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ESTIMATING POLLUTANT EXPOSURES FROM COAL FIRED POWER
PLANTS IN A RURAL REGION

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Introduction

A critical issue in epidemiological studies of ambient air pollution is the measurement of pollutant exposure in the study population. Accurate characterization of air quality is necessary in any study relating exposure to health effects, and is essential in attempting to quantify risk estimates for specific exposure concentrations. Despite the importance of accurate air quality data, most epidemiological investigations have used relatively crude estimates of pollutant exposure.¹ Results from such investigations may be only qualitative at best.

Early studies of air pollution health effects were limited by a lack of air pollution monitoring sites, and thus, exposures were often based on surrogate measures such as tons of coal consumed.² With the introduction of reliable and reasonably accurate measurements of pollutant concentrations, several important constraints remained. These limitations include the relatively sparse siting of monitor sites and the variable relationship of monitor concentrations to the exposure experience of the study population. Other considerations in using monitor data include the selection of the pollutant specie(s), the duration of the sampling period, the use of short-term versus long-term averages, peak versus mean concentrations and the cyclical variation in pollutant levels.

The Chestnut Ridge region of Pennsylvania is the site of an ongoing study of health effects from air pollution. This site was selected in part because of the extensive and well maintained air pollution monitoring network, and the previous studies of pollutant dispersion in

the area.³ Several studies of respiratory symptoms and pulmonary function in women and school age children have been carried out in the area. The current study evaluated aspects of air pollution exposure estimates which are relevant to these epidemiologic studies. Subsequent papers will discuss findings of the various epidemiologic studies which employ these air pollution measures.

Methods

The Study Area

Chestnut Ridge is a hilly rural area of mid-western Pennsylvania located about 100 kilometers east of Pittsburg and about 50 kilometers northwest of Johnstown. The area covers approximately 6400 square kilometers and includes the lower half of Indiana County and portions of Westmoreland and Armstrong Counties (Figure 1). Seventeen air quality monitors have been set up and are maintained by the local electric utility. The monitors were established by the utility, in part to fulfill initial licensing requirements for the construction and operation of the several large electric power plants in the area. However, the capabilities of this monitoring network go beyond state requirements. The network forms part of the Pennsylvania Electric Association's data base, which is aimed at collecting all meteorologic and pollution information in a common accessible data base. Each monitor site collects hourly sulfur dioxide and coefficient of haze data, and either daily or every sixth day 24-hour samples of total suspended particulates. In addition, six of the sites monitor nitrogen oxides and ozone. Meteorologic

information for the area comes from the Penview meteorologic tower (Tower in Figure 1).

The four mine-fed coal-fired power plants in the Chestnut Ridge area have a total peak generating capacity of 4,700 MW(e), making this one of the largest concentrations of coal fired electric generation in the U.S. In addition, a coal gassifier is located near Homer City. Each power plant presently is equipped with tall stacks, from 797 to 1000 feet in height. The stack at the Connemaugh plant was raised to 1000 feet from 230 feet in 1976. Two of the power plants, Connemaugh (1700 MW) and Seward (218 MW), are located in a valley formed by the Laurel Hills to the southeast and the Chestnut Ridge to the northwest, two roughly parallel ridges approximately 2000 to 2500 feet in height. The Homer City (1200 MW) and Keystone (1640 MW) power plants are located in more gentle, rolling terrain in the north-western part of the region.

Pollutant Representation

Over four years of hourly sulfur dioxide (1975-1978) and over five years of daily to approximately weekly total suspended particulate (1974-1978) concentrations at each of the 17 monitors were condensed into a data format known as the "arrowhead profile"⁴ (Figure 2). In contrast to the work of Larsen⁴ which used non-overlapping or "block" averages, the arrowhead curve used in the Chestnut Ridge investigation uses running averages. The arrowhead profile or curve is a concise way of expressing concentrations and frequency of occurrence at various averaging times. This analytic and display technique permits the convenient construction of various pollutant measures for estimating population exposures. Other

advantages to operating in the arrowhead format include computational speed, ease of data handling and transformation, greater accuracy of spatial interpolation, and significantly reduced data storage requirements.

The study area was divided into 36 numbered districts using township and highway boundaries to localize the residence of subjects. An triangulation scheme using three monitors estimated the concentration at the population-weighted centroids of the districts. The same procedure was used to derive pollutant scores at the exact location of each of the 14 schools in the children's study. This scheme used the three closest (terrain-adjusted) monitors, that formed a triangle in which the minimum angle was 10 degrees, in a planer interpolation (distance squared and normalized) and half gradient extrapolation. Terrain-adjusted distance is the actual distance plus 1/4 km for every 100 feet of cumulative distance elevation distance.

Several additional schemes, e.g. closest monitor, to estimate pollutant concentrations at the districts were also used. All schemes were evaluated by the "jack-knife" technique. Predictions of concentrations at each of the 17 monitors were compared with actual concentrations using correlations, analysis of variance and graphical techniques.

Exposure Measures

The arrowhead profile permitted the construction of four types of exposure measures. These include pollutant concentrations at various averaging times and percentiles, such as the National Ambient Air Quality

Standards, represented by indices 4, 5, 6 and 11 in the study (Table 1). "Exceedence measures" are the second type of exposure measure, which estimate the amount of time that a particular concentration is exceeded (indices E1 and E2). Thirdly, "arrowhead indices," which combine concentrations at selected averaging times and percentiles, provide a relative indication of pollutant patterns such as "cleansing" or "acute" (high level) periods (indices 3 and 8). The fourth type of exposure measure is a true cumulative exposure measure, that is, the product of concentration and exposure time at that concentration. Assuming a linear dose-response relationship, the simplest case, a cumulative exposure measure is simply an average concentration. In addition, several non-linear exposure-response functions were modeled by giving either increasing or decreasing weight to high percentile concentrations, resulting in a linear risk measure. All together, over seventy pollutant measures for both TSP and sulfur dioxide at the Chestnut Ridge site were analyzed, only a few of which are described here. A complete description and evaluation of the pollutant measures may be found elsewhere.⁵

Analysis of Stability of Pollutant Measures

The annual variation in pollutant measures was evaluated by comparing correlations and isopleths of concentrations of individual years of the various pollutant indices with long term (four or five year) averages of the same indices. Two weighting schemes, which gave either increasing or decreasing weight to more recent years, also were used to reflect long-term changes in pollutant patterns.

The coefficient of variation (COV) of each monitor and the mean COV

of the 17 monitors was used to assess the stability of the pollutant measures. In the absence of major changes in source emissions and long-range transport, low COVs should indicate pollution measures which are stable over time.

