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ABSTRACT

A simple but physically realistic model of the ground level concentration distribution resulting from area sources of pollution is presented. It is shown that the results are not greatly dependent upon the form of the vertical concentration distribution. This area-source model, which satisfies the two-dimensional equation of diffusion with height-variable wind and diffusivity, is well adapted to simple, hand computation. The ground level concentration in any grid square of a two-dimensional grid covering the area sources is given by the sum of the source strengths of all the grid squares, each multiplied by a simple weighting factor. This factor depends mainly on distance from the receptor square, the frequency with which the wind blows from that square to the receptor square, wind speed, and atmospheric stability. The matrix of weighting factors is independent of the location of the receptor square. Comparisons with urban air pollution computations based on more complex urban diffusion models (e.g. Lamb's model applied to Los Angeles, Fortak's model applied to Breman, and Martin and Tikvart's model applied to Atlanta) illustrate that this simple model adequately represents urban diffusion for most air pollution problems.

INTRODUCTION

Of the three great natural sinks for pollution, the air, the water, and the land, only the air cannot be purified or controlled by man, once it is contaminated. Material emitted into the air is removed or diluted only by naturally occurring processes. Whereas river water can, and often does, undergo many stages of pollution alternating with purification as it travels downstream, there is no such possibility for the air. Also pollutants from all kinds of sources, once they are emitted to the atmosphere, mix together and can't be distinguished. This means that the problem of calculating air pollution becomes a particularly crucial one.

• Specific requirements for calculating levels of urban air pollution range from the need to design "air quality control regions," through the establishment of air pollution control regulations, with their related enforcement activities, to operational (i.e. real-time) air resource management. All can involve quantitative estimation of air pollution levels, and it is the business of the air pollution meteorologist to make such estimates.

Following Lucas'[1] early study a series of simple urban air pollution models were described in papers by Leavitt[2], Pooler[3], Clarke[4], and Miller and Holzworth[5]. These studies have much in common. They each approach the urban area-source concentration problem by way of the usual Gaussian point source diffusion model. Differences occur only in the details of how the area source summation is carried out and in how various meteorological parameters are included.

More recently urban diffusion models of far greater intricacy have been described, for instance by Turner[6], Martin and Tikvart[7], Shieh, Davidson, and Friend[8], Roberts[9], and Fortak[10]. These models use much the same basic point source scheme as the earlier group, but differ in the detail with which meteorological factors are included. The execution of these later models requires appreciable amounts of high speed digital computer time. Even apart from the expense involved, this is a practical difficulty. If urban diffusion models are to be used in real-time pollution control, the time to run the model must not be so great that it conflicts with the requirement for prompt control action. Furthermore the meteorological calculation is only one element in the control or analysis system. It should not consume a disproportionate share of the available computer time. So the question naturally arises, is this elaboration necessary? Are the numbers produced by the current crop of models better than those produced by the earlier ones? Should we anticipate, as Stern[11] suggests, yet a third round of urban diffusion models, presumably of still greater complexity and which will consume even more computer time? At the moment there is no easy answer. Probably detailed models will always be studied in research applications, where the need is to understand detailed complexities of urban pollution; and perhaps this is justifiable. However for many operational uses, including legislative and enforcement activities as well as engineering design, it seems crucial to retain essential simplicity in urban diffusion models so that the meteorological factor can be introduced into the environmental pollution problem in as uncomplicated a way as possible. There remains of course the possibility that a quite simple model may give all or nearly all of the precision that is available.

In the following paragraphs a simple model of urban air pollution is presented, based on reasonable first principles and incorporating some attempt at rigor. The result, a simple, easily applied area-source concentration formula, is compared with several of the previous formulas and the conclusion is that it performs well.

THE ATDL AREA-SOURCE MODEL

We assume, in the first place that the problem of urban air pollution can be simplified by considering separately the isolated point sources such as tall stacks and lumping the contribution of the multitude of lesser sources of all types into a spatially variable area-source concentration, X_A. This is assumed to obey the steady-state diffusion equation in two independent variables,

$$u(z)\frac{\partial X_A}{\partial x} = \frac{\partial}{\partial z} K(z) \frac{\partial X_A}{\partial z} \quad , \qquad (1)$$

where the mean wind, u(z), blows in the x-direction. Neglect of the y-component of the diffusion is equivalent to the observation that point-source plumes in the atmosphere tend to be long and narrow, and so the concentration at a point can be influenced only by sources in a narrow, plume-shaped upwind sector [see Gifford[12].] If u and the eddy-diffusivity, K, are assumed to obey the usual power laws,

$$u(z) = u_1 \left(\frac{z}{z_1} \right)^m \qquad (2)$$

$$K(z) = K_1 \left(\frac{z}{z_1} \right)^n \qquad (3)$$

the "partial" solution to equation (1) for the ground level concentration distribution, X_{AO}, due to an area source has been shown by Gifford[13] to be

$$X_{AO} = \frac{z_1^m}{c_1 u_1 B(1-s)} \left(\frac{\Delta x}{2} \right)^{1-s} \left\{ Q_o + \sum_{i=1}^{N} Q_i \left[(2i+1)^{1-s} - (2i-1)^{1-s} \right] \right\} \quad (4)$$

where s = $(m+1)/(2+m-n)$ and the distance, x, from the receptor point to the upwind edge of the city is given by $x = (N+\frac{1}{2})\Delta x$. N is the number of upwind grid squares in the source inventory, and Δx is the grid size, as given by the usual "checkerboard" source-inventory pattern. Source strength, Q, is constant for each square.

