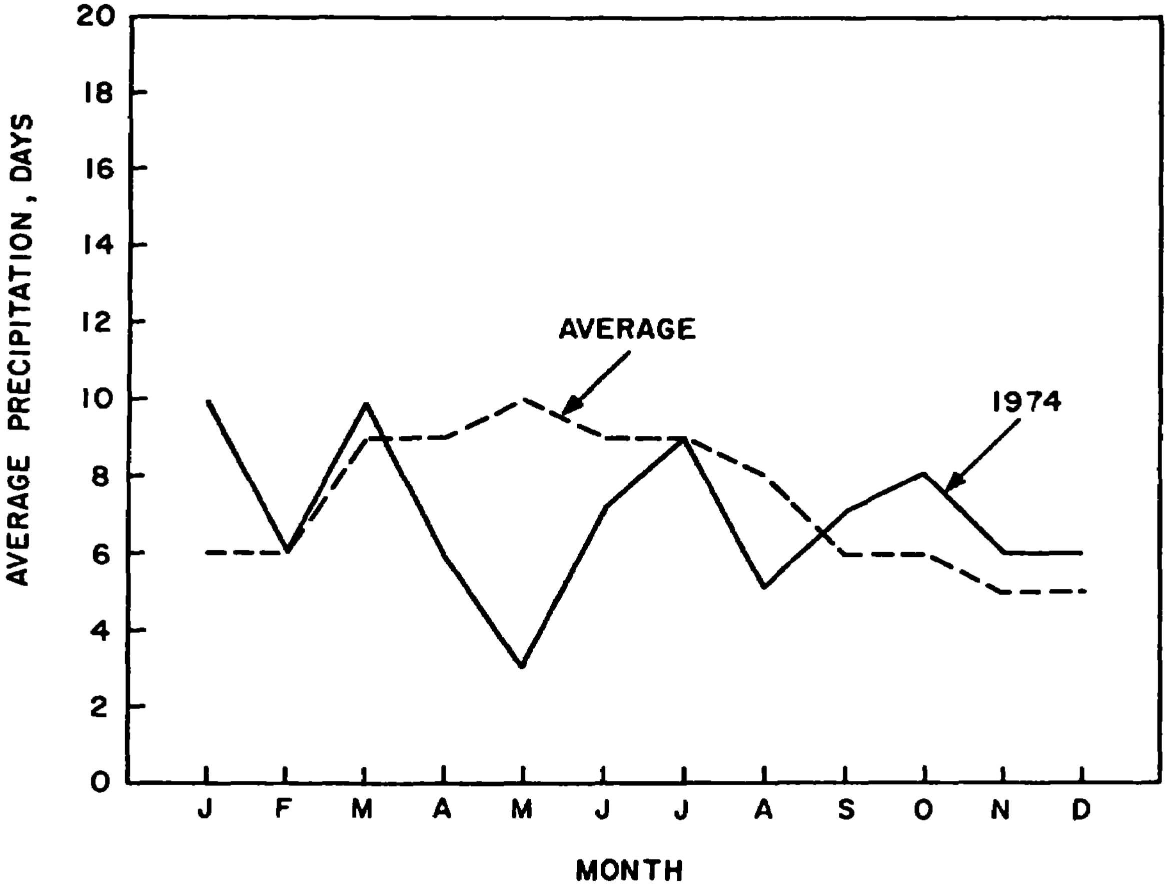

Figure 26. Monthly number of days of rain in Denver

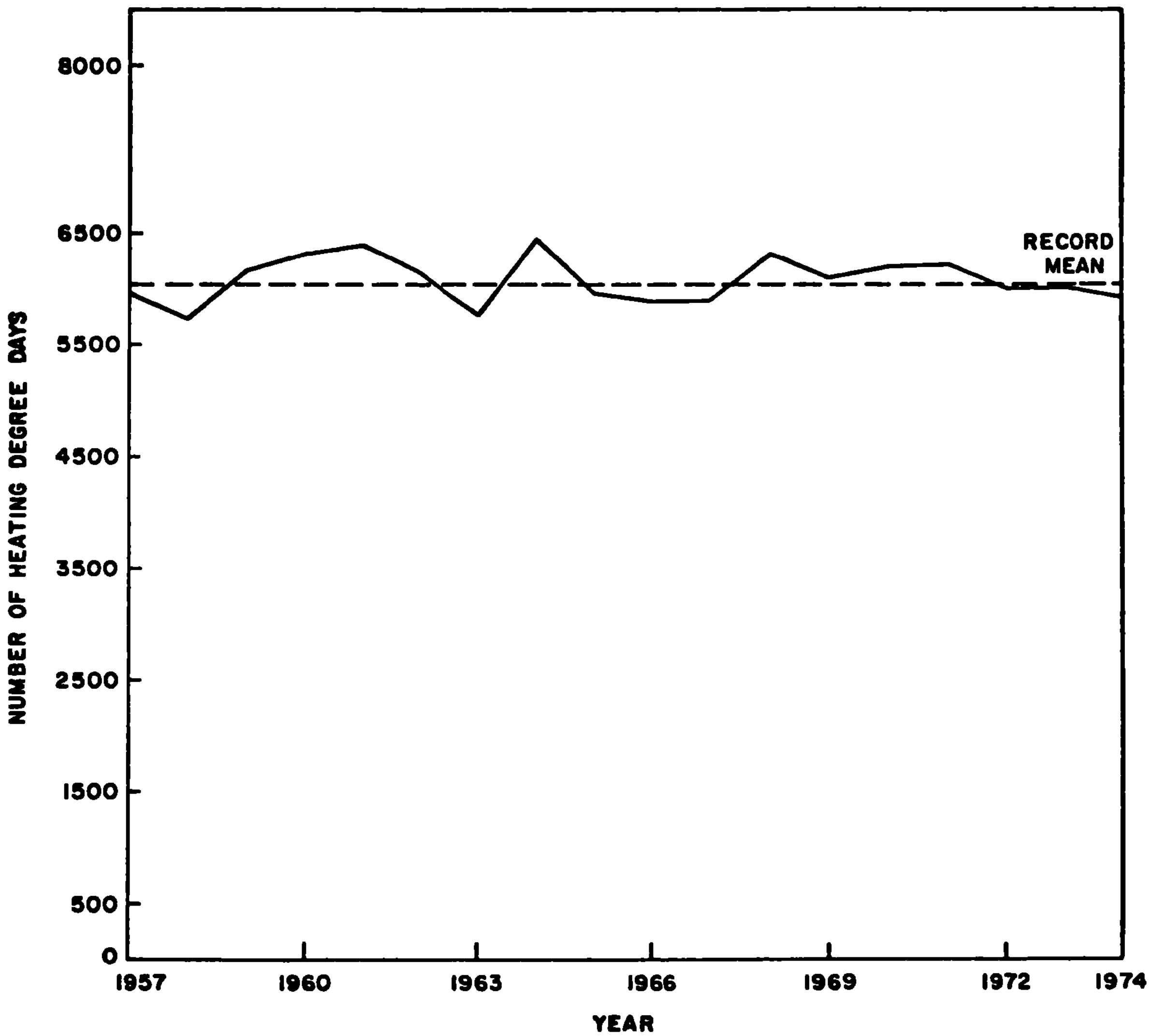

Figure 27. Yearly heating degree days in Denver

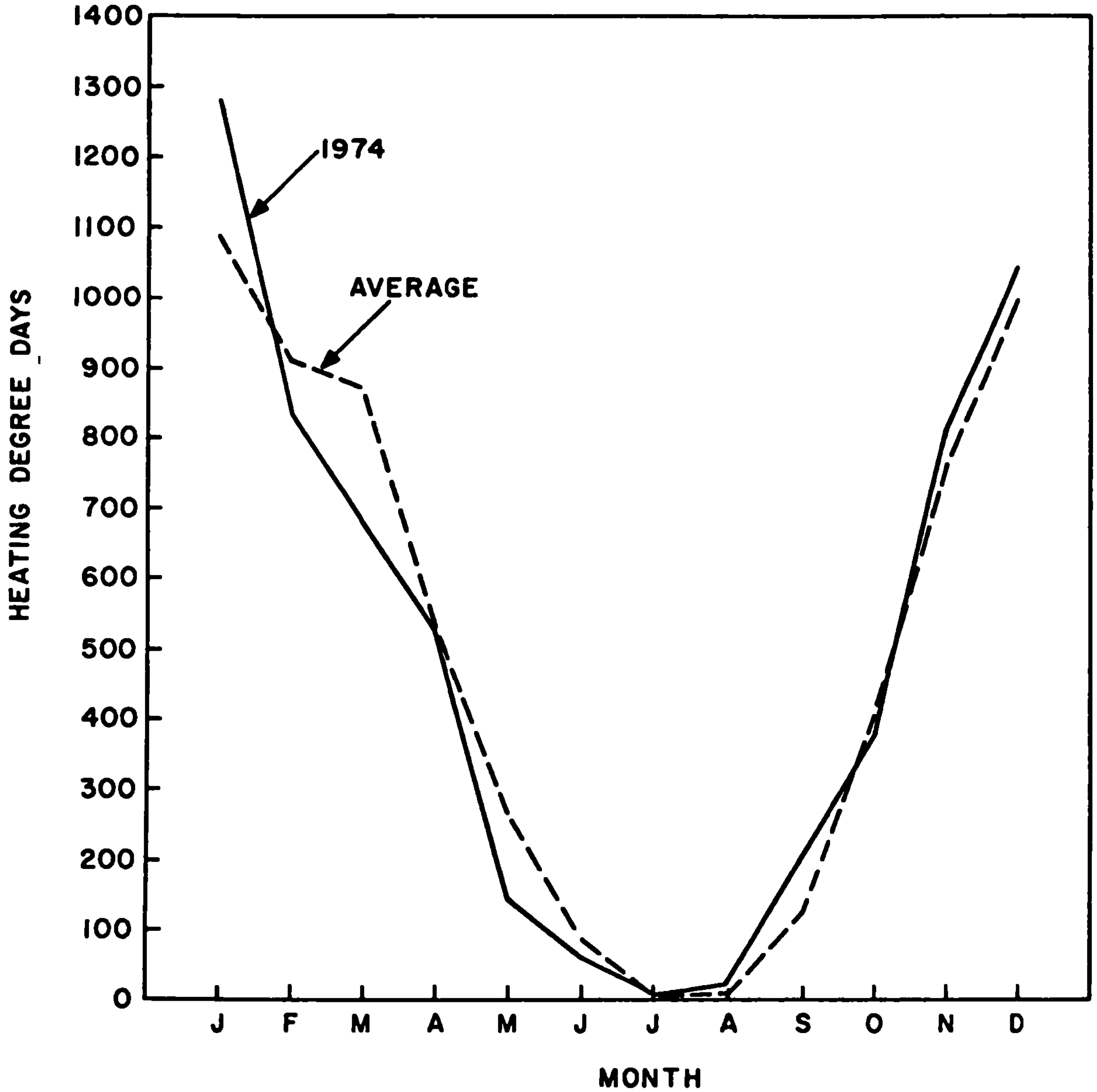

Figure 28. Monthly heating degree days in Denver

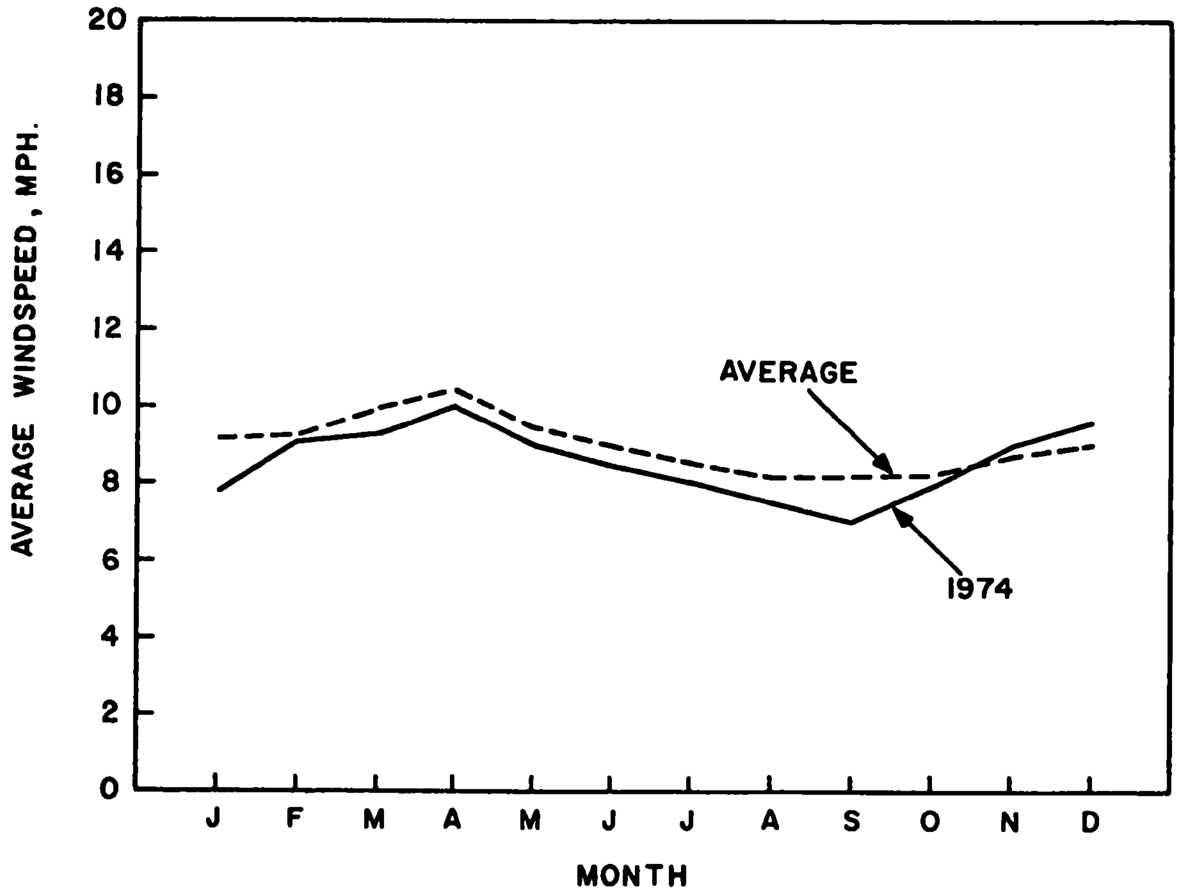

Figure 29. Monthly windspeed in Denver

APPENDIX B

PARTICLE CHARACTERIZATION

For most of the study cities members of the GCA study team acquired hi-vol filters from the 1974 filter banks of the cognizant local agencies. In addition, several filter samples for 1974 and selected earlier years were obtained from state and federal filter banks. Although some filters underwent chemical and/or detailed physical analysis, the principal purpose of obtaining filters was to utilize optical microscopy to identify each of the constituents that comprised more than five percent of the particulate mass. The selected filters, which were representative of