Computer Facilities

The arrowhead profiles were constructed using the TROLL statistical package in conjunction with the VS/1 batch processing system at the M.I.T. Information Processing Center. The program provides data smoothing and interpolation to supplement missing data. Fortunately, monitor availability was good, and missing data was generally less than 20%. TROLL was also used for developing the exposure measures and interpolations, and for the statistical analysis of these measures.

Results

Pollutant Patterns

Air quality monitoring data in the Chestnut Ridge area show considerable diversity and complexity in the levels of pollution, gradients, and temporal relationships. Several monitor sites have exceeded the National Ambient Air Quality Standards (NAAQS) for both TSP and sulfur dioxide in recent years. However, the region presently is classified as an "attainment area" by the Commonwealth of Pennsylvania. The long term mean sulfur dioxide concentration at the 17 monitors is 70 micrograms per cubic meter (ug./c.m.), which represents 88% of the annual

NAAQS of 80 ug./c.m. (Table 2). The corresponding average for TSP concentrations is 67 ug./c.m., or 90% of the annual NAAQS of 75 ug./c.m. Yearly averages at the 17 monitors of sulfur dioxide concentration increased from 1975 to 1977, and then decreased slightly, and concentrations of TSP decreased slightly from 1974 to 1978. One way analysis of variance showed significant changes in annual mean sulfur dioxide concentrations, but not TSP concentrations. Two way analysis of variance showed significant differences across monitors and years for both pollutants. Running annual averages show similar but slightly more dramatic behavior during this period.

In general, the Chestnut Ridge area experiences a pollution gradient which increases to the south and east, and small changes in distance may produce substantial variations in pollutant concentration (Figure 4). This gradient is most pronounced in the south-eastern part of the area due to the complex terrain and the importance of local sources. For example, the 1976 sulfur dioxide concentration varied from 120 ug./c.m. at monitor 17 to 54 ug./c.m. at monitor 15, which is only 6 kilometers away. Each power plant forms a localized "hotspot," with occasional, high peak pollutant concentrations due to downwash from the stacks and stagnant air conditions. Also, because prevailing winds originate from the SW to WNW sector approximately 53% of the time (as measured at the Penview Tower), west facing slopes, particularly of the Laurel Hills, tend to be in the direct path of exhaust plumes which originate from the Connemaugh and Seward power plants (Figure 1). Therefore, these areas experience high average annual concentrations, although only moderate peak concentrations.

Another source of air pollutants in the Chestnut Ridge area

originates from the Pittsburgh urban area which is 60 kilometers to the west. Prevailing winds carry emissions from Pittsburgh, as well as those from the Ohio River Valley, directly over the region. The north-western part of the region shows moderately high annual concentrations of both TSP and sulfur dioxide, but generally low peak concentrations of these pollutants (monitor 9, Figure 4). The high annual concentrations may be attributed to medium range transport of pollutants from the Pittsburgh area. Only major local sources, e.g., the power plants, would be expected to produce high peak concentrations.

Relationship between TSP and Sulfur Dioxide

Pollutant patterns of TSP are very different than those of sulfur dioxide, probably reflecting fugitive dust and not power plant emissions. Annual averages of TSP and sulfur dioxide concentrations for the years 1975-1978 had a correlation coefficient of 0.341 (Table 3). There was little correlation between 24-hour peaks of the two pollutants: correlation coefficients range from 0.015 in 1975 to -0.140 in 1976. Few districts have high concentrations of both sulfur dioxide and TSP (Figure 5). Several observations besides low correlations suggest that TSP measures at the monitors are only partially related to power plant emissions, including (1) less dramatic long-term variation of TSP levels than sulfur dioxide levels, (2) less defined gradients of TSP around power plants and lower overall variation, as reflected by a coefficient of variation of 0.15, versus 0.20 for sulfur dioxide for annual average concentrations, and (3) relatively high TSP and low sulfur dioxide levels in the northwest area of the region, away from known major fossil fuel

emission sources.

Different measures of the same pollutant are not necessarily closely correlated. Using the short-term NAAQS for example, correlation coefficients for 3 and 24-hour second highest peak to calendar year average of sulfur dioxide concentrations are 0.626 and 0.764, respectively (Table 3). The correlation coefficient for 24 hour peak to annual TSP concentrations is 0.402, considerably lower and less consistent on a yearly basis.

Year to Year Variation

Changes in pollutant patterns over the study period were large, presumably due to meteorological effects and emission source alterations. For example, the exhaust stack of the Connemaugh power plant was raised to 1000 feet from 230 feet in 1976, causing a significant shift in pollutant dispersion in the south-eastern section of the Chestnut Ridge area. Even air pollution monitors which are not affected by known changes in source emissions also show considerably fluctuation from year to year. The TSP arrowhead profiles seen earlier for monitor 1 (Figure 3) for the years 1974 to 1977 demonstrate dramatic differences in the shape, sharpness, asymmetry, and spread of the profile. This causes instability and uncertainty in characterizing a study district as "clean" or "dirty" with respect to other districts (Figure 6). Annual variation in concentrations causes low correlations among measures of different years, as well as significant changes in ranking of the geographic units when data from any particular year are used. For example, mean 1975 sulfur dioxide levels correlated only 0.205 with 1978 levels. 1975 levels have a

correlation coefficient of 0.765 with the mean of 4 years of sulfur dioxide levels. The corresponding correlation coefficient for 1978 with the four year average is 0.558. Peak measures change yet more significantly. For example, the correlation coefficient for 24 hour second highest peaks between 1975 and 1978 of sulfur dioxide is only -0.153. Thus, stability was deservedly a prime criterium of the pollutant measure used to estimate pollutant exposure.

Stability of Pollutant Measures

The coefficients of variation (COV) for the year to year fluctuations of pollution scores ranged from about 0.10 to 0.30 (Table 4). However, the highest COV among the 17 monitors was generally several times the average, and was usually from monitor 17, near the Connemaugh and Seward plants, the latter of which had its stack raised during the study period. Annual means and the cleansing index (index 8) have a much lower COV than peak measures. In general, longer averaging times and percentile concentrations near the median tend to show less year to year variation. The calendar year average (index 11) is slightly more stable than the running annual average (index 6), as expected, since the running average is designed to discern peaks that are not necessarily confined to the calendar year.

Exceedence measures (E1 and E2) were stable at short averaging times and had a smaller COV than all other sulfur measures. Long averaging times of these measures resulted in a lack of exceedences at several monitors and thus high COVs. Correlation coefficients for exceedence measures at the lowest concentration (80 and 75 micrograms per cubic meter

for sulfur and TSP respectively) and shortest averaging time (one hour for sulfur) to annual concentrations are 0.855 for sulfur dioxide, and 0.921 for TSP. However, correlations for sulfur dioxide exceedence measures at higher concentrations are much lower (Figure 7). The variation in exceedences at different concentrations shows that a measure based on the frequency of peak concentrations may be considerably different than one based on the concentrations.