The receptor point is assumed to be located at the center of a source square. There is no particular difficulty involved in adapting the model to other geometries, including irregular area-source patterns.

The parameter B depends on the vertical concentration distribution. The total concentration distribution X_A is related to the ground-level value, X_{AO}, by

$$X_A = X_{AO}(x)\ f\left(\frac{z}{Z}\right) \quad . \qquad (5)$$

Here the reference height, Z, essentially represents the "top" of the polluted air, and increases with distance from the upwind edge according to the formula

$$Z = c_1\ x^{\frac{1}{2+m-n}} \quad . \qquad (6)$$

This assures that a "variables separable" solution of the type of equation (5) will satisfy equation (1). Then, with $\zeta = z/Z$, the value of B follows from the continuity condition

$$\int_0^\infty u(z)\ X_A\ (x,z)dz = \int_0^x Q(x)dx \quad . \qquad (7)$$

From this and equation (5),

$$B = \int_0^\infty \zeta\ f(\zeta)d\zeta \quad . \qquad (8)$$

The constant c_1 is determined from the relation $c_1 = 3a^{1/(m+1)}$

where a is defined by the usual power-law formula for the standard deviation of the vertical concentration distribution

$$\sigma_z = a\,x^b \quad , \tag{9}$$

and $Z \approx 3\,\sigma_z$. Values of a and b based on extensive observational data have been summarized by for instance Slade[14], and Smith[15]. Table I is based on the values given by Smith and includes our estimate of the value corresponding to Pasquill's type-D (slightly stable) condition. We believe that this, rather than Smith's "stable" value is more appropriate to urban conditions; unfortunately few data are as yet available on diffusion over cities.

Table I

Meteorological Conditions:	a	b	(1-b)	a(1-b)
Very unstable :	0.40	0.91	0.09	.036
Unstable :	0.33	0.86	0.14	.046
Neutral :	0.22	0.80	0.20	.044
Estimated Pasquill "D" :	0.15	0.75	0.25	.037
Stable :	0.06	0.71	0.29	.017

For a Gaussian vertical distribution, with the above assumptions, $B = \frac{1}{3}\left(\frac{\pi}{2}\right)^{1/2}$. For a linear decrease in concentration, $B \approx 0.4$. In general it is unlikely that B will differ much from these values.

Equation (4) can be generalized in the usual ways, by introducing wind direction and speed frequency class intervals, and varying the meteorological parameter, s. The only real problem that arises in the extension of equation (4) to the case of annual average concentrations is that of adapting the basic rectilinear source configuration to radial wind directions other than the cardinal ones. Our arbitrary but simple scheme for doing this is illustrated in Figure 1.

COMPARISON WITH OTHER AREA SOURCE MODELS

There are at the moment no urban air pollution observations that are accepted as definitive for the purpose of testing diffusion models, so the comparisons to follow are with the results of calculations using several other urban diffusion models, those of Fortak, Lamb[16], and Martin and Tikvart. Our intention is to show that the comparatively simple, easily and quickly performed calculations required by equation (4) give area-source concentration values comparable with these more complex models.

Fortak's model: In common with several area source diffusion models, Fortak's is based on the integration over a plane area of the Gaussian plume formula. Other models employing the same idea are those by Turner, and Martin and Tikvart. Models such as those by Roberts, et al. and Shieh, et al., which employ an instantaneous Gaussian puff as the basic diffusion element, do not seem to us to be essentially different from these. Fortak assumes a constant mean wind speed and so the comparable special case of equation (4) is given by the values $m = 0$, $b = s$, and $B = \frac{1}{3}\left(\frac{\pi}{2}\right)^{1/2}$. The working equation is

$$X_{AO} = \left(\frac{2}{\pi}\right)^{1/2} \frac{f_k}{a(1-b)u} \left(\frac{\Delta x}{2}\right)^{1-b} \left\{ Q_o + \sum_{i=1}^{N} Q_i \left[(2i+1)^{1-b} - (2i-1)^{1-b} \right] \right\} \quad (10)$$

where u is the (constant) mean wind speed, and f_k is the frequency of wind of this speed from direction k.

Equation (10) has been compared with a representative area source calculation for Bremen, Fortak's Figure 22. Using the values $u = 3 \text{ m sec}^{-1}$, $a = 0.15$, and $b = 0.75$, corresponding to neutral conditions, and for a south wind, concentration values predicted by equation (10) for each source square are given in Figure 2 and the source data, the sum of the source strengths given in Fortak's Figures 13 and 14, appear in Figure 3. Using these source data the concentrations can be reproduced from equation (10) in a few minutes. The concentration pattern as well as the maximum values are seen to correspond well with Fortak's isopleths, which are shown in Figure 4.

