NOAA Research Laboratories

Air Resources
Atmospheric Turbulence and Diffusion Laboratory

Oak Ridge, Tennessee

December 1970

AIR POLLUTION METEOROLOGY OF THE ROCKWOOD-HARRIMAN, TENNESSEE, VALLEY

Steven R. Hanna
S. D. Swisher

U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

Air Pollution Meteorology of the Rockwood-Harriman, Tennessee, Valley

by S. R. Hanna and S. D. Swisher

ABSTRACT

Domestic and industrial heating and emissions from a single, large, low-level industrial source are approximately equally responsible for the high concentrations of suspended particles observed in the Rockwood-Harriman industrial corridor at times of poor atmospheric dilution. The air in the industrial corridor cannot support any additional air polluting industries unless coal is discouraged as a means of residential and industrial space heating and corrective measures are taken to reduce emissions from the large industrial source.

1. Introduction

The Air Resources Atmospheric Turbulence and Diffusion Laboratory (ATDL) was asked by the Tennessee Valley Authority (TVA) and Oak Ridge National Laboratory to cooperate in a joint regional planning study for the Rockwood-Harriman industrial corridor by analyzing the air pollution there. The major air pollution sources in this corridor are strong particulate emissions from a single, low-level industrial source, particulate emissions from coal burning in the towns, and emissions from a tall TVA power plant stack. The presence of a high ridge to the NNW of the corridor complicates matters by channeling the wind into WSW and ENE directions. This aligns the predominant wind directions with the axis of two of the major pollution sources.

In this report meteorological and diffusion aspects of these air pollution problems will be discussed. The observed particulate concentrations, measured at four TVA monitoring stations, will be related to the wind speed and direction observations. Instantaneous and yearly average particulate concentrations due to industrial process emissions from the low-level sources (Roane Electric Co.) will be calculated and compared with observations. The contribution of space heating in the cities of Rockwood and Harriman to the total particulate load will be estimated by using data on yearly coal sales. Also, the contribution of the Kingston TVA steam plant to the measured concentrations will be determined. Finally, additions to the pollutant concentrations due to new industries will be briefly considered.

2. Data obtained by TVA

A sketch map of the Rockwood-Harriman area is shown in Figure 1. The valley is oriented WSW-ENE and is about 2km wide. Walden Ridge, the northern boundary

ORNL-DWG 71-398

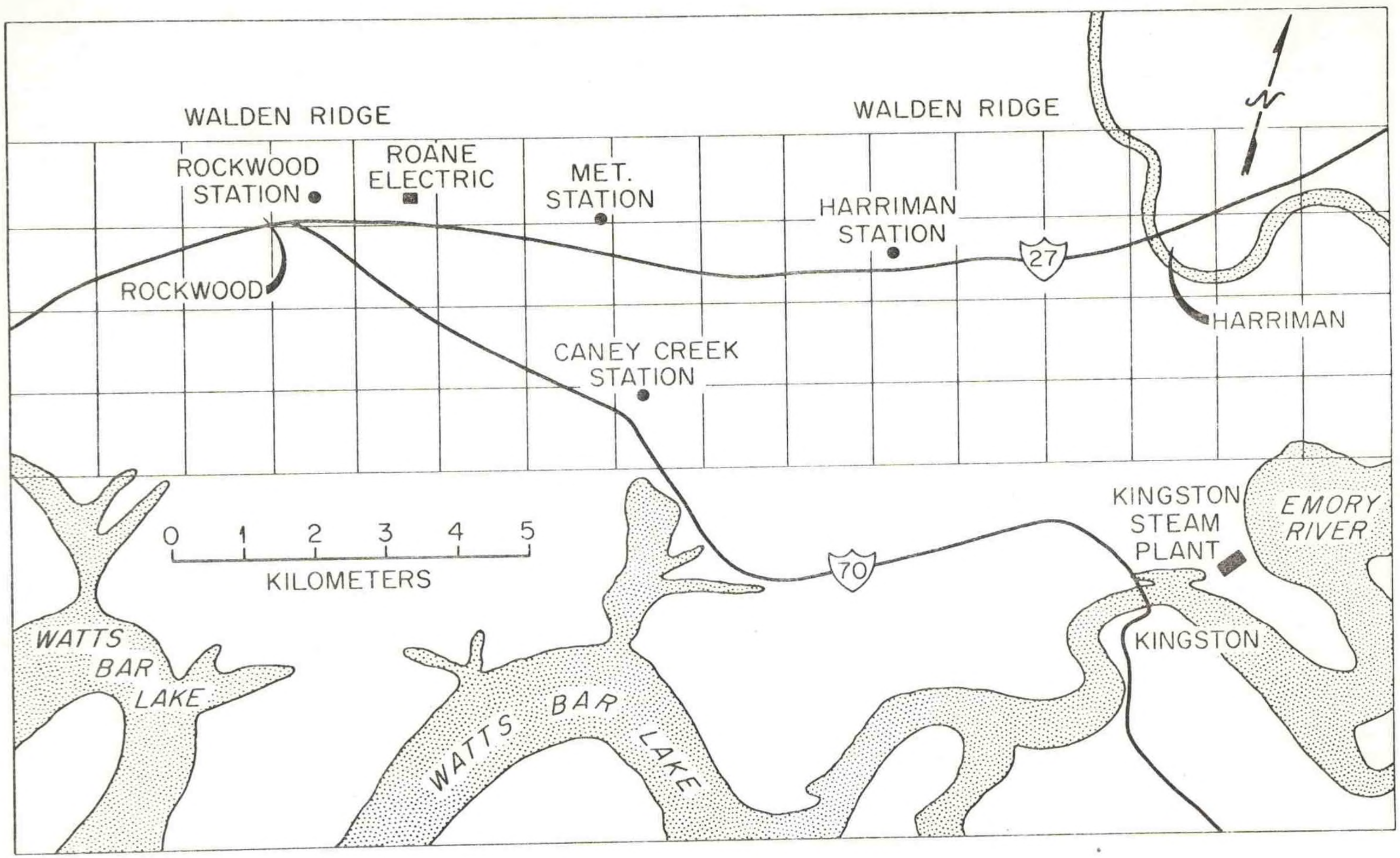


Figure 1 - Map of Rockwood-Harriman industrial corridor, illustrating locations of towns, air sampling and meteorology stations, Roane Electric Co., and the Kingston steam plant.