The approximately log-normal distribution of pollutant concentration results in considerable heteroscedasticity in peak measures, that is, an increasing variance with increasing mean concentration. COVs of the 90th percentile concentrations are significantly lower than that of the 99th percentile, while COVs of logarithms of both percentile groups are approximately equal (Table 6). A two-way analysis of variance at various averaging times shows that all measures have significant differences across monitors (Table 6). However, only the 99th percentile showed no significant differences ($p < 0.05$) across 4 years of data for averaging times less than 24 hours. Thus, the variance is too large at averaging times less than 24 hours to observe yearly differences in 99th percentile concentrations which are seen in 90th percentile concentrations.

Interpolations between Monitors

The time independence of the arrowhead profile permits accurate interpolation of peak and low percentile concentrations. Several interpolation schemes using arrowhead data were evaluated using the "jack knife" technique. These included (1) the use of the closest monitor, the most common technique, (2) averaging schemes using 2, 3, 4, or 5

monitors, where monitor scores are weighted by inverse of distance to interpolation point and normalized, and (3) several triangulation extrapolation/interpolation schemes including full, half, third, and quarter planer, several transformations of the distance correcting term, and 10 and 25 degree minimum angle criteria (for the selection of 3 monitors used). Attempts to optimize the parameters in the triangulation scheme by non-linear least squares regressions failed, because the series frequently diverged. When it did converge (only on very small data sets), results varied greatly depending on which pollutant was used. The triangulation scheme that resulted in the highest correlations for both TSP and sulfur dioxide used half planer extrapolations, planer interpolations, distance squared correction terms, and the 10 degree criteria. Using an inverse distance squared term gave just slightly higher correlations than the nominal or cubed value. Full planer extrapolations resulted in several negative concentrations, and lower correlations. Third and quarter extrapolations reduced the range of predictions, and had a slightly lower correlation coefficient than the half planer scheme. Using a triangle with minimum angle criteria of 25 degrees severely reduced the correlations, and forced the average monitor to predictor point distance to increase greatly.

No schemes were able to predict 24 hour peak concentrations of TSP (indice 4) in the region (Table 7). As more monitors are used in the nondirectional averaging scheme, correlations generally decrease, as does the overall range of the predicted scores. The use of the closest monitor had the highest correlations with actual peak and annual scores of sulfur dioxide, although the planer scheme did as well with annual averages of this pollutant. However, the triangulation procedure is able to produce

distinct pollution scores at the population weighted centroid of each district or school location. These scores were in close agreement with hand drawn isopleths in all but one instance, which concerned a school location where the first choice of the algorithm used a very acute triangle (11 degrees), and produced clearly erroneous results. The second triangle, with less extreme angles, produced expected scores.

Thus, pollution scores for both schools and district centroids were available using the planer technique. This detail permits considerable flexibility in estimating pollutant exposure. For example, school and residence pollution scores may be combined to reflect the proportion of time a child spends at school and at home. Since most rural schools are regional schools and many children are bused out of their township (and district), exposure scores did vary significantly depending upon which location was used to characterize exposure.

Discussion

The study demonstrates that efforts to characterize the air pollution burden in epidemiological investigations of geographic areas may be drastically influenced by the use of different types of pollution measures. Different air pollution measures which used the same data may have a large effect on both the stability of the pollution measures and the interpretation of relative pollutant levels. Moreover, the determination of ambient pollutant levels in geographic units, selected to give representative (population weighted) pollution scores, may be very sensitive to monitor location and/or interpolation scheme.

Short averaging times (less than 24 hours), and high percentile

concentrations (peaks, second highest peaks, and even 90th percentile concentrations), tended to vary greatly from year to year. Such high concentrations are caused by stack downwash, fumigation and plume centerline impaction at monitoring sites. These events are likely to happen several times each year, usually in the proximity of the emission source. However, they may not be representative of the exposure experience of the population in the geographic unit. Very high peak concentrations do indicate which areas may be very polluted at times, but the frequency of such episodes can only be determined by examining lower (90th, 84th) percentile concentrations. Exceedence measures may serve the same purpose, and with an appropriately selected concentration threshold (to give about 15 to 45% exceedence), such measures were somewhat more stable estimates than the annual average and peak concentrations. This suggests that measures derived from two or more percentiles, perhaps the 50th and 84th, will provide more stable estimates than measures based on one concentration. In addition, exceedence measures are largely insensitive to averaging time although short averaging times appear to be slightly more stable, possibly due to the greater frequency of exceedences that occur. (High thresholds and long averaging times result in an excess of "zeros" in these measures, thus increasing the COV.)

Sulfur dioxide gave results more consistent with known power plant emission and dispersion patterns in the region than total suspended particulates (TSP). TSP does not seem to be a good indicator of power plant emissions, and has a low correlation to sulfur dioxide concentrations in this study region. Fugitive dust, from agricultural, roadway and other open sources sources, is a large component of TSP measurements. Measures of fine or respirable particulates would probably

give more useful exposure estimates for epidemiologic studies of health effects.

Choice of Pollution Measure

These complexities point out several areas of major uncertainty in determining ambient pollution levels to represent exposure in health effects research. Foremost among these is the selection of the proper measure of ambient air pollution. A population's exposure to pollution or pollutant dosage is usually expressed as a concentration measure. Typically, the annual mean, 3 and 24 hour peak concentrations are used, reflecting the National Ambient Air Quality Standards (NAAQS) in the Clean Air Act. One or two exceedences of these measures per year represents a violation of ambient standards. However, pollution measures for epidemiological purposes have a significantly different use than the determination of compliance with standards. Exposure estimates should be clinically significant, that is, related to the exposure-response relationship, and address the pattern of exposure, or the exposure history of the population to the pollutant(s). Running averages were used in this study because the health response should not be sensitive to the arbitrary boundaries of calendar years or months. Running annual averages tended to better depict changes in pollutant patterns than calendar year averages. However, four or five year averages of the two were similar.

The second consideration, concerned with the pattern of exposure, is easier to handle. Ideally, exposure estimates would provide a measure of pollutant exposure during the critical induction or disease initiation period. The association between pollutant levels and health effects will

be diluted to the extent to which inappropriate time frames for health and air quality data are used. For example, if the prevalence of a chronic respiratory symptom such as chronic mucus hypersecretion is related to several years of high level pollutant exposure, a measure of air pollution in the most recent year may not provide an accurate estimate of exposure, especially if pollutant patterns have changed.⁶ Thus, air quality information must be collected over an appropriate time period. Also, several years of data should be collected, to determine both typical peak concentrations and the overall trend in ambient levels. Peak concentrations at monitors are relatively rare events, since it is unlikely that when a plume centerline touches the ground it will effect impact a monitoring site, given low monitor site densities. Three to five years of data can probably establish 99th percentile peaks with acceptable accuracy; 90th percentile concentrations require perhaps one year of data.