Martin and Tikvart's model: This straightforward model is closely related to Turner's area source model; both are based on the Gaussian plume. The many "Reports for Consultation" issued by DHEW to establish air quality control regions in the United States used a version of Martin and Tikvart's model. These consultation reports differ considerably among themselves in the amount of air pollution source data included. The report for the Atlanta, Georgia, region[17] is representative of this large body of literature and includes a reasonable amount of source strength data. We made a calculation of annual average particulate concentrations for Atlanta, based on the source strengths given in the Atlanta report. The annual average wind speed was used, but equation (10) was modified by multiplying by the wind frequency in each direction and summing. Neutral conditions ($a = .15$, $b = .75$) were again assumed.

The results of our Atlanta calculation are shown in Figure 5. We include the concentration isopleths appearing in the DHEW report for comparison. The Atlanta source data included emissions from a number of tall stacks. Concentration patterns for these were calculated separately by the usual plume rise and dispersion formulas [see Gifford[18], and Briggs[19]] and added to the area source values of equation (10) to give the totals in Figure 5, so that these would be comparable with the isopleths of the DHEW report. Equation (10) reproduces the absolute values and general pattern of the DHEW isopleths reasonably well. The DHEW isopleths seem, however, to have been smoothed. The pattern of our values indicates a somewhat greater elongation toward the south and the northwest, and our maximum value in Atlanta is considerably higher. It should be remembered that the purpose of the DHEW studies was to delineate regional areas, and not necessarily to determine maxima.

Lamb's model: Having demonstrated, at least to our own satisfaction, by the above and several similar calculations that equation (10) reproduces the results of area source calculations based on the Gaussian assumption, we wished to compare it with a model based on solution of the diffusion equation. An ambitious attempt along this line is the interesting study by Lamb at UCLA, of diffusion in the Los Angeles basin. Lamb's model, although it employs constant eddy-diffusivities, and wind not varying with height, is in other respects the most complete and flexible model we have examined. For instance it includes time-variable sources, space-variable winds, ground absorption, and even simple chemical reactions.

We compared Lamb's model with equation (10) using source data on natural gas emissions in the Los Angeles Basin, for a particular 16-hour period. Calculations of ground-level concentrations using these data were kindly provided to us by Mr. Lamb. This is a very severe test of equation (10). For annual or seasonal concentrations, such as in the previous comparison, it is not too surprising that equation (10) performs well. Over any long period the average ground concentration from an area source is obviously strongly weighted by the local source-strength. But for a short period such as 16 hours all possible complexities come into play.

The results of these calculations are illustrated in Figure 6. Our model seems to be giving area-source concentration values of the same order as the UCLA model, perhaps a factor of two higher. Figure 7 is a scatter-diagram presentation of the same information. The open points come from the top three grid-rows of Figure 6. We suspect that the UCLA model is computing higher values there because it takes into account flow convergence caused by the ring of mountains. Lamb uses a streamline and isotach analysis of hourly records from 32 wind observation stations in the L A basin, varying the wind field each hour. We simply used the annual average Los Angeles wind direction frequencies and a single mean wind speed, choosen so as to agree with the average of Lamb's wind speed data. Doubtless agreement between the two models could be improved by recomputing ours for each hour, using the actual wind data. Of course we don't know which model is giving the best values as there are as yet no entirely satisfactory verification data.

DISCUSSION AND CONCLUSIONS

The above comparisons lead us to conclude that our area source model performs well, producing ground level concentration values comparable with those from other, more complex models. We also believe that the success of these comparisons amply justifies our basic physical assumption, namely neglect of lateral dispersion [Calder[20] refers to this as the "narrow plume hypothesis."] In several respects our model is more general than other steady-state area-source models. It permits both u and K to vary with z and makes no a priori assumption about the form of the concentration distribution. Since our area source model is quite simple to apply, requiring little computational effort (a few minutes on a desk calculator or several seconds of high-speed digital computer time) it should be of considerable use in air pollution applications.

One problem with area source diffusion models that depend on numerical integration of a point source diffusion equation (all the models in the references are of this type) is that it is not obvious how any single variable in the basic formula influences the final result. This has led to several analyses of "sensitivity," in which parameters are varied in an attempt to establish their influence on the ground level concentration. Such studies have been carried out by Hilst[21], and Milford, et al.[22], and another, by Thayer[23], is in progress.

It is a virtue of the present, explicit solution of the problem that the parametric behavior of the result is obtained essentially by inspection. Our basic physical assumption, which appears to be quite reasonable, is that ground-level area source concentration is essentially independent of the lateral dispersion. The behavior of the ground concentration, X_{AO}, with respect to the remaining parameters of equation (4) is summarized in Table II, in which the fractional change of X_{AO} is given by

$$\delta X_{AO} / X_{AO} = (\text{Coefficient})\ \delta P/P \qquad (11)$$

where P stands for any parameter on the right hand side of equation (4).