of the valley, rises sharply to about 250m above the valley floor. The southern boundary of the valley is a relatively low ridge, about 100m high. The cities of Rockwood and Harriman, at either end of the proposed industrial corridor, are about 8km apart. The significant sources of suspended particles are the Roane Electric Company, TVA's Kingston Steam Plant, and space heating in the towns of Rockwood and Harriman. The locations of the four air monitoring stations, one of which includes the meteorological (Met.) station, are also shown on this map. Daily averages of the variables measured by the instruments at these stations were recorded by TVA personnel two or three times a week for a year. The data and further details are given in a TVA report.[1] In this study we will be concerned only with the wind speed and direction data and observed suspended particle data.

a. Wind speed and direction

The annual wind rose at the Met. Station, shown in Figure 2, illustrates the strong influence of the ridges and valley on the frequency distribution of wind direction. Over 60% of the time the wind flows from WSW ± 45° or ENE ± 45°, i.e. up or down the valley. Most of the WSW cases occur during the day, and the ENE cases occur primarily at night. The average wind speed is 2 to 3m/sec.

b. Suspended particulate concentrations

Some characteristics of the measured concentrations of suspended particles at the four stations are summarized in Table 1.

ORNL-DWG 71-399

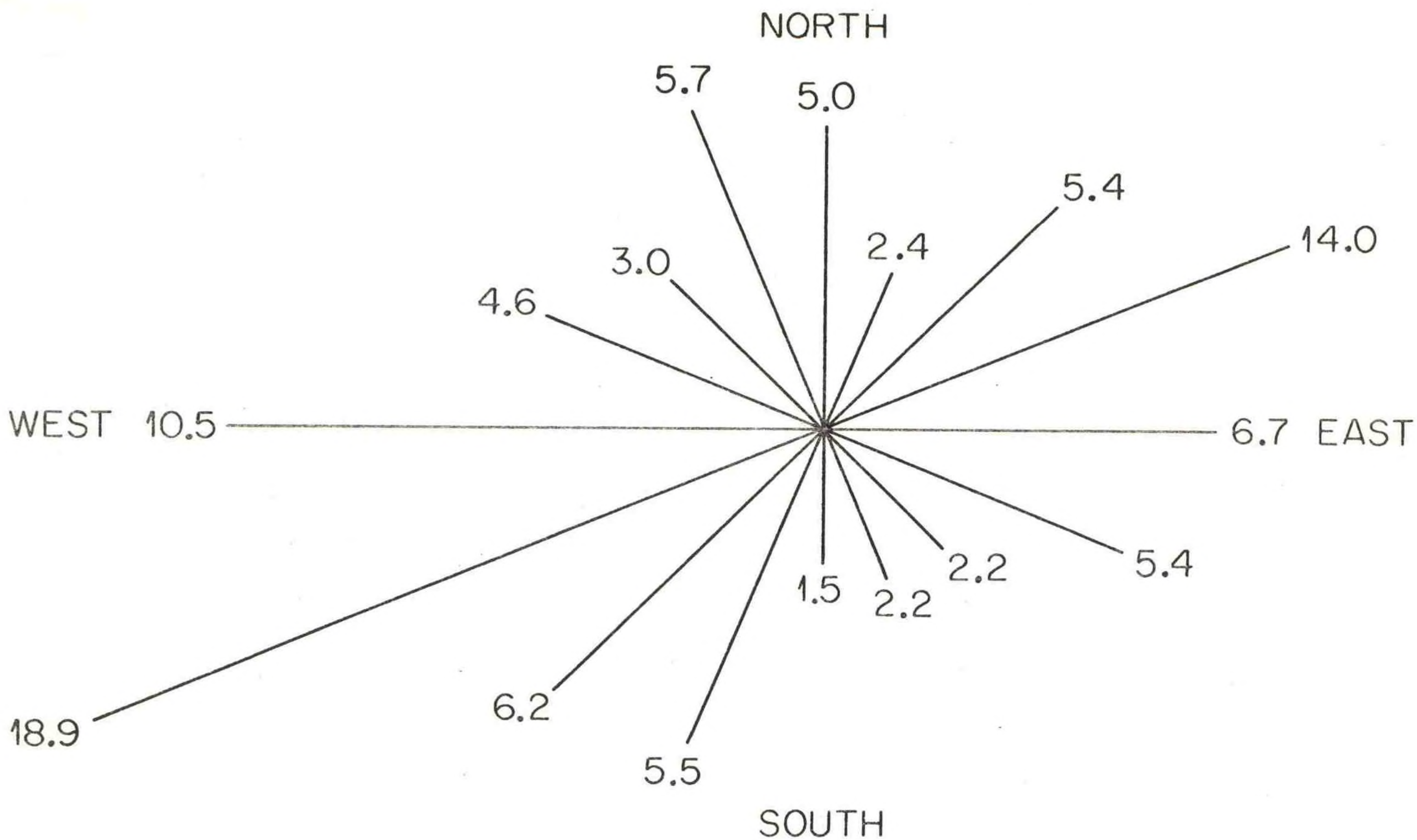


Figure 2 - Annual wind direction frequency distribution measured at the meteorology station in the Rockwood-Harriman industrial corridor.