Pollutant trends may be identified with annual pollutant averages, as well as peak measures. For example, changes in dispersion due to the increased height of the Seward stack were dramatically illustrated by an examination of 24-hour peak concentrations (Figure 3). Concentrations in the valley were lowered as the plume tended to disperse over a larger area and "punch through" the ceiling level more frequently (resulting in little dispersion in the area). This new pollution pattern tended to have an impact on ridgetops over a large area rather than the valley floor. Such changes could only be identified through an examination of several years of data.

Characterizing Geographic Units

This study highlights the difficulty of accurately characterizing geographic units and individual exposures, even with a high monitor density. The effect of uncertainty in estimating an individual's exposure may have been increased, due to the relatively small size of the Chestnut Ridge region, the complex terrain and the sharp pollution gradients. However, this small size gives power to the health estimates, since potentially confounding factors which exist between geographic regions tend to be minimized.

Pollution scores for populations may be defined using the nearest monitor, interpolations between two or more monitors, isopleths, and dispersion models (preferably supplemented with monitor data). The triangulation scheme used in the study provides an imperfect estimate of pollutant concentrations for population-weighted exposures, especially for peak measures. In some cases, the procedure was very sensitive to monitor selection. Potential error increases as distances increase, or if the extrapolation point lays outside the triangle formed by the three monitors. Also, the use of several monitors tends to decrease the magnitude of extreme observations, and thus reduce the range of district pollution scores as compared to that of monitors.

Despite its approximate nature, the triangulation scheme may provide more valid exposure estimates than other methods, such as the use of the nearest monitor site. Measurements from any particular monitor are influenced by the site location and meteorology, with respect to the location of emission sources. For example, with the consistent directional winds in the Chestnut Ridge area, a monitor which is not

located downwind of primary emission sources will not accurately characterize pollutant levels for downwind populations, despite otherwise close proximity to the population. Incorporation of wind rose information could further refine the triangulation procedure. On the other hand, the planer technique will give poor results when no consistent pollution gradient exists, as in the case of peak TSP measures in this area. Averaging schemes which did not account for gradients proved inferior to the planer and closest monitor approaches.

The low correlation coefficients for the jack knife analysis are in part due to the distances which separate the monitors. Predictions of pollutant levels at the districts, with shorter distances, are more consistent. For example, the correlation coefficient for district sulfur dioxide scores using the closest monitor and the planer technique is 0.90 for both annual average and 8 hour peak concentrations, and about 0.73 for both peak and mean TSP scores.

The major problem in using isopleths for characterizing pollution exposure is their arbitrariness given low monitor site density, complex terrain, and multiple emission sources. Isopleths (Figure 4) could in fact be drawn in numerous patterns with quite different results. Triangulation gives similar results without this arbitrariness.

Lastly, the triangulation procedure permits pollution scores to be produced at location of interest, a considerable advantage. For example, air pollution exposures may be evaluated for a school or other daytime location for particular population groups.

Conclusion

We cannot suggest a definitive methodology for estimating the pollution exposure of a population from the Chestnut Ridge Study. Rather, it seems clear that the investigator should use considerable discretion and caution in using available pollution measures such as the National Ambient Air Quality Standards (NAAQS). These measures may not provide sufficient information for the quantification of exposure. Shortcomings of typical air pollution measures include (1) the inconsistency of different measures, e.g., peaks and annual averages, as well as inter-pollutant discrepancies; (2) limited spatial representativeness of many monitor sites even with high monitor density; (3) lack of temporal information to identify trends; and (4) uncertainty in the exposure-response relationship of pollutants, which precludes firm agreement on the use of measures better than the NAAQS.

The study demonstrates that measures of air pollution exposures, once taken as a routine and trivial matter, are in fact as complex and important as other considerations in the epidemiological investigation. Biased or erroneous air pollution measures produce invalid exposure estimates as would any other incorrectly measured risk factor. The selection of the best pollution measure for an area is influenced by regional characteristics, such as terrain, meteorology, pollutant sources and monitor location. Lacking a standardized procedure, good judgement is essential in selecting pollutant measure for a particular study.

We feel that the appropriate criteria for selecting a pollution measure are:

(1) Appropriateness, in terms of agreement with clinical hypothesis about exposure-response and exposure history hypotheses. Thus, it is important that concentrations at different percentile groups be collected and analyzed. (Arrowhead curves are a convenient analytic tool.)

(2) Stability or consistency, that is, without major changes in source emissions, measures should consistently identify clean or dirty areas with a minimum of year to year variation. It may be necessary to normalize distributions, combine measures, or average several years of data, to achieve this goal.

These criteria should help identify geographic areas which are consonant with known emission and dispersion patterns in the region. Several procedures are suggested to achieve these criteria:

(1) An indepth investigation of the topography and meteorology of the region, especially with respect to the locations of major pollution sources, monitors and the study population.

(2) Based on the above, monitor density should be high enough to depict major differences in pollution levels which occur in nearby areas.

(3) Interpolations, averaging or other schemes may be employed to assure that a pollution score is representative in the geographic units. If possible, geographic units should be defined on the basis of pollutant patterns.

(4) Pollution data should be collected over a long enough period to (a) indentify trends in ambient levels (b) bound uncertainties in characterizing levels or making stratifications and (c) and correspond with the specific disease and population being investigated.

(5) Data may be stratified into 2 or 3 exposure classes which represent the investigators best judgement using all relevant information.

These efforts should reduce the error and inconsistency which is likely to exist when monitor data is generalized to reflect the exposure experience of a population.

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<u>Index</u>	<u>Name</u>	<u>Description of Sulfur Index</u>	<u>Description of TSP Index</u>
3	Short-term High	Sum of 99, 84 and 50 for 1, 3, 8 and 24 hours *	Sum of 100, 84 and 50 for 24 hours *
4	Short-term Standard	Ratio of 99 percentile to 3 hour threshold	Ratio of 100 percentile to 24 hour threshold
5	Mid-term Standard	Ratio of 99 percentile to 24 hour threshold.	Ratio of 99 percentile to hypothetical 15 day standard of 147 ug/cu.m.
6	Annual Running Standard	Ratio of 99 percentile to annual threshold	Ratio of 100 percentile to annual threshold
11	Annual Calendar Standard	Ratio of calendar year average to 1 yr threshold	Ratio of calendar year average to 1 yr threshold
8	Long-term Cleansing	Sum of 16 and 0 for 72, 168, 730 and 2190 hours	Sum of 16 and 0 for 168, 336, 730, 1460, 2190, 4380, and 8760 hours
E1	Low Threshold Exceedence	Percentage of time above 80 ug./c.m. (Annual NAAQS)	Percentage of time above 75 ug./c.m. (Annual NAAQS)
E2	Medium Threshold Exceedence	Percentage of time above 210 ug./c.m.	Percentage of time above 150 ug./c.m.