Table II

Parameter	Range	$\delta X_{AO}/X_{AO} =$	Coefficient of $\delta P/P$
u	1-30m $\sec^{-1}$	$-\ \delta u/u$	-1
Δx	5-50 km	$\frac{\delta \Delta x}{\Delta x}(1-b)$	(1-b)
1-b	.09 - .29	$\frac{\delta(1-b)}{(1-b)}(1-b)x^{1-b}\ell n\ x$ (for $Q_i = Q_o$)	$(1-b)x^{1-b}\ \ell n\ x$
N	5 - 10	$\frac{\delta(N+1)}{(2N+1)}(1-b)$	(1-b)
Q_o (Central source box)	Many orders	$\frac{\delta Q_o}{Q_o}\left(1+\sum_{1}^{N}\frac{Q_i}{Q_o}F_i\right)^{-1}$	$\simeq$ 0.6 for type D and $Q_i = Q_o$
Q_j (j'th source box)	Many orders	$\delta Q_j\ F_j\ \left(\frac{Q_o}{Q_j} + \sum_{i=1}^{N}\frac{Q_i}{Q_j}F_i\right)^{-1}$	$\simeq$ .10 to .15 for type D and $Q_i = Q_o$
B	0.4 - 1	$-\ \delta B/B$	-1
f_i	.01 - 1	$\delta f_i/f_i$	1

In the above, $F_i = (2i+1)^{1-b} - (2i-1)^{1-b}$. The result for $(1-b)$ was obtained, assuming for simplicity that $Q_i = Q_o$ = constant, from the continuous form of equation (4),

$$X_{AO} = (2/\pi)^{1/2}\ Q_o x^{1-b}\ [a(1-b)u]^{-1}\ . \qquad (12)$$

In view of the small variability of a(1-b) over the expected range, from unstable to type-D conditions, this product was assumed constant in evaluating the effect of (1-b).

Table II displays the behavior of this area source model rather completely. As to sensitivity to small changes it reveals nothing very spectacular, except for the fairly large variation of the coefficient of $\delta P/P$ which, over the range of the stability parameter (1-b), changes by a factor of about 20 under stable conditions. This means that, with this exception, small changes in any of the parameters produce only small changes in ground-level concentrations, X_{AO}. Consequently extremes in X_{AO} must be sought in connection with extreme values of the quantities P. For example, high values of X_{AO} will be associated with large Q_o, the central area source strength, or with high values of the source strength Q_j for nearby source areas. High X_{AO} also is associated with low u and, where a long-term average is involved, with high values of f_i. Comparatively large changes in X_{AO} will accompany changes in stability, as measured by (1-b), particularly during stable conditions and for large values of "fetch" over the city, x.

As to future research on area source models, we believe that improvements are required on three aspects. Models should be extended to account for irregular terrain, chemical reactions and removal effects, and unsteady conditions. Some work has been done on each of these but more is required. The success of such a simple approach as we have outlined leads us to hope that adequate means can be developed to introduce these additional features without sacrificing simplicity. In this connection, it is a definite implication of Table II that area-source pollution is not very sensitive to the form of the vertical concentration distribution. In the extreme and unlikely case of a uniform vertical concentration distribution, $B = 1$, i.e. not very different from the values we have used. Thus we are not inclined to regard uncertainty about the precise form of this quantity as being much of a problem.

The usefulness of any new area source diffusion model depends on its performance compared with other area source models. In the past, as new models appeared in the literature, there was no comparison with other models. Clearly, if the concentrations predicted by a complicated model are not significantly better than the predictions of, for example, the simple "box" model of diffusion, then there is no practical justification for the new model. In fact ours is the first model we know of that has been compared with other models.

Finally, we wish to record a plea. Very few published area-source models have included data on source strengths and predicted concentrations in a form that makes it easy or even possible to reproduce and compare results. It would be very helpful if authors would; 1) include the area-source strength data that they use; 2) provide calculated area-source concentration values in the same grid system as for the source data.

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REFERENCES

1. D. H. Lucas, "The Atmospheric Pollution of Cities," Int. J. of Air Poll., 1, 71-86 (1958).

2. J. M. Leavitt, "Meteorological Considerations in Air Quality Planning," J. Air Poll. Control Assoc., 10, 246-250 (1960).

3. F. Pooler, "A prediction Model of Mean Urban Pollution for Use with Standard Wind Roses," Int. J. of Air and Water Poll., 4, 199-211 (1961).

4. J. F. Clarke, "A Simple Diffusion Model for Calculating Point Concentrations from Multiple Sources," J. Air Poll. Control Assoc., 14, 347-352 (1964).

5. M. Miller and G. Holzworth, "An Atmospheric Diffusion Model for Metropolitan Areas," J. Air Poll. Control Assoc., 17, 46-50, (1967).

6. D. B. Turner, "Urban Atmospheric Dispersion Models -- Past, Present, and Future," USPHS (1969).

7. D. O. Martin and J. A. Tikvart, "A General Atmospheric Diffusion Model for Estimating the Effects of One or More Sources on Air Quality," US DHEW, NAPCA mss (1968).