Table 1

Measured Yearly Average and Peak 24 hr. Average Concentration of Suspended Particles

Station	Avg. Conc.($\mu g/m^3$)	Peak Conc.($\mu g/m^3$)
Harriman	77	219
Caney Creek	61	153
Met. Station	93	387
Rockwood	129	456

The average background particulate concentration in rural areas of the U.S. has been found to be about $30 \mu g/m^3$,[(2)] representing the burden of contamination of the air by sources far upstream. For comparison, typical values of concentrations in other cities are: $180 \mu g/m^3$ in Chattanooga; $123 \mu g/m^3$ in Dayton; and about $105 \mu g/m^3$ on the average in cities over the U.S. Thus the concentrations at the Caney Creek Station are only slightly above the background rural concentration, whereas the concentrations at the Rockwood Station are equal to values usually measured in cities. The Harriman Station is on the edge of town and so its measured concentrations are not as high as in Rockwood. The Met. Station is several miles from the towns but often comes under the influence of the plume from the Roane Electric Company.

c. Comparison of wind and concentration data.

Daily average wind speed and direction were compared to the daily average suspended particulate concentrations at the four stations. The following conclusions can be drawn:

1) High (> 200$\mu g/m^3$) concentrations in Rockwood come with variable direction (NE-SW), light winds.

2) High (> 120$\mu g/m^3$) concentrations in Harriman come with either variable direction (NE-SW), light winds, or moderate WSW flow. The latter condition causes the plume from the Roane Electric Company to pass over the Harriman station.

3) Although one might at first expect high concentrations at Rockwood with NE winds, the data show that persistent NE flow usually occurs after cold front passages, when vertical mixing is good.

4) Caney Creek concentrations are higher than the others only with WNW winds, when emissions from the Roane Electric Company are carried toward that station.

5) Similarly, concentrations at the Met. Station are higher than at Rockwood only for westerly winds of moderate speed.

6) When the concentration at Rockwood is greater than 200$\mu g/m^3$, the average wind speed is 3mph. Values less than 50$\mu g/m^3$, are associated with speeds of 10mph or more.

All these conclusions are what one would expect intuitively. However it is clear that during periods of high air pollution the contribution to the total concentration from space heating and small industries is as great as the contribution from the Roane Electric Company. If this were not so, concentrations would be high only at the station toward which the Roane Electric Company plume is blowing.

3. Calculation of Concentrations due to Emissions from the Roane Electric Company.

It is fortunate that a study[3] of the stack gas emission characteristics at the Roane Electric Company, which is located about 1km east of Rockwood, is available. There are eight furnaces at this plant. The large vents at the top of each furnace do not really qualify as "stacks." The hot plume wanders from one side to the other side of these large openings, and its temperature varies with time. The following approximations were used to calculate plume rise from these vents:

"Stack" Height:	20m
Average $(T_p - T_e)$:	30°C
Vertical speed, w_o:	5m/sec
(Opening area)/π:	$11m^2$

The parameter $(T_p - T_e)$ is the difference between the plume temperature T_p and the environment temperature T_e. Plume rise is calculated using the appropriate formulas from Briggs' study,[4] in which it is shown that the governing physical parameter is the initial buoyancy flux:

$$F = w_o \left(\frac{\text{Area}}{\pi}\right) (T_p - T_e) \frac{g}{T_p} = 60m^4 sec^{-3} , \qquad (1)$$

where g ($9.8m/sec^2$) is the acceleration of gravity.

As a general rule, downwash of the plume occurs when the wind speed U is greater than .67 times the vertical speed w_o of the air emerging from the vent.

For this plant downwash occurs when the wind speed U exceeds 3m/sec. Thus much of the time the plume will wash down into the "cavity," i.e. the dead-air space, behind the plant stacks and buildings, and plume rise will be negligible. This phenomenon can often be observed at the plant. For wind speeds less than 3m/sec plume rise can be calculated using the following formulas:

a.) In calm, stable atmospheric conditions the plume rise, H, is given by

$$H = 5F^{1/4}\ s^{-3/8}, \qquad (2)$$

where s is a stability parameter, defined by

$$s = \frac{g}{T_p}\left(\frac{\partial T_e}{\partial z} + .01°\text{Cm}^{-1}\right).$$

In this part of Tennessee,[5] the average nightime atmospheric temperature inversion has the strength

$$\frac{\partial T_e}{\partial z} \cong \frac{3°\text{C}}{100\text{m}}.$$

Therefore s has the value $1.05 \times 10^{-3}\ \text{sec}^{-2}$ and consequently

$$H \cong 5(60\text{m}^4\ \text{sec}^{-3})^{1/4}\ (1.05 \times 10^{-3}\ \text{sec}^{-2})^{-3/8} \cong 180\text{m}.$$

Often the vertical temperature gradient reaches the value:

$$\frac{\partial T_e}{\partial z} = \frac{6°\text{C}}{100\text{m}}$$

In this case $s = 2.1 \times 10^{-3}\ sec^{-2}$ and plume rise H is about 140m.

b.) In stable atmospheric conditions with wind the plume rise is given by

$$H = 2.9(F/Us)^{1/3}. \qquad (3)$$

Table 2 summarizes plume rise for these conditions.