* Numbers refer to percentile group concentrations on arrowhead profiles.

Table 1. Pollution indices for sulfur and TSP described in this article.

Year	Sulfur Dioxide		TSP	
	Concentration	St. Deviation	Concentration	St. Deviation
	u.g./m ³	u.g./m ³	u.g./m ³	u.g./m ³
1974	n.a.	n.a.	71	9
1975	65	21	69	11
1976	70	17	69	13
1977	79	13	66	12
1978	66	11	61	10
mean	70	15	67	11

One Way Analysis of Variance

F years	2.79	d.f. 3	1.71	d.f. 4
probability	(0.047)		(0.161)	

Two Way Analysis of Variance

F years	5.49	d.f. 3	4.21	d.f. 4
probability	(0.002)		(0.004)	
F monitors	5.92	d.f. 16	8.36	d.f. 16
probability	(0.000)		(0.000)	

Table 2. Mean calendar year averages of pollutant concentrations (index 11) at the 17 monitors, and annual standard deviation of the 17 monitors in the Chestnut Ridge area. Results from one and two analysis of variance tests show significant differences between annual concentrations at the same monitor for different years.

Year	Sulfur Dioxide to TSP		Annual to 24 hour Averages	
	Annual	24 hour	TSP	sulfur
1974	n.a.	n.a.	-0.067	n.a.
1975	0.552	0.015	0.334	0.814
1976	0.358	-0.140	0.762	0.893
1977	0.342	-0.059	0.512	0.675
1978	0.108	-0.111	0.366	0.607
mean*	0.341	-0.028	0.481	0.764

*correlation coefficients for 4 or 5 year mean of pollutant scores.

Table 3. Correlation coefficients for the 17 monitors using annual calendar year averages and 24 hour peak concentrations.

Coefficient of Variation for Arrowhead Indices						
	3	4	5	6	11	8
Sulfur						
mean	.23	.28	.28	.22	.16	.22
max	.64	.87	.49	.41	.34	.55
TSP						
mean	.20	.33	.23	.10	.11	.16
max	.53	.69	.63	.24	.22	.20

Table 4. Coefficients of variation and maximum coefficient of variation for 17 monitors and 4 (sulfur) or 5 (TSP) years of data. See Table 1 for definition of indices.

Coefficient of Variation for Exceedence Measures							
Averaging time in Hours							
	1	3	8	24	72	168	336
Sulfur E1							
mean	.15	.16	.18	.22	.23	.29	.35
max	.46	.47	.50	.58	.54	.99	.99
Sulfur E2							
mean	.15	.16	.28	.73	1.4	*	*
max	.38	.42	.61	1.3	2.0	*	*
TSP E1							
mean	n.a.	n.a.	n.a.	.19	.35	.56	.81
max	n.a.	n.a.	n.a.	.57	.89	1.4	2.3

* Not calculated.

Table 5. Coefficients of variation and maximum coefficient of variation for 17 monitors and 4 (sulfur) or 5 (TSP) years of data for exceedence indices. Index E1 is amount of time above annual NAAQS. See Table 1 for other definitions.

	90th Percentile				99th Percentile			
	Averaging Time in Hours				Averaging Time in Hours			
	1	3	8	24	1	3	8	24
Coefficient of Variation								
Actual	.17	.18	.18	.18	.28	.29	.30	.29
Log	.043	.044	.044	.046	.041	.045	.053	.061
Two Way Analysis of Variance *								
F years	8.8	9.0	8.8	9.3	.72	.30	1.2	7.0
prob.	0	0	0	0	.55	.83	.31	.001
F monitors	5.0	5.2	5.1	4.6	5.8	4.5	4.2	2.2
prob.	0	0	0	0	0	0	0	0
* d.f. for years = 3 d.f. for monitors = 16								

Table 6. Analysis of 90th and 99th percentile concentrations at different averaging times. Coefficient of variation and results from two-way analysis of variance tests.

Estimation Technique	TSP		Sulfur Dioxide	
	Index 4	Index 6	Index 4	Index 6
Closest	-0.022 (.89)	0.383 (.80)	0.324 (.93)	0.480 (1.06)
Averaging				
2 *	-0.078 (.62)	0.189 (.69)	0.270 (.88)	0.372 (.95)
3	-0.091 (.51)	0.195 (.54)	0.239 (.72)	0.443 (.79)
4	-0.060 (.40)	0.123 (.46)	0.279 (.64)	0.479 (.73)
5	-0.075 (.35)	0.168 (.43)	0.275 (.58)	0.472 (.69)
Triangulation	-0.044 (.97)	0.397 (.87)	0.057 (1.08)	0.422 (.97)

* Number of monitors used in averaging scheme.

Table 7. Correlation coefficients between predicted scores and actual pollution scores at the 17 monitors for several estimation techniques. Correlations for 4 years (sulfur dioxide) or 5 years (TSP) of scores at the 17 monitors. Averaging schemes use the closest 2, 3, 4 or 5 monitors, with weights equal to inverse of distance. The triangulation scheme uses 3 monitors in half gradient extrapolation (see text). Standard deviation of predicted scores/standard deviation of actual monitor scores in parentheses, giving indication of compression or expansion of range for the different estimation techniques.