8. L. J. Shieh, B. Davidson and J. P. Friend, "A Model of Diffusion in Urban Atmospheres; SO_2 in Greater New York," preprint, Symposium on Multiple Source Urban Diffusion Models, 54 pp (1969).

9. J. J. Roberts, E. J. Croke and A. S. Kennedy, "An Urban Atmospheric Dispersion Model," Presented at the Symposium on Multiple Source Urban Diffusion Models (Oct. 1969).

10. H. G. Fortak, "Numerical Simulation of the Temporal and Spatial Distributions of Urban Air Pollution Concentrations," preprint, Symposium on Multiple Source Urban Diffusion Models, 16 pp (1969).

11. A. C. Stern, "Summary of Symposium; Symposium on Multiple Source Urban Diffusion Models," proceedings to be published (1969).

12. F. Gifford, "Computation of Pollution from Several Sources," Int. J. of Air Poll., 2, 109 (1959).

13. F. Gifford, "Atmospheric Diffusion in an Urban Area," presented at 2nd IRPA Conference in Brighton, England, May 1970, 5 pp, 2 figs.

14. R. Lamb, "An Air Pollution Model of Los Angeles," Master's thesis, UCLA, viii and 104 pp mimeo. (1968).

15. D. Slade (Editor), "Meteorology and Atomic Energy, 1968," USAEC, Rep. No. TID-24190, x and 445 pp (1968).

16. M. E. Smith (Editor), "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents," ASME, ix and 85 pp (1968).

17. U. S. Department of Health, Education, and Welfare, "Report for Consultation on the Metropolitan Atlanta Intrastate Air Quality Control Region (Georgia), ix and 57 pp mimeo (1970).

18. F. Gifford, "An Outline of Theories of Diffusion in the Lower Layers of the Atmosphere," [Ch. 4 in reference 15] (1968).

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

20. C. Calder, 1969, "A Narrow Plume Simplification for Multiple Urban Source Models," unpublished mss, 11 pp mimeo (1969).

21. G. Hilst, 1969, "The Sensitivities of Air Quality Predictions to Input Errors and Uncertainties," paper presented at the NAPCA Symposium, Multiple Source Urban Diffusion Models, Oct. 27-30, 1969, Chapel Hill, N.C.

22. S. N. Milford, G. C. McCoyd, L. Aronowitz, J. H. Scanlon, and Conrad Simon, 1970, "Air pollution models of the New York, New Jersey, Connecticut Air Quality Region," paper presented at the 63rd Annual Meeting of the APCA, June 1970.

23. S. D. Thayer, 1970, "Sensitivity analysis and evaluation of multiple source urban air pollution diffusion models," Geomet Report No. 7517-1 prepared under Contract No. CPA 70-94, NAPCA.

CAPTIONS

Figure 1. Scheme for combining rectilinear source-grid squares with radial wind directions.

Figure 2. Calculated wintertime ground-level SO_2 concentrations, X_{AO} in mg SO_2/m^3, based on equation (10), for Breman: wind direction, south; wind speed 3 m sec^{-1}; atmospheric stability, neutral.