Table 2

Plume Rise During Stable Conditions with Wind

Wind Speed, U	Plume Rise, H for $\partial T_e/\partial z = 9°C/300m$	Plume Rise, H for $\partial T_e/\partial z = 18°C/300m$
$1\frac{m}{sec}$	120m	90m
$3\frac{m}{sec}$	83m	62m

c.) In nearly neutral conditions the plume rise is given by

$$H = 1.6F^{1/3}\ U^{-1}\ x^{2/3}. \qquad (4)$$

Final rise is achieved at a distance x downwind from the stack of about 200m. For wind speeds of 1 and 3m/sec., the plume rise, H, is 210 and 70m, respectively. Based on the above calculations a typical value for the height h of the plume above the ground at the Roane Electric Plant is about 100m, for wind speeds less than about 3m/sec. The height h is the sum of the plume rise H and the stack height, 20m. The height h refers to the height of the centerline or axis of the plume. It is used in the following equation(6) to calculate downwind concentration, χ:

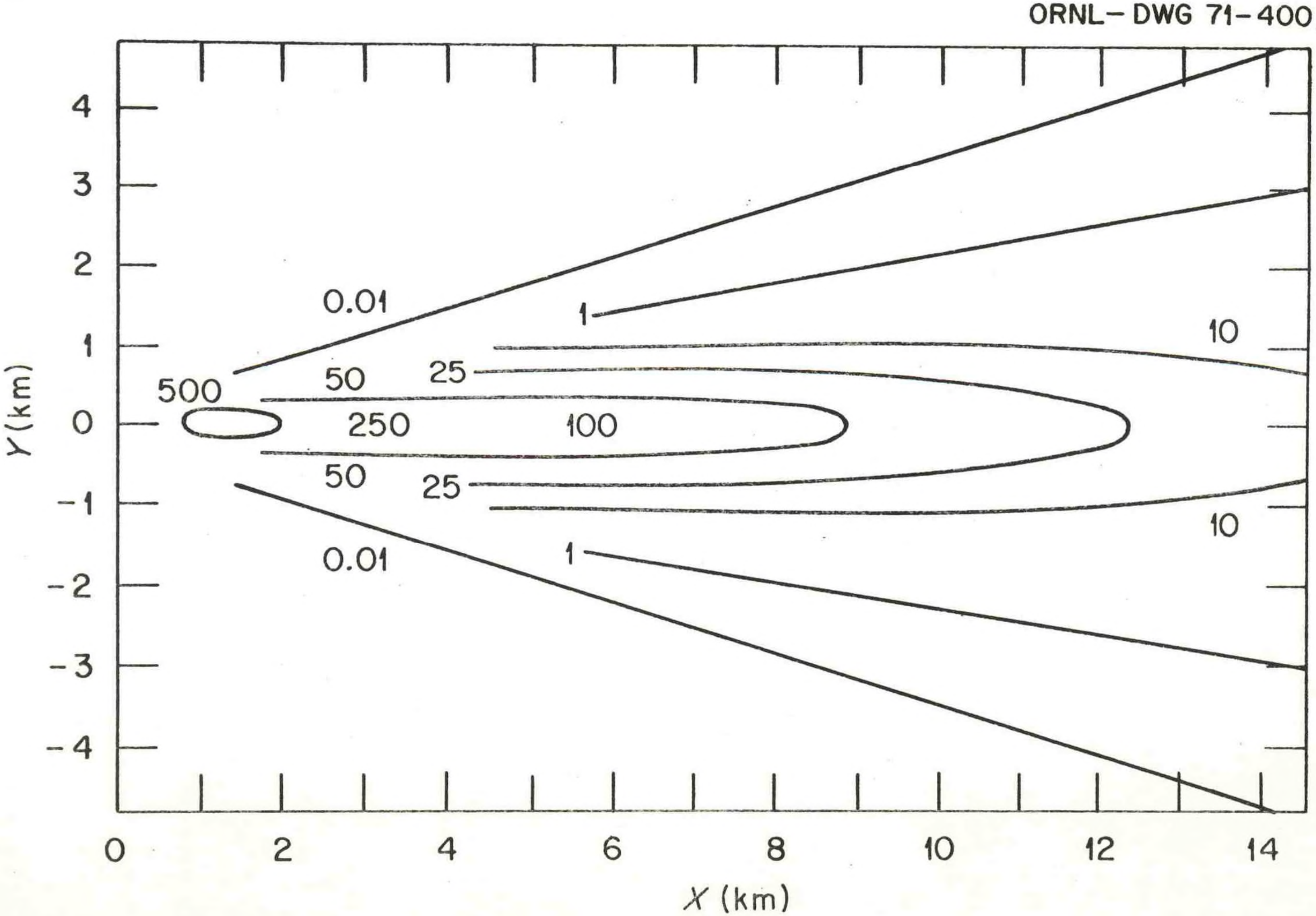
$$\chi = \frac{Q}{\pi U \sigma_y \sigma_z} \, e^{-\frac{y^2}{2\sigma_y^2} - \left| \frac{(z-h)^2 + (z+h)^2}{2\sigma_z^2} \right|} . \qquad (5)$$

Here y is the cross-wind distance from the plume axis, z is height, and σ_y and σ_z are lengths equal to the standard deviations of the horizontal and vertical crosswind distribution of particle concentration at the distance x from the stack. The diffusion lengths σ_y and σ_z are functions of stability and distance from the stack. Slade(6) gives typical values based on measurement of these parameters by many authors under various conditions.

The source strength Q of the Roane Electric Plant is about 10 tons/day, or 10^8μg/sec, of suspended particles. Using this value, and assuming slightly unstable conditions (typical for instance of a partly cloudy winter day), the concentration χ(μg/m^3) was calculated for ground level (z = 0) and a wind speed of 2m/sec. The resulting concentration pattern is presented in Figure 3, in which the distance scale is the same as in Figure 1. The pattern shown in Figure 3 can be placed over Figure 1, with the point 0 centered over the Roane Electric Plant, and the resulting surface concentration χ at any point obtained for any wind direction.

For WSW winds, the concentration at the Met. Station is estimated to be about 250μg/m^3, and at the Harriman Station, 80μg/m^3. For ENE winds, the concentration

Figure 3 - Distribution of surface concentrations ($\mu g/m^3$) of suspended particulates due to emissions from the Roane Electric Co., assuming slightly unstable conditions, a wind speed of 2m/sec, and an effective source height of 100m.



in Rockwood is about 200 - 500$\mu g/m^3$. These estimates are in rough agreement with observations.