several different site types and TSP levels within each study area, were returned to a clean room at GCA/Technology Division and carefully inspected for artifacts and evidence of sampler or filter malfunctions.

Each filter was then assigned a randomly generated five digit number which served as the only identifier for the filter sample so that each analyst had no information concerning the city, site, TSP loading or probable local sources associated with the sample. Furthermore, the use of two laboratories for the microscopy, coupled with the randomly generated identifying numbers, permitted a fairly comprehensive quality control program in the form of blind replicate analyses. Since both laboratories utilized more than one analyst, these procedures resulted in as many as four microscopists observing samples from the same filter and, in some cases, the same analyst examining replicate samples from the same filter as many as three times.

The results of this quality control effort, which are presented in Volumes I and II, warn against relying very heavily on the results of any one filter analysis. However, the random match-up between analyst and filter sample should minimize systematic bias in composited results.

Twenty filters from four sites were selected for analysis in Denver and Table 15 summarizes the meteorological data for the selected sampling days. To gain some insight into the contribution of secondary particulates, much of which is too small to be observed by the microscopists, the annual average sulfate and nitrate concentrations for the NASN site are shown in Table 16. The results of each of the samples submitted for routine analysis are presented in Table 17. The results for the filters at each site have been averaged to give a composite of the particulate composition as shown in Table 18. Six filters underwent replicate analyses, and the results of this task are presented in Table 19.