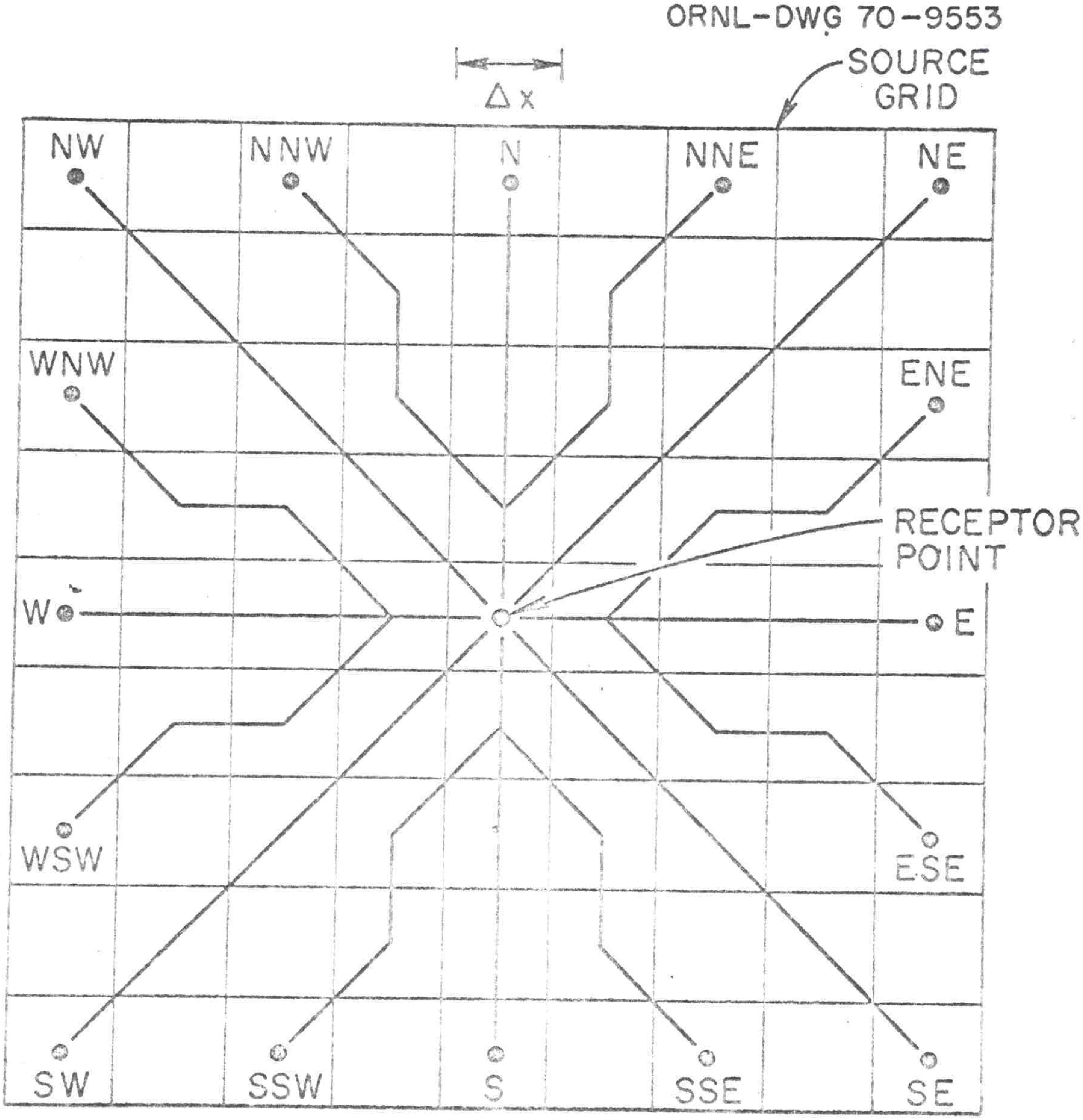
Figure 3. Source strength data for calculation shown in Figure 2 mean emission rates in kg SO_2/km^2 hr for heating period (space-heating plus small industries).

Figure 4. Isopleths of wintertime ground-level SO_2 concentration, mg SO_2/m^3, calculated by Fortak.

Figure 5. Calculated wintertime ground level particulate concentrations, mg/m^3, based on equation (10), for Atlanta (numbers in squares). Isopleths are the calculated values, mg/m^3, presented in reference 17.

Figure 6. Ground level concentrations of natural gas in Los Angeles, cc/m^3, as calculated using Lamb's model (numbers above the line) and equation (10) (numbers below the line). Source data, 10^3 ft^3/day mi^2, are indicated at the bottom of each square.

Figure 7. Scatter diagram of the information presented in Figure 6. Open points refer to the top three rows of Figure 6.



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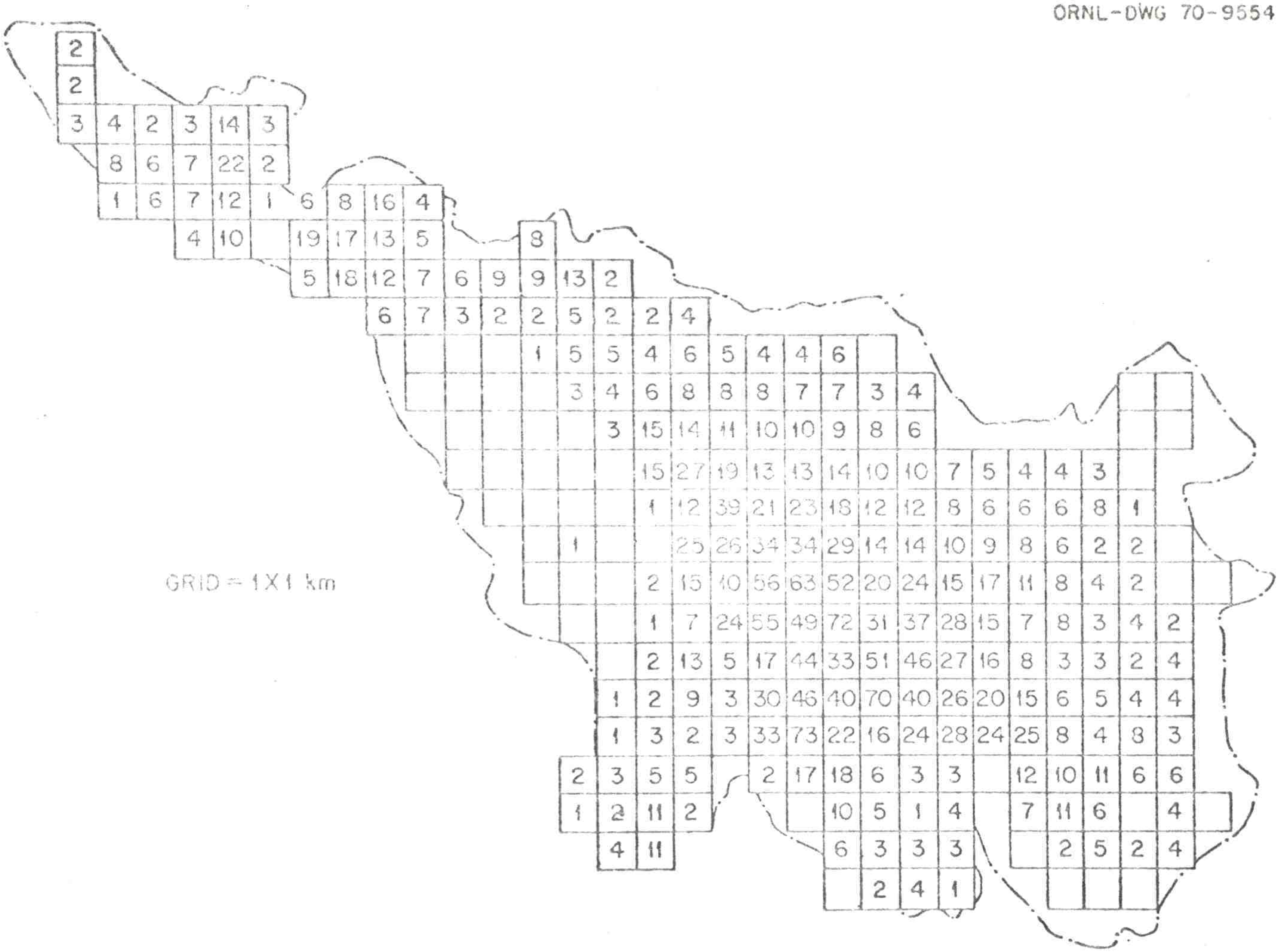