Of course, the wind obeys the wind rose of Figure 2 only when averaged over long periods of time. During the year slightly unstable conditions prevail about 40% of the time and stable conditions about 60% of the time.[5] Using the corresponding values for σ_y and σ_z[6] and the average wind direction rose, the average concentration patterns are found to be as in Figure 4. The contributions at the Rockwood, Harriman, Caney Creek, and Met. Stations are 15, 10, 2 and 15$\mu g/m^3$, respectively. It is clear that average surface concentrations from the Roane Electric Plant emissions would be relatively small if a plume rise of 100m were always acheived.

When downwash occurs, surface concentrations rise markedly because the effective height h in equation (5) becomes zero. In this case, during slightly unstable conditions, concentrations along the axis of the plume are high as shown by Table 3:

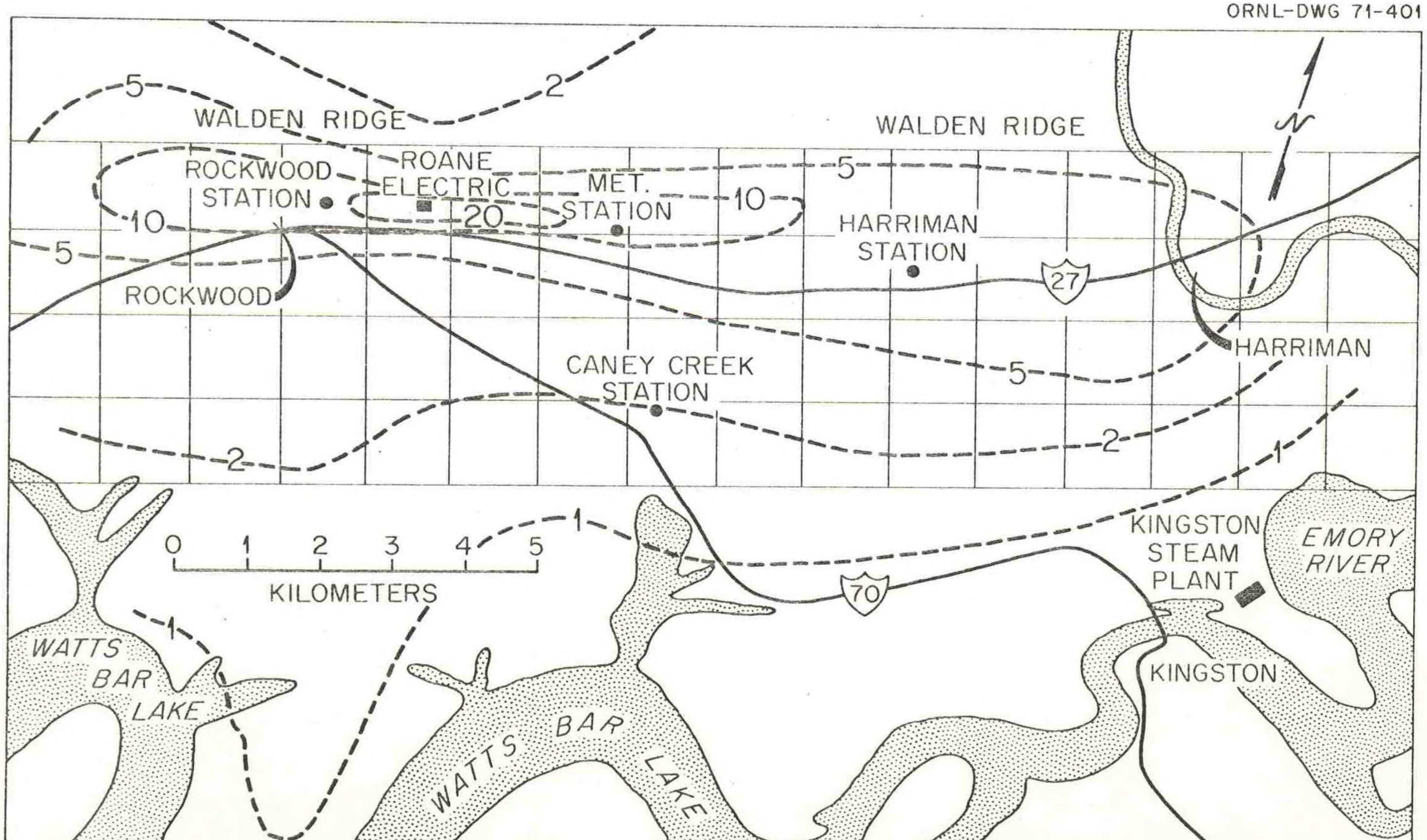
Table 3

Maximum Concentrations from the Roane Electric Plant Emissions When Downwash Occurs.

x(m)	$\chi(\mu g/m^3)$ $(U = 5\frac{m}{sec})$	$\chi(\mu g/m^3)$ $(U = 10\frac{m}{sec})$
500	6000.	3000.
10^3	1000.	500.
5×10^3	60.	30.

Figure 4 - Annual average distribution of surface concentrations ($\mu g/m^3$) of suspended particulates due to emissions from the Roane Electric Co., assuming 40% slightly unstable conditions and 60% stable conditions, a wind speed of 2 m/sec, and an effective source height of 100m.

ORNL-DWG 71-401



These concentrations would be likely to occur on windy afternoons. At such times the plume is often seen hugging the ground. Fortunately, the wind in the valleys of East Tennessee is not usually strong for periods of more than a few hours. Also, the direction of the plume changes irregularly so that the probability that a point at the surface will remain beneath the axis of the plume for longer than a few minutes is small.