The composite particulate characterization for all filters from Denver that underwent routine analysis, presented in Table 20, shows that minerals predominate the particulate material. Of the 14 study cities, only one showed higher average percent minerals than Denver. The high mineral contribution apparently is a citywide phenomenon with the average of each of the four sites studied ranging from 79 percent to 87 percent. The major mineral constituent is quartz, which by itself comprises over half of the mass of the observed particles.

The relative contribution of combustion products to the Denver aerosol appears to be very low. It is, in fact, the lowest percent contribution for the category in any of the 14 study cities. If the microscopy results are a reliable indicator of the makeup of all the particulate collected on the hi-vol filters, then the weighted average concentration of combustion products on the 20 Denver filters would be only 11 $\mu g/m^3$.

Denver was also one of just two study cities that were found to have a higher percent contribution of rubber than combustion products. The average percent rubber content in Denver was not excessively high compared to the other study cities (Denver was fifth highest), but it does support the theory of fugitive emissions, especially after road sanding operations, being an important consideration.

Three of the filters from Denver were also submitted for determination of particle size as a function of particle type, as shown in Figures 30 through 32. Two of these filters were also subjected to chemical analysis. The filter from the State Health Department on June 14, 1974, had 4 $\mu g/m^3$ benzene solubles and just over 12 $\mu g/m^3$ total carbon with nearly all of it reported as organic carbon. The filter from the School Administration Building on the same day had over 12 $\mu g/m^3$ benzene solubles and about 15 $\mu g/m^3$ total carbon, again nearly all reported as organic carbon. The State Health Department filter from June 14, 1974, was also selected for detailed physical analysis, and the results are presented in Table 21.

Table 15. METEOROLOGICAL DATA ON SELECTED SAMPLING DAYS (STAPLETON INTERNATIONAL AIRPORT, DENVER)

Date	Precipitation, in.		Wind speed, mph		Wind direction, deg	
	Day of obs.	Preced-ing day	Average	Resultant	3-hour observation	Resul-tant
1/25/74	0	0	6.0	4.2	C, 220, 210, 200 190, 80, 250, 250	210
6/14/74	0	0.02	7.1	3.3	320, 230, 200, 120 120, 90, 160, 200	150
6/26/74	t	0	10.2	4.8	180, 220, C, 10 50, 260, 130, 180	190
7/20/74	0	0	5.5	1.3	180, 190, 240, 30 80, 20, 310, C	30
12/19/74	0	t	15.2	12.8	310, 360, 270, 270 360, 310, 290, 330	300
12/27/74	0	t	11.2	10.8	210, 190, 190, 210 220, 160, 200, 190	200

Note: C = Calm
t = Trace

Table 16. ANNUAL AVERAGE CONCENTRATIONS OF SULFATE AND NITRATE IONS AT THE DENVER, COLORADO, NASN SITE NO. 060580001 ($\mu g/m^3$)

Year	Sulfate		Nitrate	
	Arithmetic mean	Geometric mean	Arithmetic mean	Geometric mean
1972	6.65[a]	5.70[a]	3.55[a]	3.13[a]
1973	8.41[a]	7.92[a]	7.36[a]	6.11[a]
1974	4.92[a]	4.80[a]	4.27[a]	4.08[a]

[a]Indicates insufficient data for statistically valid year.

Table 17a. **RESULTS OF FILTER ANALYSES FOR SELECTED SITES IN DENVER AND VICINITY (STATE HEALTH DEPARTMENT — NO. 2)**

Date	25 January 1974			14 June 1974			26 June 1974			20 July 1974			19 December 1974			27 December 1974		
TSP ($\mu g/m^3$)	204			77			74			68			76			90		
Components	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm
Minerals	(9)	<1-76	9	(7+)	<1-66	15	(8+)	<1-95	15	(9-)	<1-75	9	(7)	<1-31	15	(8)	<1-60	9
Quartz	8+			4			5+			5			4+			6+		
Calcite				1			1			1-			1					
Feldspars				1			1			1			1			1		
Hematite				1-						2-			1-					
Mica				1-			1-			1-								
Combustion Products	(1-)	<1-12	1	(0+)			(0+)			(0+)			(1-)			(2)	<1-2	1
Soot:																		
Oil																		
Coal	1-																	
Fine soot													1-					
Glassy fly ash																		
Incinerator fly ash																		
Burned wood																		
Burned paper																		
Magnetite																		
Carbon black																2		
Biological Material	(0+)			(0+)			(1-)			(0+)			(0+)			(0+)		
Pollen																		
Spores																		
Paper																		
Starch																		
Misc. plant tissue																		
Miscellaneous	(1-)			(2+)			(1)			(1)	9-21	12	(3)	9-75	21	(0+)		
Iron or steel																		
Rubber	1-			2+			1			1			3					

