The Effect of Meteorological Factors on Air Pollution in a Narrow Valley[1]

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ABSTRACT

The Air Pollution Division of the State of Pennsylvania has conducted simultaneous measurements of meteorological variables and air quality at Johnstown, Pa. An analysis of the observations for two fall seasons showed that fluctuations in the concentrations can be fairly well explained by the changes in wind speed and fluctuations of vertical air velocities. Wind direction is relatively unimportant, except for the rare east winds, when the air at Johnstown is affected by a major steel plant.

This paper presents a simple mathematical model that predicts variations in air pollution from a large number of low-level sources in a narrow valley. This theory and observations are in good agreement. It is likely, therefore, that most of the pollution at Johnstown and similar sites is locally produced.

Due to the fact that there usually are no important high-stack sources upwind at Johnstown at present, fumigation is not generally a factor there.

1. Introduction

Johnstown, Pa., is an industrial town in a narrow, Y-shaped valley, formed by several rivers cutting through the Allegheny plateau. Air pollution in such valleys is considerable due to the combination of climate, topography, industrial activity, and home heating. Since the situation of Johnstown is typical for that of many industrial cities, it is hoped that a study of the effects of meteorological factors on air pollution at Johnstown will be useful for the understanding of air pollution characteristics of many other, similar sites.

From about July 1964 through February 1966, a moderate program of air-quality sampling and meteorological observations was carried out at Johnstown, by personnel of the Pennsylvania State Department of Health, under the direction of Victor Sussman, under a grant by the U. S. Public Health Service. The observations were analyzed under a separate grant by the same agency at the Pennsylvania State University.

Within the general observing period, four 2-month sections were selected for intensive study: October–November 1964, July–August 1965, October–November 1965 and January–February 1966. The analysis of the observations during the first of these periods, October–November 1964, has been described in Interim Report,[2] Project AP 00224, Air Pollution Division. It gives detailed information regarding location, instrumentation, and relationships among the variables, too lengthy to be included in this paper. The purpose of this paper is to present the most relevant results and to compare them with the observations made a year later. Since meteorological conditions were generally similar in the two fall seasons, the results in the second period can be regarded as a test of the conclusions drawn from the data obtained in the first year on the basis of rather limited information.

2. Characteristics of site, sources, and observations

Fig. 1 shows the general location of Johnstown and the 300-ft contour relative to the river valleys. The center of the city is located near the confluence of three rivers. It is seen that the valley is narrow and the slopes steep, leading to potentially serious air pollution. Fig. 2 shows the location of the major sources of pollution, along with the location of the sites of the air quality and meteorological measurements.

It is seen that all sources are concentrated along the river valleys. Many smaller sources such as laundries and small industries are not shown, but are also concentrated along the rivers. Further, residential areas along the rivers are mostly heated by soft coal producing additional pollution. Residential areas along the slopes and on the plateau are generally heated by cleaner fuels.

By far the strongest single source of effluents is the Franklin Works of Bethlehem Steel, northeast of the center of town. This is not meant to imply, as will be seen later, that this plant is a major source of pollution in Johnstown itself.

Air-quality information was limited to particulates: high-volume filters gave one- or two-day average con-

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[2] Available upon request from the Department of Meteorology, Pennsylvania State University.

Fig. 1. Map of Johnstown, Pa., showing rivers and 300-ft contour.