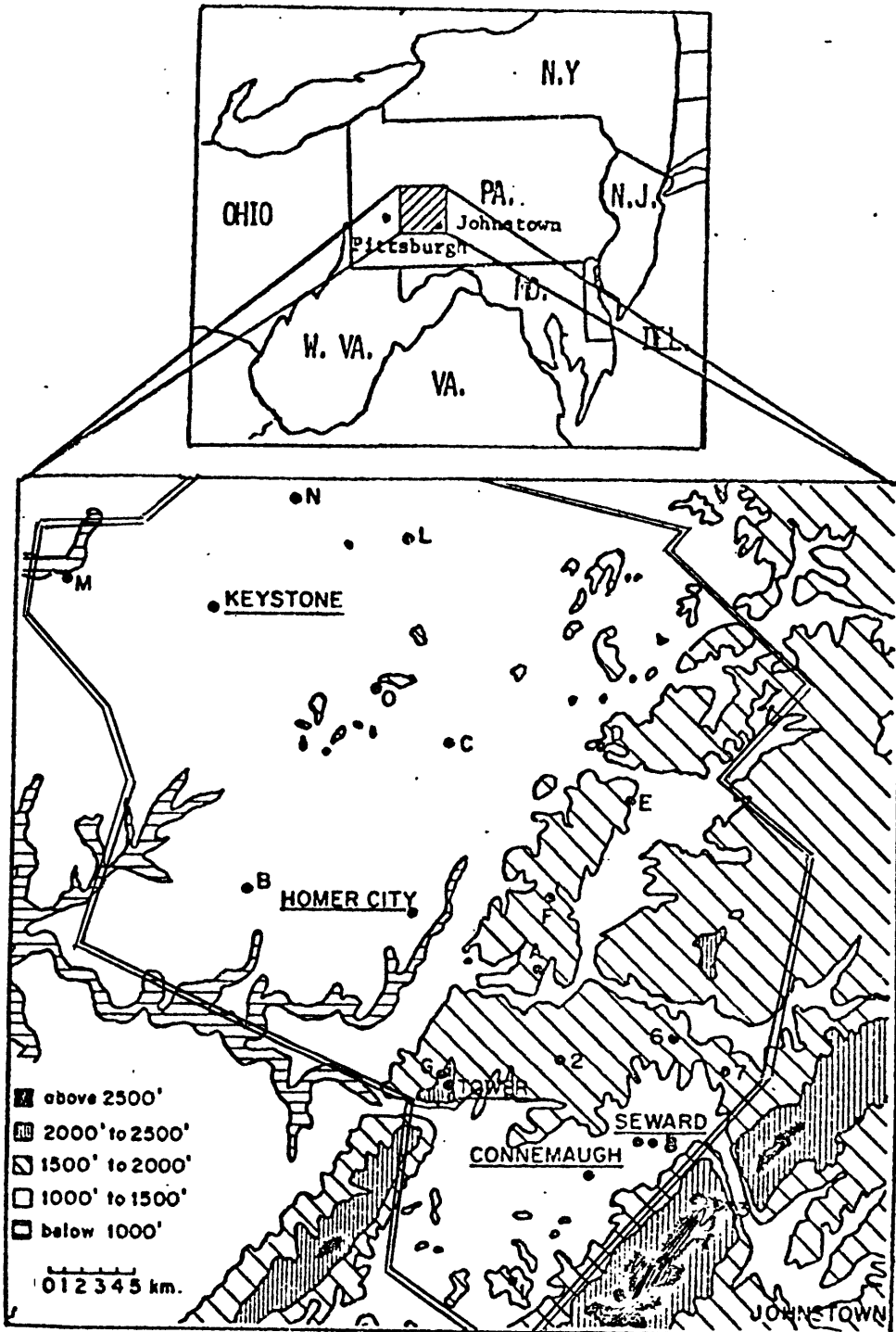


Figure 1. The Chestnut Ridge area in mid-western Pennsylvania. Sites of air pollution monitors and power plants are indicated. Study region is outlined with double lines.

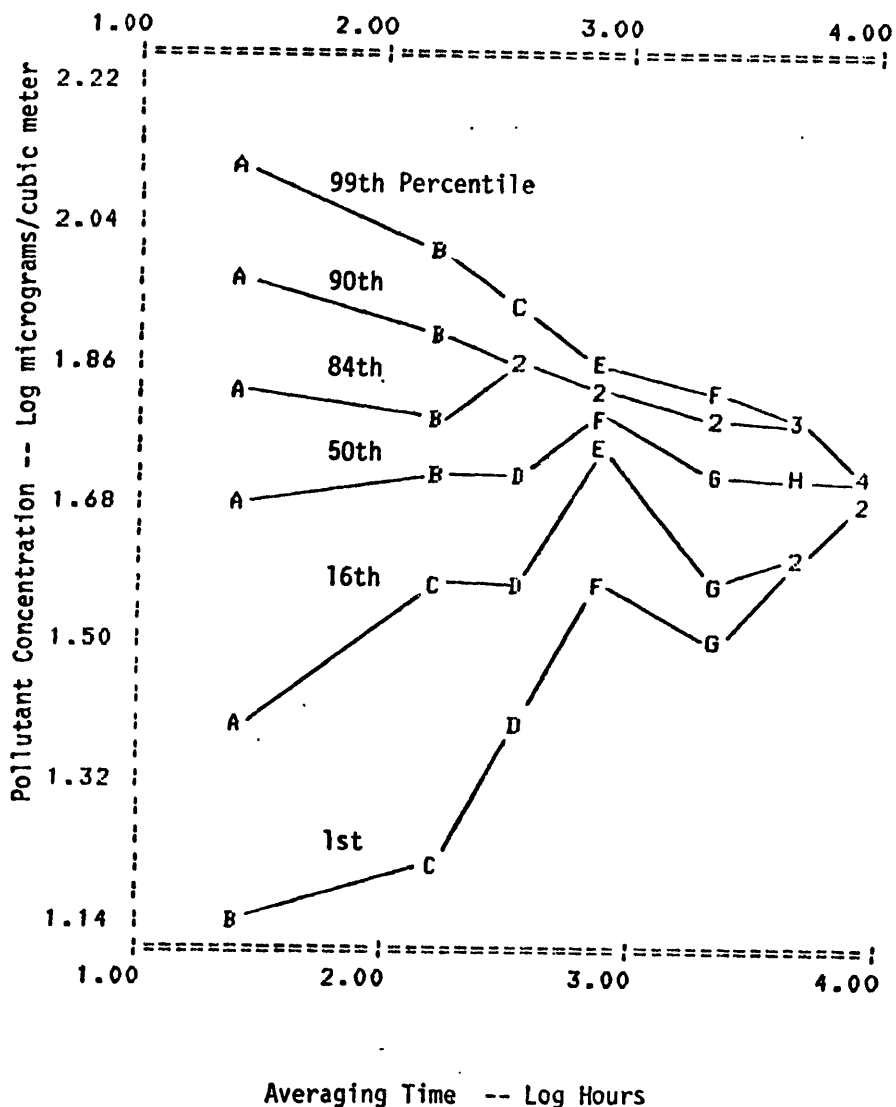
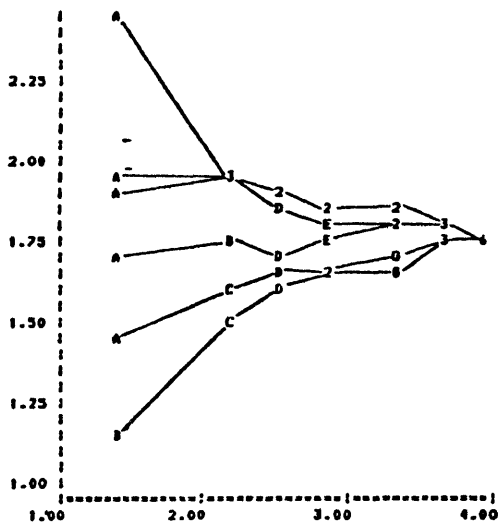
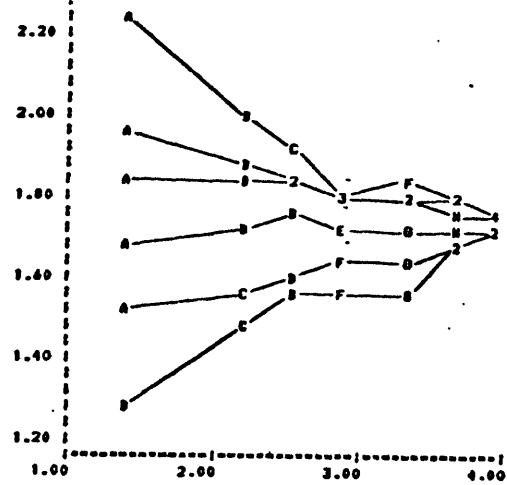