Table 17b. **RESULTS OF FILTER ANALYSES FOR SELECTED SITES IN DENVER AND VICINITY (SEWER PLANT — NO. 4)**

Date	25 January 1974			14 June 1974			26 June 1974			20 July 1974			19 December 1974			27 December 1974		
TSP ($\mu g/m^3$)	565			111			241			95			143			226		
Components	Quantity, tenths	Size range, µm	Avg. size, µm	Quantity, tenths	Size range, µm	Avg. size, µm	Quantity, tenths	Size range, µm	Avg. size, µm	Quantity, tenths	Size range, µm	Avg. size, µm	Quantity, tenths	Size range, µm	Avg. size, µm	Quantity, tenths	Size range, µm	Avg. size, µm
Minerals	(9)	<1-80	12	(8)	1-80	12	(9)	<1-75	10	(7)	<1-140		(8)	1-140	15	(8+)	<1-36	6
Quartz	6			4			7			4+			4+			7		
Calcite	1+			2+			1			1+			1+					
Feldspars	1-			1+			1-			1-			1-			1-		
Hematite													1-			1-		
Mica													1-					
Combustion Products	(1-)	<1-18	9	(1)		1	(1-)	<1-20	7	(1-)			(0+)			(1-)		
Soot:																		
Oil																		
Coal																		
Soot	1-			1-												1-		
Glassy fly ash							1-											
Incinerator fly ash																		
Burned wood																		
Burned paper																		
Magnetite																		
Biological Material	(0+)			(1-)			(0+)			(1-)			(0+)			(0+)		
Pollen				1-														
Spores																		
Paper																		
Starch																		
Misc. plant tissue										1-								
Miscellaneous	(1-)	5-45	21	(1)	5-80	30	(1-)			(2)	10-175	20	(2)	10-130	30	(1)	9-75	30
Iron or steel																		
Rubber	1-			1						2			2			1		

Table 17c. RESULTS OF FILTER ANALYSES FOR SELECTED SITES IN DENVER AND VICINITY (SCHOOL ADMINISTRATION BUILDING — NO. 5)

Date	25 January 1974			14 June 1974			26 June 1974			20 July 1974			19 December 1974			27 December 1974		
TSP ($\mu g/m^3$)	436			89			132			74			104			197		
Components	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg size, μm
Minerals	(9)	<1-105	15	(8)	<1-25	9	(6)			(7-)	1-75	7	(8+)	<1-60	9	(9)	<1-90	5
Quartz	5			5-			4+	<1-65	3	5			4-			7		
Calcite	3+			2			1	<1-25	5	1			1+					
Feldspars										1-			1			1		
Hematite				1			1-	<1-50	0.5				2-			1-		
Mica																1-		
Combustion Products	(0+)			(1)	<1-5	<1	(4-)	<1-22	1	(0+)			(1+)	<1-75	1	(1)	<1-25	1
Soot:																		
Oil																		
Coal							2-		10									
V.f.soot				1			1+											
Soot particles													1			1-		
Glassy fly ash													1					
Incinerator fly ash																		
Burned wood																		
Burned paper																		
Magnetite																		
Biological Material	(0+)			(0+)			(0+)			(0+)			(0+)			(0+)		
Pollen																		
Spores																		
Paper																		
Starch																		
Misc. plant tissue																		
Miscellaneous	(1-)	5-75	27	(1)	5-125	15	(0+)			(3)	4-105	15	(0+)			(0+)		
Iron or steel																		
Rubber	1-			1						3								

Table 17d. RESULTS OF FILTER ANALYSES FOR SELECTED SITES IN DENVER AND VICINITY (ENGLEWOOD - NO. 9)

Date	25 January 1974			14 June 1974		
TSP ($\mu g/m^3$)	230			114		
Components	Quantity, tenths	Size range, μm	Avg. size, μm	Quantity, tenths	Size range, μm	Avg. size, μm
Minerals	(10-)	<1-60	10	(8-)	<1-65	8
Quartz	8			6-		
Calcite	1					
Feldspars				1		
Hematite	1-			1-		
Mica						
Combustion Products	(0+)			(1)	<1-15	1
Soot:						
Oil						
Coal						
Fine soot				1		
Glassy fly ash						
Incinerator fly ash						
Burned wood						
Burned paper						
Magnetite						
Biological Material	(0+)			(0+)		
Pollen						
Spores						
Paper						
Starch						
Misc. plant tissue						
Miscellaneous	(0+)			(1)	10-40	20
Iron or steel						
Rubber						

Table 18. COMPOSITE SUMMARY OF FILTER ANALYSES FOR SELECTED SITES IN DENVER AND VICINITY

Site	State Health Dept. — No. 2		Sewer Plant No. 4		School Administration Bldg. — No. 5		Englewood No. 9	
No. of filters	6		6		6		2	
	Quantity, percent		Quantity, percent		Quantity, percent		Quantity, percent	
Components	Average	Range	Average	Range	Average	Range	Average	Range
<u>Minerals</u>	(80)	68-89	(82)	70-89	(79)	62-91	(87)	76-97
Quartz	56	40-84	54	40-70	49	37-68	68	56-80
Calcite	6	1-11	14	2-25	15	3-35	7	3-10
Feldspars	9	0-12	8	4-15	6	3-12	6	0-11
Hematite	6	2-16	4	1-8	6	2-18	6	5-7
Mica	3	tr-5	2	0-6	3	0-6	<1	
Hornblonde			tr	0-tr	tr	0-tr		
<u>Combustion Products</u>	(5)	1-19	(4)	1-6	(12)	2-36	(6)	2-10
Soot:								
Oil								
Coal	1	0-5	1	0-3	3	0-20		
Fine soot	1	0-4	2	0-5	6	1-14	6	2-9
Soot particles					2	0-12		
Glassy fly ash	<1	0-1	1	0-5	1	0-2	<1	
Incinerator fly ash								
Burned wood								
Burned paper								
Magnetite								
Carbon black	3	0-19						
<u>Biological Material</u>	(1)	<1-4	(3)	1-7	(1)	<1-2	(1)	0-3
Pollen	<1	0-1	1	0-4	<1	0-2	<1	
Spores	<1		<1		<1		<1	
Paper	<1		<1		<1		<1	
Starch	<1		<1		<1		<1	
Misc. plant tissue	1	0-3	2	<1-7	<1	0-1	1	0-2
<u>Miscellaneous</u>	(14)	1-28	(11)	4-19	(8)	0-32	(6)	1-11
Iron or steel			<1	0-1			<1	tr-1
Rubber	14	1-28	11	4-19	8	0-32	6	1-10