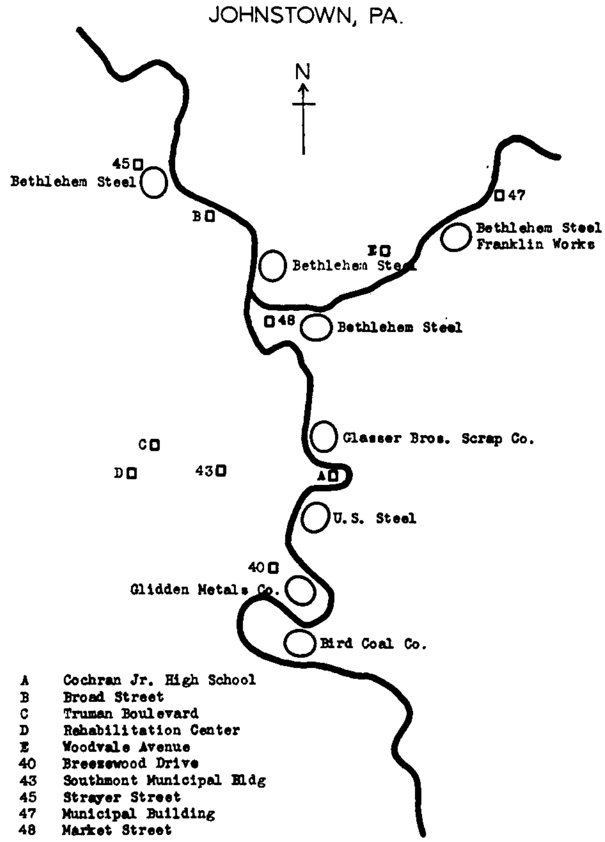

Fig. 2. Map of Johnstown, Pa., showing rivers, major industries, and location of meteorological stations and air-quality indicators.

centrations of suspended particles in a number of locations, and soiling tapes gave hourly estimates of optically active particulates. A comparison between daily average transparency and high-volume concentrations was presented in the Interim Report for one of the stations, and showed that 24-hr average transparencies were essentially a linear function of high-volume concentrations for October–November 1964. This result could not be confirmed from independent observations in 1965, because tapes and samplers were not operated during the same periods. There is some indication that the relation is not as good elsewhere.

The most complete records of air quality and meteorological variables were obtained at stations A (Cochran) and B (Broad Street). In addition, air-quality data were generally available in the downtown area at stations 47 and 48. High-volume sampler observations were also made at a number of other stations. In general, the stations on the slopes or the plateau (C, D, 43) showed much less pollution than the valley stations and are not included in further discussions.

Two 150-ft meteorological towers were operated at Cochran and Broad Streets, equipped with small cup anemometers at 50, 100 and 150 ft; bidirectional vanes (called bivanes) at 100 ft, and Thermohms at 50 and 150 ft. For details of instrumentation and reduction of meteorological data, the reader is again referred to the Interim Report.

A smaller tower, carrying an Aerovane at 75 ft, was operated on a low plateau at D. The winds at this point, however, appeared to be unrepresentative of the flow in the valleys, due to the peculiar topography, and were excluded after some preliminary analysis.

Across the street from B still on Broad Street, Pennsylvania Electric Company personnel have been operating an Aerovane for many years, the records of which were kindly made available. These records were unusually complete and furnished a check on the more haphazard, but more sensitive observations on the tower at B.

In winter 1966, a small vane was also operated just southwest of station E, giving some information about the air flow in the valley of the Little Conemaugh; however, in the periods described here, the flow in this valley had to be deduced from other considerations and occasional smoke experiments. The recent vane

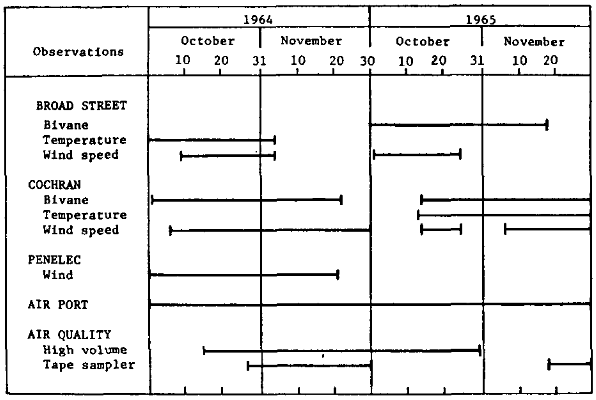

FIG. 3. Duration of records of meteorological information and air quality.

data suggest that the earlier deductions are essentially correct.

Another important source of weather information was the airways weather station at the Johnstown airport, located on the plateau, about 1000 ft above the city and about 4 miles to the east. Unfortunately, instruments were not operated for about 8 hr during the night. Nevertheless, records of precipitation, clouds and wind at the airport have been used throughout this study.

Fig. 3 shows the periods over which the various types of information were available. It is clear that the continuity of the records leaves much to be desired.

The Interim Report gives considerable detail about the inter-relationships between the meteorological variables at the various stations. For example, the wind directions in the valley could be understood in terms of the wind direction at the airport modified by the channeling effect of the valleys. Similarly, the wind speeds in the valley were proportional to, but weaker than, the wind speeds at the airport. In general, winds with easterly components are rare, so that effluents from the Franklin Works usually do not appear over the central area of Johnstown.