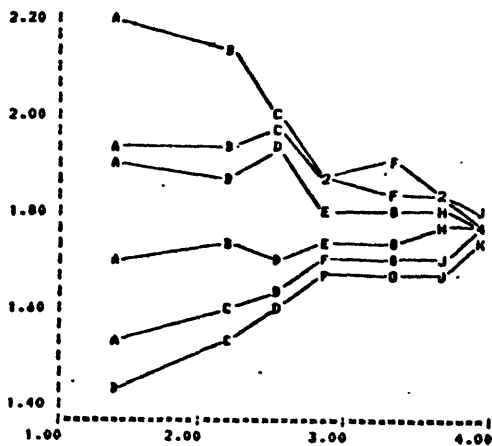
Figure 2. An arrowhead profile displaying sulfur dioxide concentrations measured at monitor 8 in 1978. The log of sulfur dioxide concentration in parts per billion is on the ordinate and log of averaging time is on the abscissa. Six lines on the plot correspond to various percentile groups which portray the percentage of time that ambient concentrations were not exceeded. These range from the uppermost line, the 99th percentile, representing the second highest pollutant concentration at that averaging time, to the bottommost line, the 1st percentile, representing the second lowest pollutant concentration. Other percentiles are indicated (16, 50, 84, 90). The 16th and 84th percentiles represent one standard deviation below and above, respectively, the mean, assuming lognormal distribution of pollutant concentrations. Profile uses running averages for all averaging time periods.



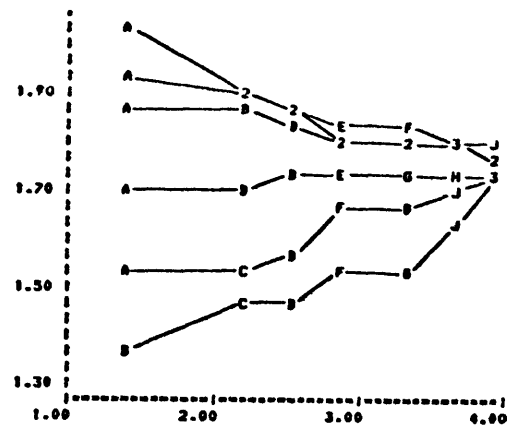
1974 Arrowhead Curve



1976 Arrowhead Curve



1975 Arrowhead Curve



1977 Arrowhead Curve

Figure 3. Four arrowhead profiles at monitor 1 for TSP. The log of TSP concentration in grams per cubic meter is on the ordinate and log of averaging time is on the abscissa. Profiles show six percentile groups: 99th, 90th, 84th, 50th, 16th, and 1st. These arrowhead profiles illustrates the relationship of pollutant measures at different percentile groups and averaging times by providing a visual interpretation of all pollutant parameters with the exception of the time sequence of events. The profile in Figure 3a is pointed and "sharp," showing a fairly constant level of air pollution. Figure 3b displays a profile which is "broad" and "blunt," having wide variation in pollutant concentrations with both both high or "dirty" episodes as well as low or "cleansing" periods. Figures 3c and 3d show significant cleansing by very low pollution in low percentiles.

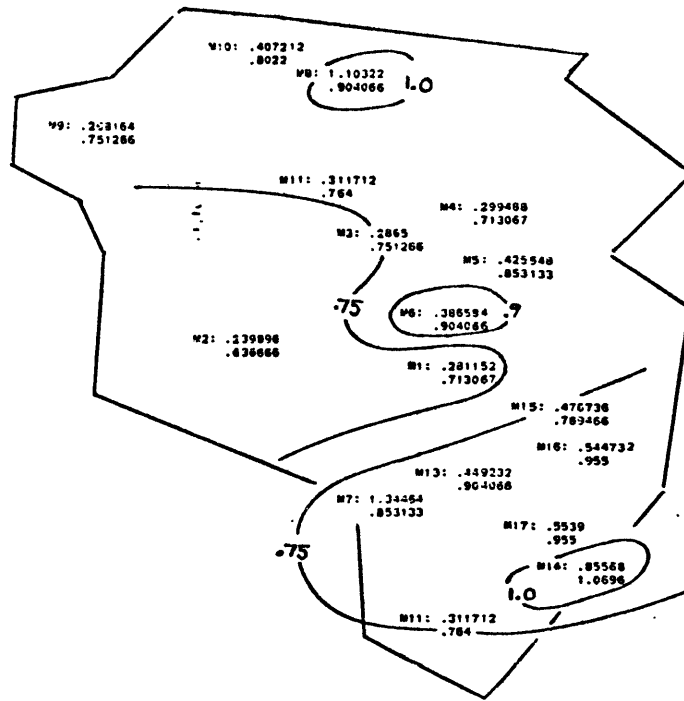


Figure 4a. Pollutant isopleths for 1978 annual average sulfur dioxide concentrations in the Chestnut Ridge area. Monitor numbers are indicated. 3 hour peak concentrations (Index 4) above annual year averages (Index 6).

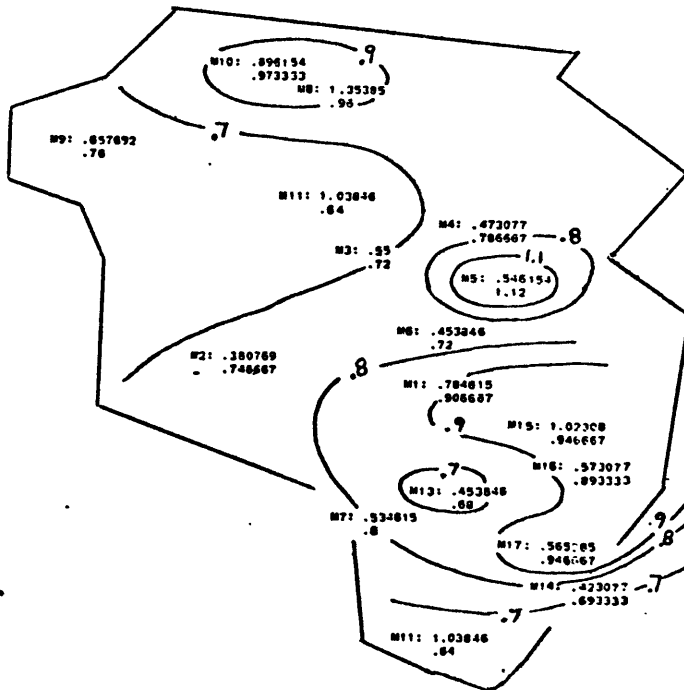


Figure 4b. Pollutant isopleths for 1978 annual average TSP concentrations in the Chestnut Ridge area. Monitor numbers are indicated. 24 hour peak concentrations (Index 4) above annual year averages (Index 6).