Table 19. RESULTS OF REPLICATE ANALYSES OF DENVER FILTERS

Site	School Administration Bldg. – No. 5						Sewer Plant No. 4		State Health Dept. – No. 2			
Date	25 January 1974		14 June 1974		27 December 1974		19 December 1974		25 January 1974		19 December 1974	
TSP (μg/m³)	436		89		197		143		204		76	
Laboratory	A	B	A	B	A	A	A	A	A	B	A	A
Analysis	1	1	1	1	1	2	1	2	1	1	1	2
Components												
Minerals	(91)	(25)	(80)	(9)	(91)	(79)	(78)	(89)	(89)	(30)	(68)	(68)
Quartz	52		46		68	60	45	50	84		45	40
Calcite	35		18		3	10	15	25	1		10	20
Feldspars	3		3		10	4	4	4			9	3
Hematite	1		9		4	5	8	10	2		4	5
Mica			4		6	<1	6	<1	2		tr	<1
Combustion Products	(3)	(75)	(10)	(91)	(8)	(16)	(1)	(7)	(6)	(70)	(4)	(12)
Soot:												
Oil						10		4				10
Coal		15		5		2		1	5	15		1
V.f.soot	2		8		7		<1				4	
Glassy fly ash	1		2		1	4	1	2	<1			1
Incinerator fly ash		60		86						55		
Burned wood												
Burned paper												
Magnetite												
Biological Material	(1)	(<1)	(<1)	(<1)	(<1)	(<1)	(2)	(<1)	(<1)	(<1)	(<1)	(<1)
Pollen			<1		<1			<1				<1
Spores	<1		<1		<1		<1	<1				<1
Paper					<1			<1			tr	<1
Starch							<1	<1	<1			
Misc. plant tissue	1				<1		2	<1				<1
Miscellaneous	(5)	(<1)	(10)	(<1)	(<1)	(5)	(19)	(4)	(4)	(<1)	(28)	(20)
Iron or steel	<1		tr		tr	<1	<1	<1				<1
Rubber	4		10			5	19	4	4		28	20

Table 20. CITYWIDE COMPOSITE SUMMARY OF FILTER ANALYSES IN DENVER

No. of filters	20	
	Quantity, percent	
Components	Average	Range
Minerals	(81)	62-97
Quartz	55	37-84
Calcite	11	1-35
Feldspars	7	0-15
Hematite	5	1-18
Mica	3	0-6
Other	<1	
Combustion Products	(7)	1-19
Soot:		
Oil		
Coal	1	0-20
Misc. soot	4	0-14
Glassy fly ash	1	0-5
Incinerator fly ash		
Burned wood		
Burned paper		
Magnetite		
Carbon black	1	0-19
Other		
Biological Material	(1)	0-7
Pollen	<1	0-4
Spores	<1	
Paper	<1	
Starch	<1	
Misc. plant tissue	1	0-7
Leaf trichomes		
Miscellaneous	(11)	0-32
Iron or steel	<1	
Rubber	11	0-32
Other		