Considerable effort went into an analysis of the wind profiles and the evaluation of the roughness length for the Johnstown valleys. This was needed to understand the fluctuations of the vertical angle, which in turn were used in the analysis of air quality, as will be seen. According to similarity theory, as discussed by Panofsky and Prasad (1965), the standard deviation of vertical angle is a function only of Richardson number for a given height and roughness. The Johnstown data confirm this hypothesis, although the scatter of the observations is considerable.

3. Diurnal variations of meteorological and air-quality data

The variation of air pollution with the hour of the day (for a given source strength) depends critically on the elevation of the source. If the source consists of one or more high stacks which penetrate into the nighttime inversion, there is relatively little pollution at the ground at night. Maximum pollution occurs early in the morning, when the sun produces convection to bring down the polluted air from the mean effective stack height (fumigation). Later in the day, continued convection dilutes the pollution. Thus, high-level sources produce relatively little pollution at night and a maximum in the early morning.

Low-level sources, on the other hand, produce most pollution at night when the wind speed and vertical mixing in the lower levels of the atmosphere are weakest. Of course, both these types of diurnal variation are produced by diurnal variation of the atmospheric variables which is pronounced only on clear days. If there are systematic fluctuations of air-pollutant concentrations throughout the day on cloudy, windy days, when the diluting power changes little throughout the day, the cause must lie in systematic diurnal variations of the sources.

In the Johnstown study, the ability of the atmosphere to produce vertical mixing was judged by the fluctuations of vertical angle, as measured by the bivane. Ranges of vertical angle R_v were obtained for each hour. Some detailed analysis (see Interim Report) had shown that the standard deviation of vertical angle is essentially one fifth of R_v.

Fig. 4 shows the average diurnal variation of R_v for cloudy and clear days at Cochran. As was to be expected, there is less variation on cloudy days than on clear days. Also, on clear days, the wind speed is greatest at daytime. Therefore, the dispersing power of the lower atmosphere is greater in the middle of a clear day and less at night. On cloudy days there is less difference between day and night.

Fig. 4 also shows that the ranges of vertical angle were indicated to be about half as large in 1965 as in 1964. Since the synoptic situations were quite similar in the two years, it is quite clear that this difference cannot be real; it must be due to instrumental deterioration, either by increased friction in the sensor or the recorder. In any case, it was assumed that the

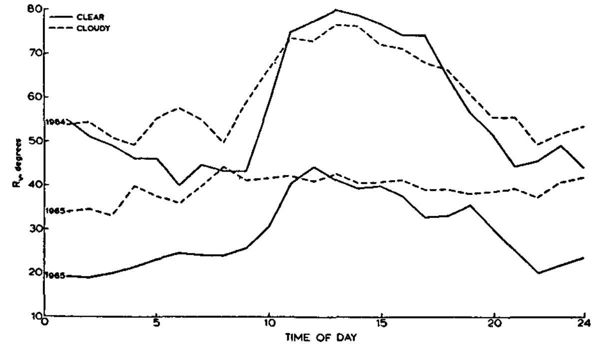

FIG. 4. Diurnal variation of the range of vertical angle R_v for clear and cloudy days at Cochran.

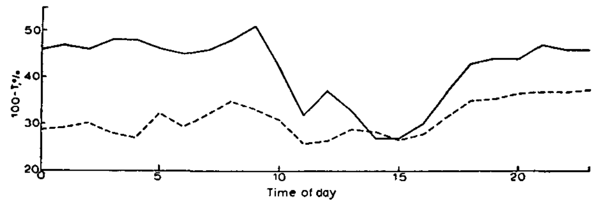

FIG. 5. Diurnal variation of tape transparencies, averaged for the three stations. Dashed line, cloudy days, 1964 and 1965; solid line, clear days, 1964.

1964 vertical angles were indicated correctly. Therefore, in what follows, the vertical ranges of 1965 were corrected by a regression equation designed to reconcile the curves in Fig. 4 for the two periods.

Fig. 5 shows the diurnal variation of tape transparency. It should be noted here that individual hourly tape transparencies are quite imprecise, as pointed out, for example, by Park *et al.* (1960). Nevertheless, much of the random variation is removed in the averages over several days shown in Fig. 5.