High concentrations also occur at night, when the plume is trapped in a volume of stable air near the surface. Under such conditions we can assume that the depth D of the plume is equal to the depth of the surface inversion layer (100 to 200m) and that the width W of the plume is equal to the width of valley (1000 to 2000m). The concentration in this case is given by the simple formula:

$$\chi = \frac{Q}{DWU} \tag{6}$$

Concentration values thus lie in the range 125 - 1000$\mu g/m^3$ for the expected range of D, W, and U (1 to 2m sec^{-1}). These values are within the range of extreme daily concentrations measured at the Rockwood Station.

The following corrective measures would reduce surface concentrations near the Roane Electric Plant:

1. Use of precipitators or other air cleaning equipment would, obviously, reduce the source strength.
2. Plume rise could be increased by:
   a) channeling all gases through one stack, thus increasing H by a factor of about two;

b) building a tall stack;

c) increasing the temperature of the effluent gases.

4. Calculations of Concentrations due to the Kingston Steam Plant.

The Kingston steam plant is only 7km to the SE of the Harriman Station and 15km to the SE of the Rockwood Station. However the wind blows from the SE, ESE, or E only about 14% of the time so that the plume from this steam plant does not often influence the concentrations at the air monitoring stations. The output of suspended particles[7] is about 67 tons/day (about 7 x 10^8μg/sec), which is seven times greater than the output of the Roane Electric Plant. But the Kingston steam plant has stacks about 100m high and plume rise is about 100m. Consequently the effective plume height h is about 200m. Downwash hardly ever occurs. The maximum calculated ground concentration of suspended particles for this plant for an averaging period of one hour, is shown in Table 4.

Table 4

One Hour Maximum Ground Concentrations from Kingston Steam Plant

Stability	χ(μg/m^3) (U = 5m/sec.)	Distance From Stack
Unstable	600	1.3km
Nearly Neutral	200	9km

Suspended particulate concentrations are routinely monitored in Kingston by TVA.[8] From May, 1969 through June, 1970 the maximum 24 hour average concentration measured at this station was 432μg/m^3 and the geometric mean of the measured concentrations was about 60μg/m^3. The maximum concentration is in line with the numbers in Table 4. Of course, local space heating also contributes to the burden of suspended particles in Kingston.

During special condition, e.g. unstable conditions with SE winds, the concentrations of suspended particles in the Rockwood-Harriman industrial corridor due to emissions from the Kingston steam plant may be high. However the average yearly concentration due to this plant is probably about 5 to 10$\mu g/m^3$, since the wind blows from any 45° segment in the SE quadrant only about 5% of the time.

5. Calculations of Concentrations Due to Residential and Industrial Space Heating.

Many homes and small businesses burn coal in this valley. These sources can be combined to give area sources, which can be treated using the ATDL area source diffusion model.[9],[10] In this model the point source equation (eq. 5) has been integrated over the required surface area. For winds blowing from one direction and nearly neutral conditions, the equation becomes:

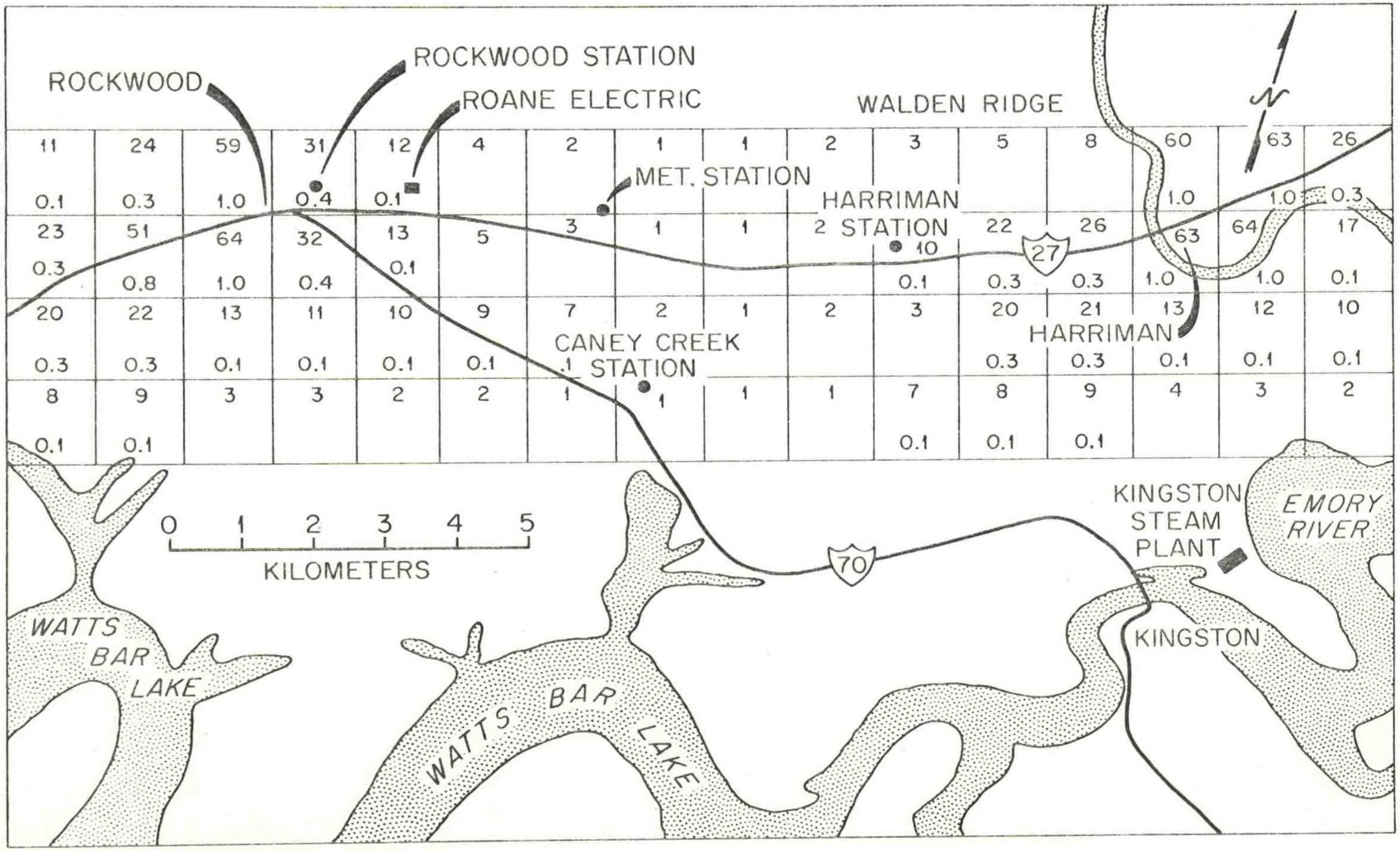
$$\chi_0 = \frac{21.3(\Delta x)^{1/4}}{U} \left| Q_0 + .31Q_1 + .19Q_2 + .13Q_4 + .10Q_5 \right| \qquad (7)$$