BREMEN 1962

Figure 2. Calculated wintertime ground-level SO_2 concentrations, X_{AO} in mg SO_2/m^3, based on equation (10), for Bremen: wind direction, south; wind speed 3 m sec^{-1}; atmospheric stability, neutral.

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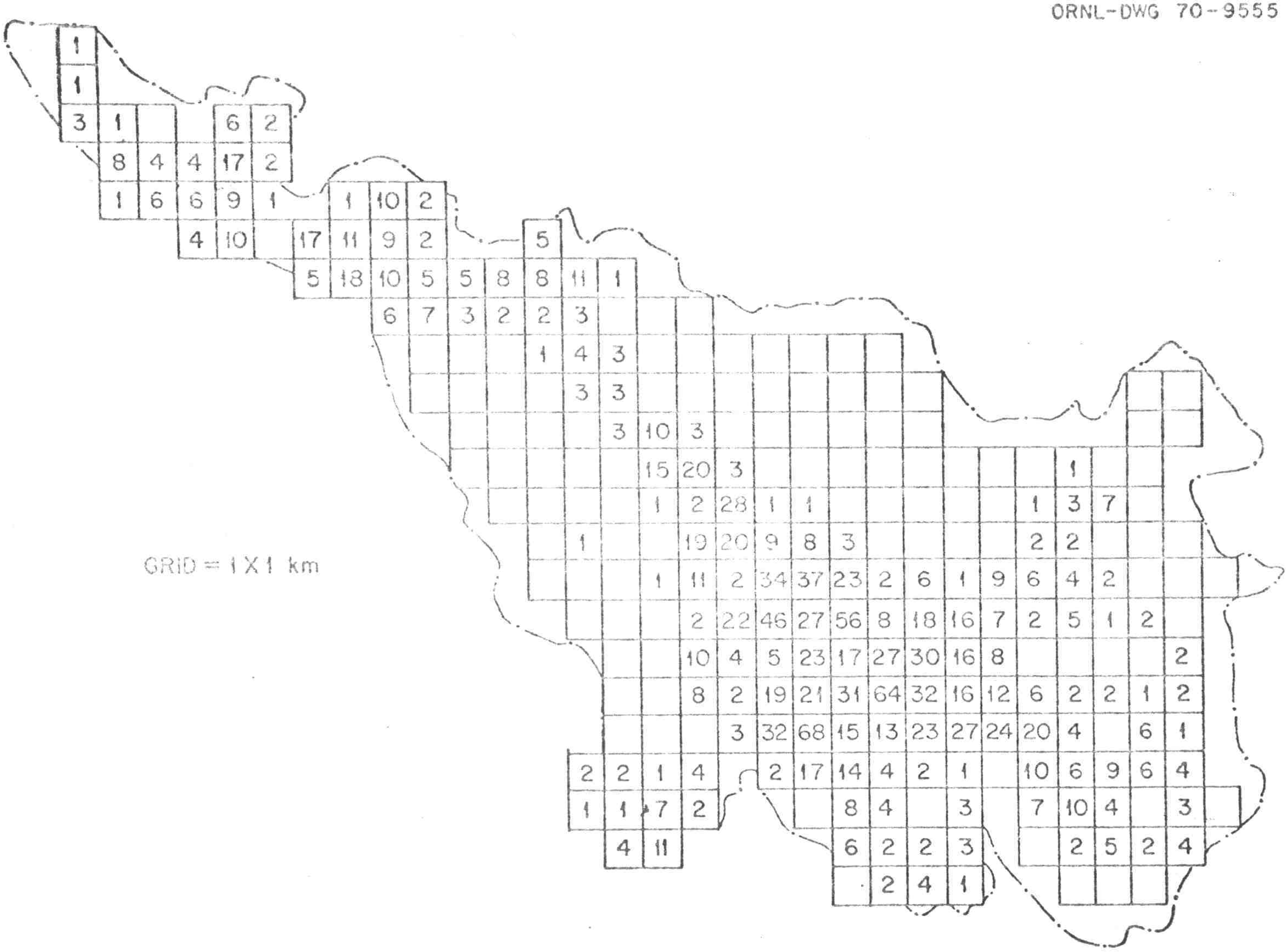