In Fig. 5, the hourly averages for the cloudy-day variation (lower curve) are obtained by averaging data for both 1964 and 1965. However, the upper curve (clear skies) was obtained only from 1964 observations, there being no completely clear days in the November 1965 period for which tape data were available.

Quite clearly, there exists very little diurnal variation of absorbing particulates on cloudy days; a slight maximum occurs early in the morning suggesting a maximum of source strength then. The same effect has been noted by Davidson at New York City (unpublished).

On clear days the soiling is greatest at night, least in the day. There exists a small maximum in the early morning, which can be explained by source-strength variation alone. The major variation from night to day, however, must be due to the diurnal variation of the meteorological elements. Strongest pollution at night can only be due to low-level sources, with fumigation of small importance.[3]

This conclusion must be qualified, however, by the realization that during none of the periods used in the construction of Fig. 5 did the winds in the lower atmosphere have an easterly component, so that the relatively hot sources of the Franklin Works did not contribute to the diurnal variation. In principle, it is likely that, on a clear day with east or northeast winds, fumigation of particulates from the Franklin Works may become important. However, easterly winds are usually accompanied by thick clouds, often with precipitation.

4. A simplified mathematical model for pollution at Johnstown

Since all the meteorological variables, wind speed, vertical angle, lapse rate, and thickness of the mixed layer, are intercorrelated, it is completely impossible to establish the relationship between concentration of pollutants and meteorological factors by statistical means alone. Instead, the statistical analysis must be guided by a mathematical model suitable for conditions at Johnstown.

Since fumigation does not appear to be a factor at Johnstown in October 1964 and 1965, it will be assumed that all important sources emit near ground level. Since the valley is narrow, lateral variation will be neglected. Then, with the usual assumption that the contaminant has a Gaussian distribution with vertical standard deviation σ_z, the center-line ground concentration due to a point source can be written as

$$\chi=\frac{\sqrt{2}Q}{\sqrt{\pi}VD\sigma_z}, \tag{1}$$

where V is the mean wind speed in the valley, D the width of the valley, Q the source strength in mass per unit time, and χ the concentration in mass per unit volume.

It is now assumed that σ_z, the standard deviation of the mass distribution, is proportional to the standard deviation of the vertical angle distribution σ_θ, and to the downwind distance x, raised to the power p, i.e.,

$$\sigma_z=b\sigma_\theta x^p, \tag{2}$$

where p is unity in neutral air and somewhat larger in unstable air. Now, the range of vertical angle R_v is proportional to the standard deviation σ_θ. Thus, summing Eq. (1) over many sources, we may write

$$\chi=\frac{a}{VR_v}\sum\frac{Q}{x^pD}, \tag{3}$$

where a and b are constants. The function $\sum\frac{Q}{x^pD}$ will be denoted by S and called a source function. This can be a function of wind direction, time of day, and time of year. However, since Fig. 5 indicated little diurnal variation of air pollution when the meteorological variables remained constant, it is not likely that S varies greatly with time of day, though it will slightly increase in the morning, particularly at Market Street, as was shown earlier.

With this definition of S, then, we have

$$\chi=\frac{aS}{VR_v}, \tag{4}$$

showing that concentration should be inversely proportional to VR_v.

[3] Of course, if large high-stack power plants are to be built near Johnstown, fumigation will certainly become important. Even now, there is some indication of occasional fumigation from distant sources during summer 1965, described by Zook (unpublished).