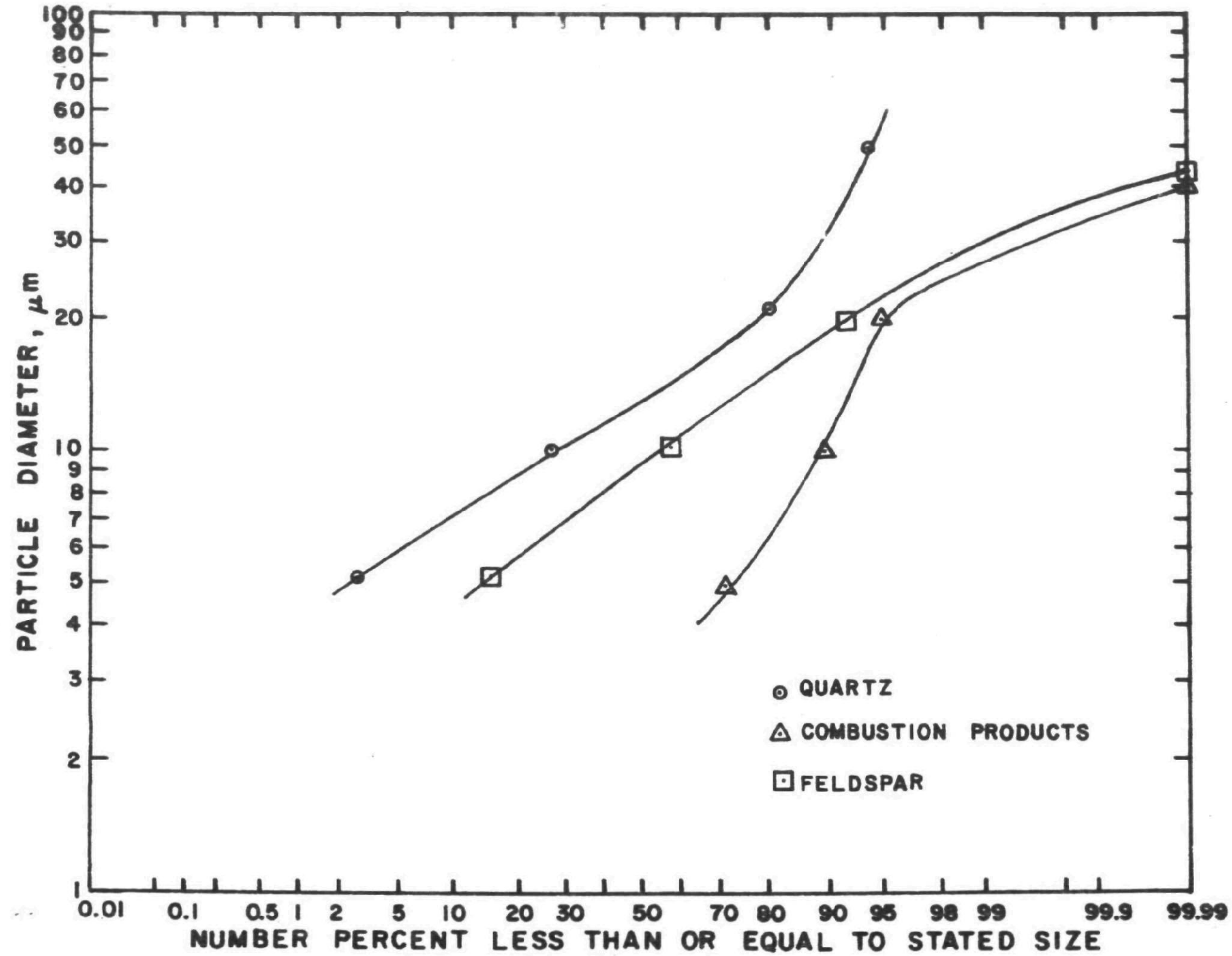

Figure 30. Cumulative size distributions for three particle types, State Health Building, Denver, January 25, 1974

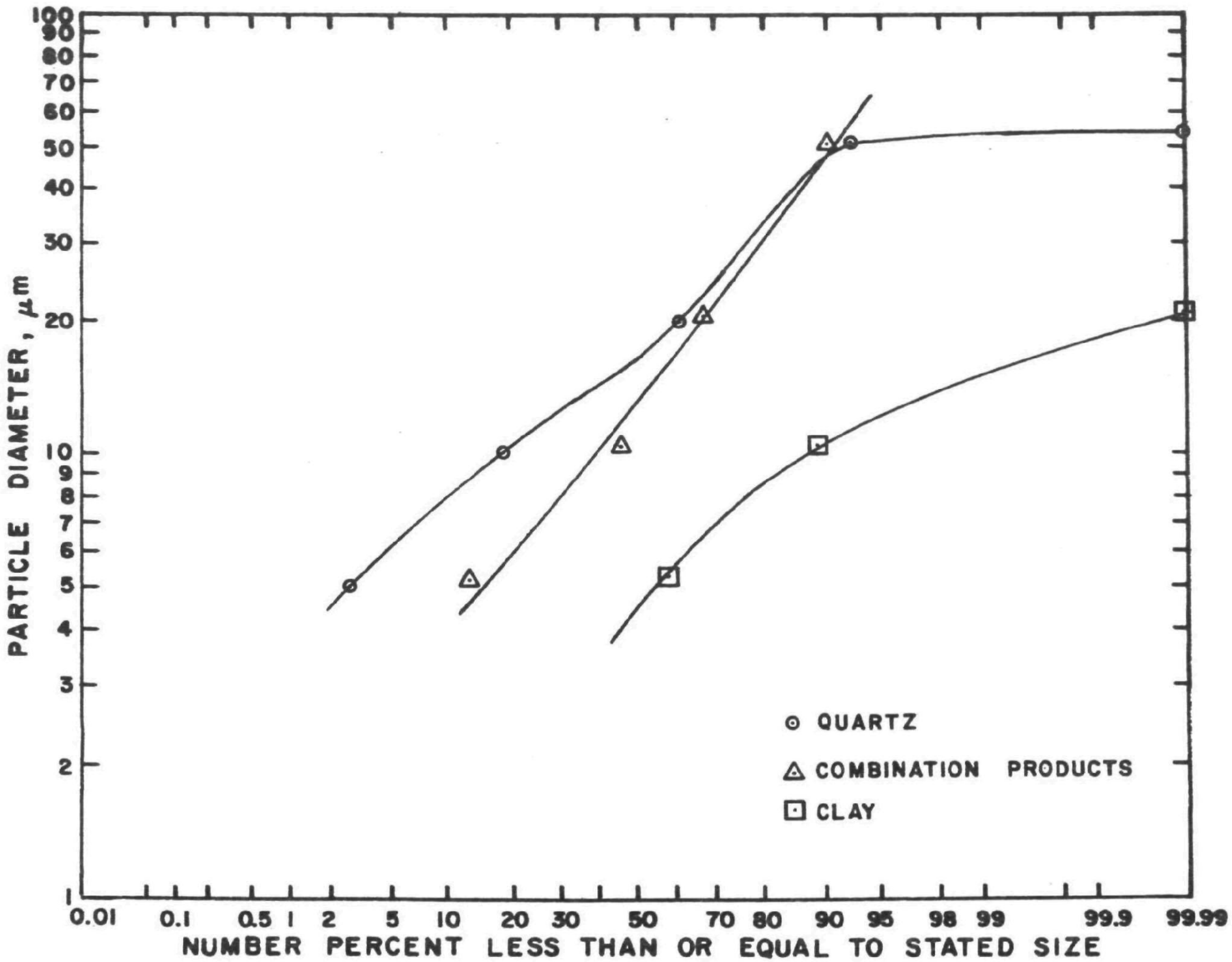

Figure 31. Cumulative size distributions for three particle types, State Health Building, Denver, June 14, 1974