where the area source strengths (in $\mu g/m^2 sec$) are given on a checkerboard grid pattern with grid spacing Δx. The subscript "0" represents the central block and subsequent subscripts represent adjacent blocks upwind from the central block "0". In order to account for the wind frequency distribution, the right side of equation (7) must be weighted by the corresponding wind direction frequency of Figure 2.

The TVA[11] contacted coal dealers in the area in order to establish an inventory of space-heating sources, and kindly provided us this information. Using these data, and assuming that five percent of the weight of coal burned is released to the atmosphere in the form of suspended particles, a grid pattern of area source strengths was established. This grid pattern, for which Δx = 4000 ft or 1220m, is shown in Figure 5. The numbers at the bottom of each square are yearly average source strength in $\mu g/m^2$ sec. On this basis the

Figure 5 - Annual average distribution of surface concentrations of suspended particulates due to emissions from homes and small industries that burn coal. It is assumed that $\sigma_z = .15\ x^{.75}$ and the wind speed is 2m/sec. Numbers at the bottom of each grid block are source strengths in $\mu g/m^2 sec$. Numbers at the top of each grid block are concentrations in $\mu g/m^3$.

ORNL-DWG 71-402



total output of the area is two tons per day, a factor of five less than the output of the Roane Electric Plant. Of course, on cold days the area source output will be greater.

The average yearly concentration of suspended particles from space-heating sources is given in Figure 5, assuming that on the average atmospheric stability is nearly neutral ($\sigma_z = .15 x^{.75}$). Near the center of the towns, concentrations are about 60μg/m^3. At the Rockwood, Harriman, Caney Creek, and Met. Station air monitoring stations, concentrations are 30, 10, 1, and 2μg/m^3, respectively. Figure 6, the result of similar calculations, shows that for stable conditions ($\sigma_z = .06 x^{.71}$) concentrations at the above stations are 90, 30, 3, and 8 respectively.

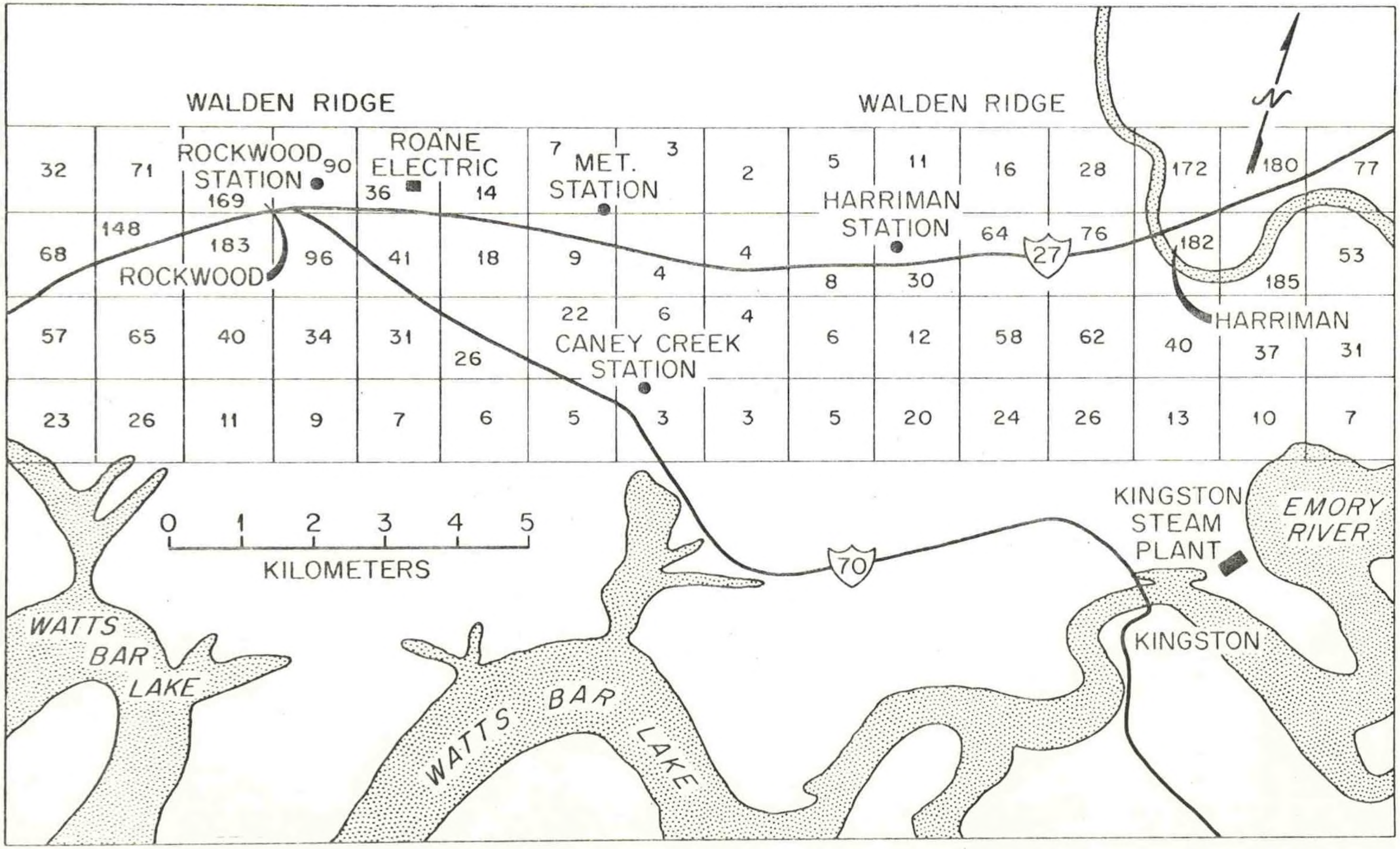
At the Caney Creek and Met. Stations, space heating is contributing very little to the suspended particulate burden. However at the Rockwood and Harriman Stations possibly one half of the total yearly burden is due to space heating. In the summer, this contribution is of course much less.