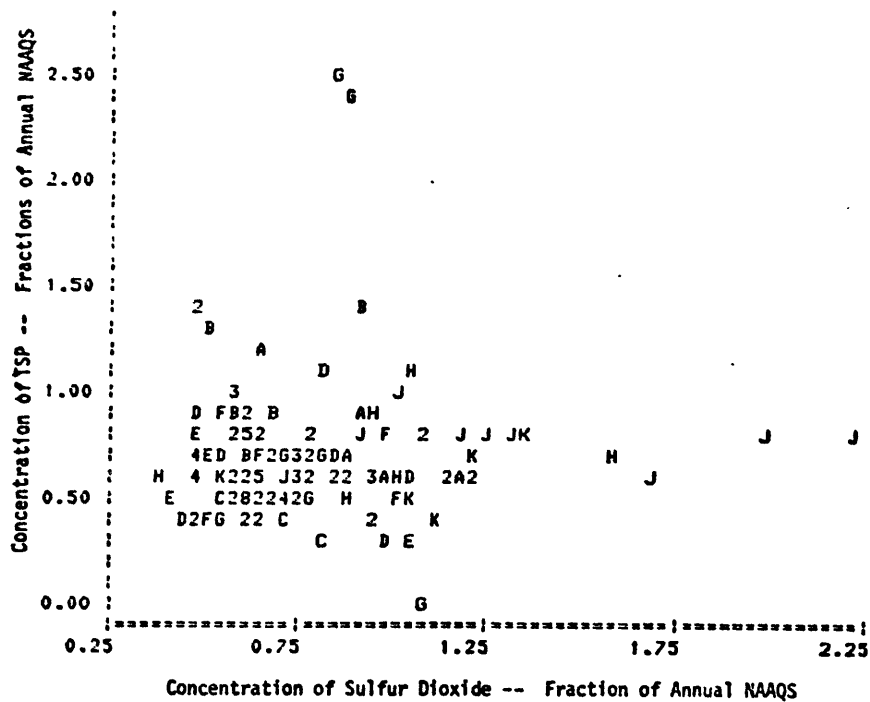


Figure 5. Scatterplot of calendar year averages of sulfur dioxide versus TSP concentrations for 4 years at the 36 districts.

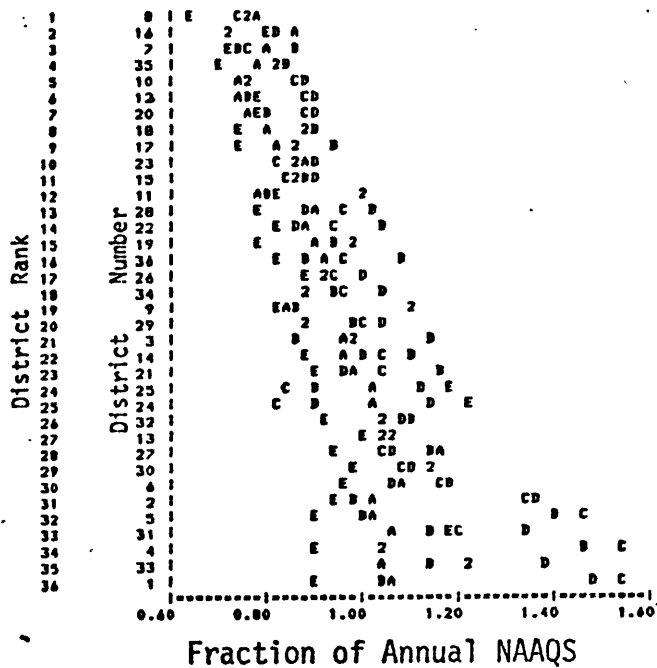


Figure 6. Five years of mean annual TSP concentrations at the 36 districts. Districts have been ranked by the five year average concentration.

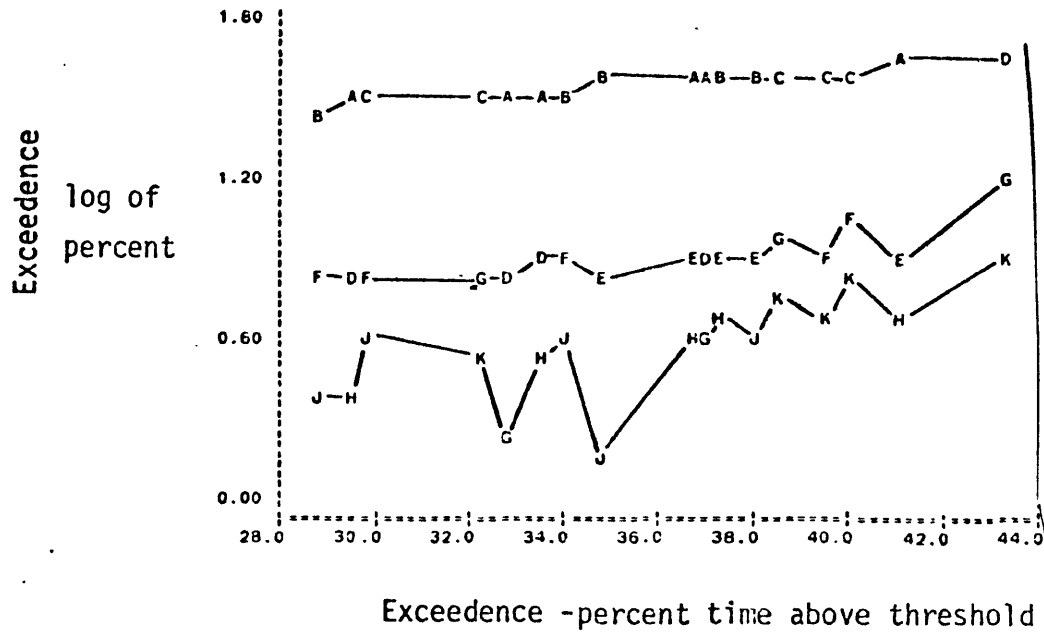


Figure 6. Relationship of sulfur exceedence measures. Mean of 4 years of monitor scores. Exceedences at different concentrations versus lowest concentration exceedence (30 ppm) on log scale. Fluctuations of exceedences show that the frequency of high peak concentrations is not highly correlated with the frequency of lower peak concentrations or averages.

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