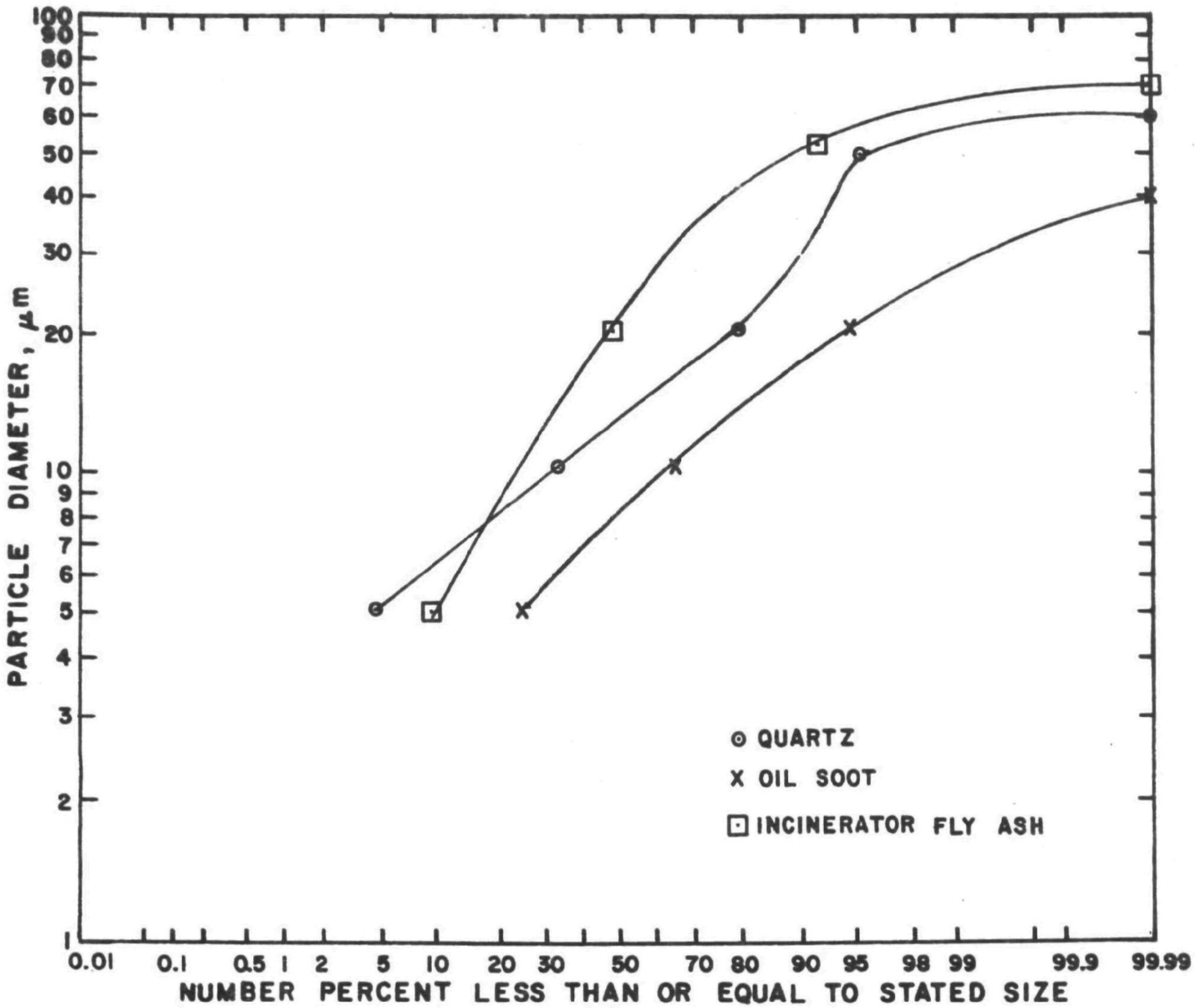

Figure 32. Cumulative size distributions for three particle types, School Administration Building, Denver, June 14, 1974

Table 21. DETAILED PHYSICAL EXAMINATION: STATE HEALTH BUILDING, DENVER, JUNE 14, 1974

A. Quartz confirmed by dispersion staining and (-) uniaxial interference figure. EDXRA shows only silicon and trace of iron (from hematite).

B. Calcite confirmed by EDXRA — shows only calcium.

C. Feldspars show plagioclase twinning, refractive indices above 1.530, EDXRA shows aluminum, silicon, calcium, sodium.

D. Hematite confirmed by high refractive indices, birefringence, and deep red color. EDXRA shows only iron.

E. Mica confirmed by crystal optics. Refractive indices and platy habit, showing biaxial interference figure (centered) with small 2V and negative optic sign. EDXRA shows only potassium, silicon, aluminum and trace of iron.

F. Glassy fly ash was confirmed by its morphology and EDXRA spectrum: showing only aluminum and silicon.

G. Rubber was confirmed by its elastomeric nature, surface appearance and EDXRA spectrum showing mostly carbon with minor amounts of calcium, aluminum, silicon (all probably from road wear products), sulfur, chlorine, iron, titanium and zinc.

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(Please read Instructions on the reverse before completing)

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16. ABSTRACT

This document is one volume of a sixteen-volume report presenting an overall assessment of the particulate problem, which was conducted by GCA/Technology Division for EPA.

This particular document is one of fourteen single-area volumes that provide working summaries of data gathered in the fourteen urban areas studied. These city reports primarily provide documentation and background information for Volume I of the study - National Assessment of the Particulate Problem - Final Report. Volume I should be considered the primary output of the report.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Particulate Matter	Optical Microscopy	
Total Suspended Particulate	Secondary Particulates	
Emission Sources	Fuel Combustion	
Control Methods	Process Emissions	
Air Quality Measurements	Fugitive Emissions	
	Fugitive Dust	
	Monitor Siting	
	Meteorology	

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