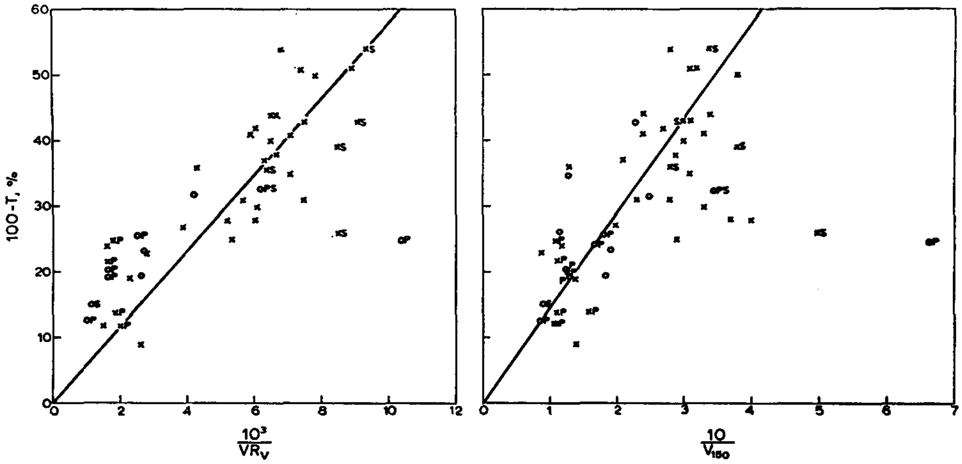

FIG. 6. 12-hr average (0700 to 1900) tape transparency, wind speed, and range of vertical angle at Broad Street. P represents precipitation and S Sundays; R_v in degrees; V in mph. (Crosses, 1964; circles, 1965).

Eq. (4) was tested for 2–19 November 1964 and 19–30 November 1965. In order to eliminate the larger random irregularities, but still preserve the important meteorological differences between day and night, the first comparison of theory and observations was based on 12-hr averages, extending from 0700 to 1900 EST and 1900 to 0700 EST. The wind at 150 ft was chosen since it had the best exposure, and appeared generally the most reliable. The air pollution concentration was taken to be proportional to the 12-hr average of $(100-T)$ where T is the transmission of the soiling tape.

The left parts of Figs. 6–8 show the relation between 100−T and $1/VR_v$ at three locations: Broad Street, Cochran, and Market Street. In all cases, the wind speed at Cochran was used. The relations are good, if Sundays and precipitation days are excluded. Further, and quite surprisingly, the best line of fit (estimated by eye) seems to be independent of wind direction.

There appears to be no systematic difference between the relations in 1964 and 1965.

The right portions of Figs. 6–8 show the same 12-hr average tape transparencies as function of the reciprocal of wind speed alone. Apparently, linear relationships are still quite adequate, though the fit is somewhat poorer, if the unrepresentative observations on Sundays and during precipitation are disregarded. In other words, wind speed alone is a fair indicator of air pollu-

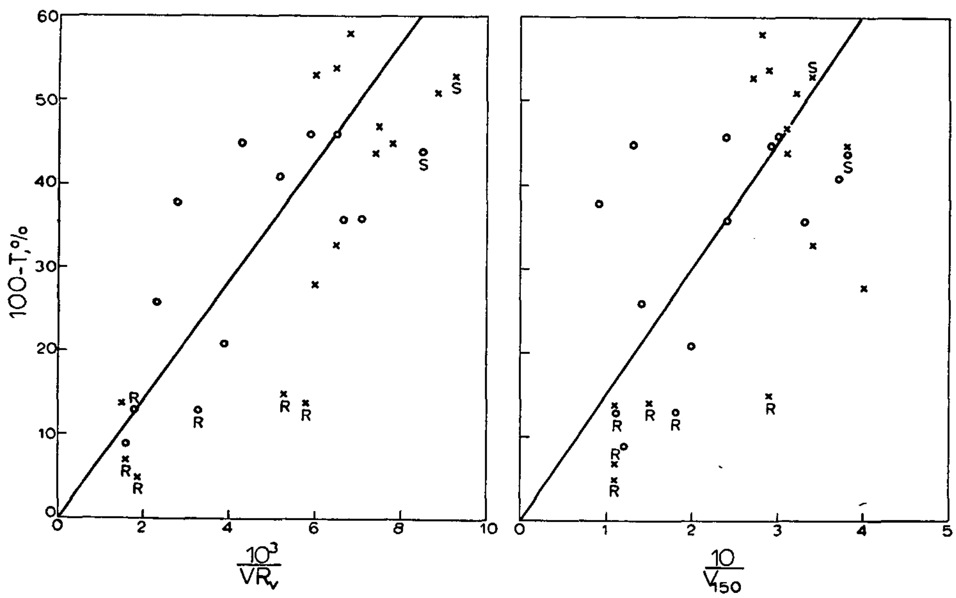

FIG. 7. 12-hr average (0700 to 1900) tape transparency, wind speed, and range of vertical angle at Cochran. R represents precipitation and S Sundays; R_v in degrees; V in mph. (Crosses, northerly winds; circles, southerly winds).