6. Summary of the Existing Suspended Particulate Pollution in the Rockwood-Harriman Corridor.

A significant part of the measured suspended particulate concentration is background pollution from more remote sources, including upwind cities such as Nashville, Chattanooga, or Knoxville. This contribution is probably about 40μg/m^3, based on measurement at other sites. Added to this are the contributions from the Kingston steam plant, Roane Electric Company, and local space heating and smaller industries. The average contribution from the Kingston steam plant is probably about 5 to 10μg/m^3. In Rockwood, the average contribution

Figure 6 - Distribution of surface concentrations of suspended particles due to emissions from homes and small industries that burn coal, for stable conditions ($\sigma_z = .06\ x^{.71}$) and a wind speed of 2m/sec. Concentrations have the units $\mu g/m^3$.

ORNL-DWG 71-403



from the Roane Electric Company is about 50μg/m^3, with daily averages reaching 200μg/m^3. In Harriman, the Roane Electric Company contributes about half this much. The overall average contribution due to space heating in both towns is about 50μg/m^3, and daily averages reach 200μg/m^3. Strong southwesterly winds generally give rise to high concentrations NE of the Roane Electric Company, due to downwash of the plume. In general, high concentrations in the towns are due to both residential and industrial space heating and the emission of the Roane Electric Company.

7. Effects of Additional Industries.

The air sampling instrument in Rockwood shows that the 24-hour average suspended particulate concentration exceeds 200μg/m^3 about 20% of the time. This concentration value is the recommended standard for 24-hour averages in Tennessee. Clearly there is currently too much pollution in this valley, and as things now stand the only new industries that should be permitted are non-polluters. The air quality could be improved by taking the following steps:

1.) homes could change from heating with coal;

2.) schools and small industries could change from coal heating and reduce other emissions;

3.) Roane Electric could add precipitators or other air-cleaning equipment, build a single tall stack, and emit at a higher temperature.

Once the concentration from existing sources is sufficiently low, then the possibility of new polluting industries can be considered. The concentrations due to any source of strength Q located at an effective height h can be calculated from equation (5). Average yearly concentrations can be estimated by combining these results and the wind rose in Figure 2. However, unless the new industries have tall (higher than about 100m) stacks, the experience with Roane Electric suggests that the total output of suspended particles from all sources should not exceed about five tons per day.

References

1. "Interim Evaluation of Air Pollution, Harriman-Rockwood Industrial Corridor," prepared by Regional Air Quality Staff, Air Quality Branch Division of Environmental Research and Development, Tennessee Valley Authority, Muscle Shoals, Ala., 12pp + appendices. (1970).

2. Rossano, A. T., Jr., ed., Air Pollution Control. E.R.A., Inc., 750 Summer St., Stanford, Conn., pp 45-47 (1970).

3. Stafford, J. R. and W. E. Woodbridge, "Report on June 1970 Survey of Ferroalloy Electric Furnace Emissions at Roane Electric, Rockwood, Tennessee," prepared by Mead Corp. Air and Water Resources Group, The Mead Corp., Central Res. Lab., Chillicothe, Ohio, 7pp + 9 tables (1970).

4. Briggs, G. A., Plume Rise, USAEC rep. no. TID-25075, 81 pp (1969).

5. Holland, J. Z., "A Meteorological Survey of the Oak Ridge Area," Final report covering the period 1948-52, USAEC Report ORO-99, Weather Bureau, Oak Ridge, Tenn., 584 pp. (1953).

6. Slade, D., ed., Meteorology and Atomic Energy, 1968, USAEC rep. no. TID-24190, x and 445 pp (1968).

7. Larry Montgomery, TVA, Private communication, Nov. 10, 1970.

8. Air Quality Branch Quarterly Reports, Fiscal Year 1970 and first quarter of 1971. Tennessee Valley Authority, River Oaks Bldg., Muscle Shoals, Ala. (1970).

9. Gifford, F. A., Jr., "Atmospheric Diffusion in an Urban Area" presented at 2nd IRPA Conference in Brighton, England, 5 pp (1970).

10. Gifford, F. A., Jr., and S. R. Hanna, "Urban Air Pollution Modelling," presented at the 1970 Int. Air Poll. Conf. of the Int. Union of Air Poll. Prev. Assoc., Washington, Dec. 11, 1970, 17 pp (1970).

11. Thomas, F. W., private communication, letter dated Oct. 5, 1970.