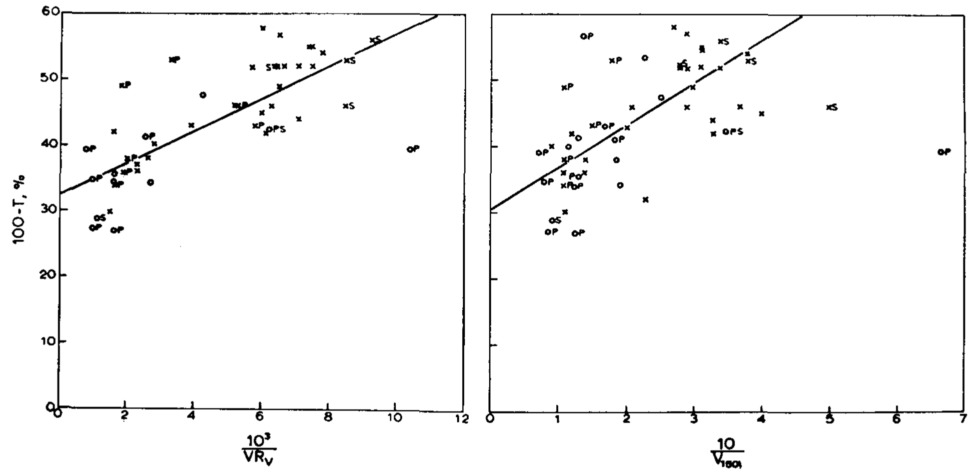

FIG. 8. 12-hr average (0700 to 1900) tape transparency, wind speed, and range of vertical angle at Market Street. P represents precipitation and S Sundays; R_v in degrees; V in mph. (Crosses, 1964; circles, 1965).

tion at Johnstown and similar locations. This is a useful result since information for R_v is usually lacking. Of course, with some practice, it is possible to estimate vertical angle fluctuations from time-of-day, season, wind, and cloud cover.

It is essential to realize that in none of the situations depicted in Figs. 6–8 did the wind have an easterly component. If east winds had been included, pollution for a given wind would have been larger than indicated.

The observations in Fig. 8 (Market Street in downtown Johnstown) differ systematically from the observations at the other sites, still within the city but farther from the center. At Market Street, the tape transparency was still low for strong wind speeds, whereas it was high for strong winds at the other locations. The explanation is not known. Blowing dust, or local sources of black smoke may be responsible.

TABLE 1. Variance of 12-hr tape transparency accounted for by $1/VR_v$ and by $1/V$.

Station	Variance by $1/VR_v$	Variance by $1/V$
Broad Street	0.72	0.58
Cochran	0.55	0.22
Market Street	0.75	0.43

Table 1 shows the fraction of the variance of 12-hr tape transparency accounted for by $1/VR_v$ and by $1/V$. Clearly, the results for $1/VR_v$ are superior to those based on $1/V$ only. There is no such difference between

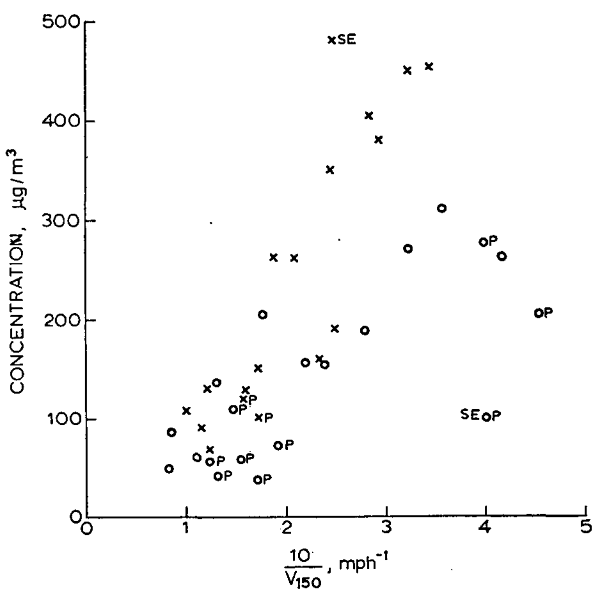

FIG. 9. High-volume concentrations at Broad Street as function of noon-to-noon wind speed at 150 ft at Cochran. P stands for precipitation. (Crosses, 1964; circles, 1965).

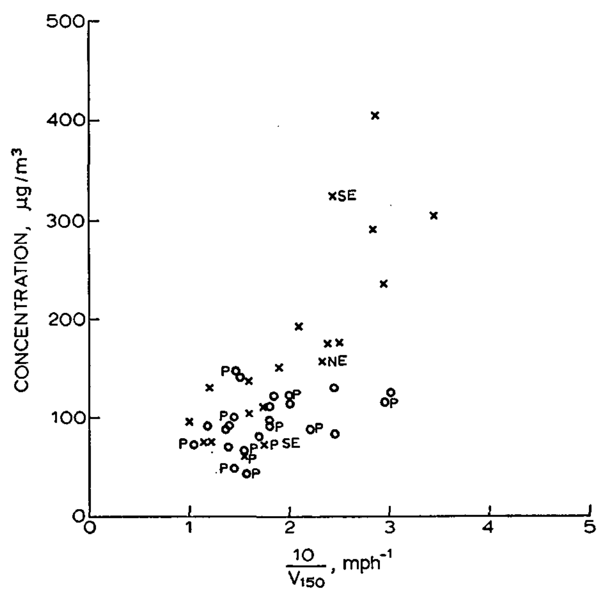

FIG. 10. Same as Fig. 9, except for concentrations at Cochran.

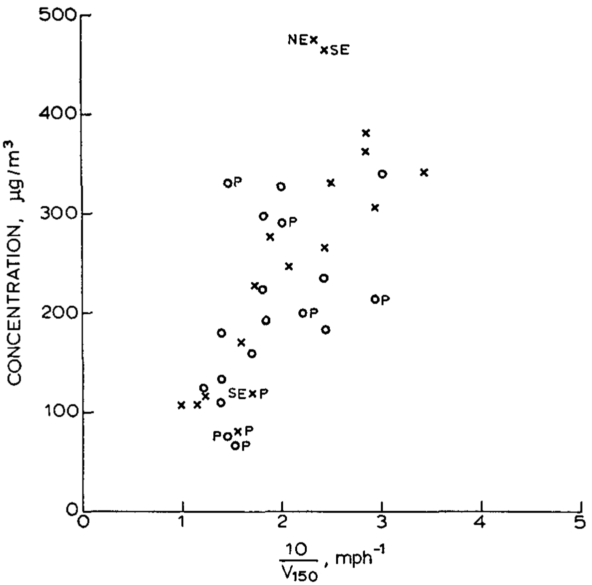

FIG. 11. Same as Fig. 9, except for concentrations at Market Street.

the stations in the high-volume concentrations, as is seen in Figs. 9–11. These figures relate high-volume concentrations to the reciprocal of the wind speed at Cochran at 150 ft, averaged over 24 hr from noon to noon. R_v was not used, because its variation is almost entirely diurnal, and 24-hr averages do not vary much from day to day. Again, the relations are fairly good and nearly linear. There are a few points in Figs. 9–11 which represent situations with easterly winds. Clearly, the pollution for these situations at Broad and Market Streets is larger than what would be expected otherwise with the same wind speed. The figures thus demonstrate that the huge Franklin Works do significantly affect the air pollution at Johnstown, but only in the case of the relatively infrequent east winds. Of course, the low-cost residential areas to the northeast and east of the Franklin Works encounter serious air pollution problems.

TABLE 2. Variance of high-volume concentration accounted for by $1/V$.

Station	Variance
Broad Street	0.57
Cochran	0.54
Market Street	0.64

Table 2 shows the variance of high-volume concentration accounted for by the reciprocal of mean velocity at the three sites. Apparently, the result is a fair confirmation of the adequacy of the model. The unexplained variance, which is less than 50%, must be due to variations in source functions, mixing depth, and other variables not considered.

An attempt was also made to relate air quality at Johnstown to mixing-layer depth and mean wind above the surface which were kindly furnished by the Public Health Service in Cincinnati. Observations were available for Pittsburgh, but did not correlate well with air quality at Johnstown.

In summary then, fluctuations of air pollution in downtown Johnstown in October 1964 and 1965 can be explained reasonably well by the assumption of low-level sources in the industrial valley itself, the concentration of pollutants varying inversely with the wind speed and fluctuations of vertical angle. Wind direction is unimportant except, rarely, when the wind has an easterly component, in which case the pollution is increased. Precipitation has a tendency to depress the air pollution which would otherwise be expected.

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