BREMEN 1962.

Figure 3. Source strength data for calculation shown in Figure 2, mean emission rates in kg SO_2/km^2 hr for heating period (space-heating plus small industries).

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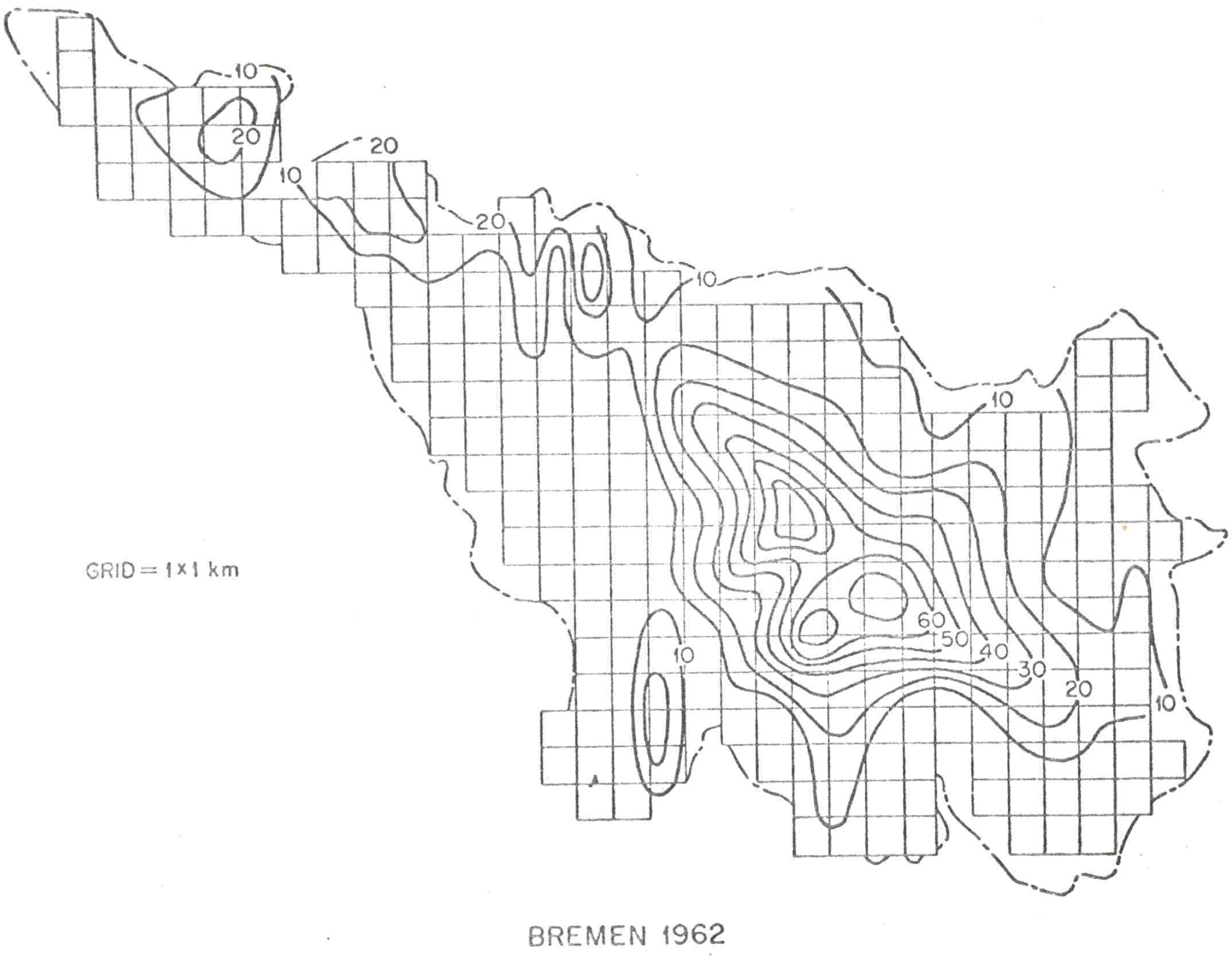

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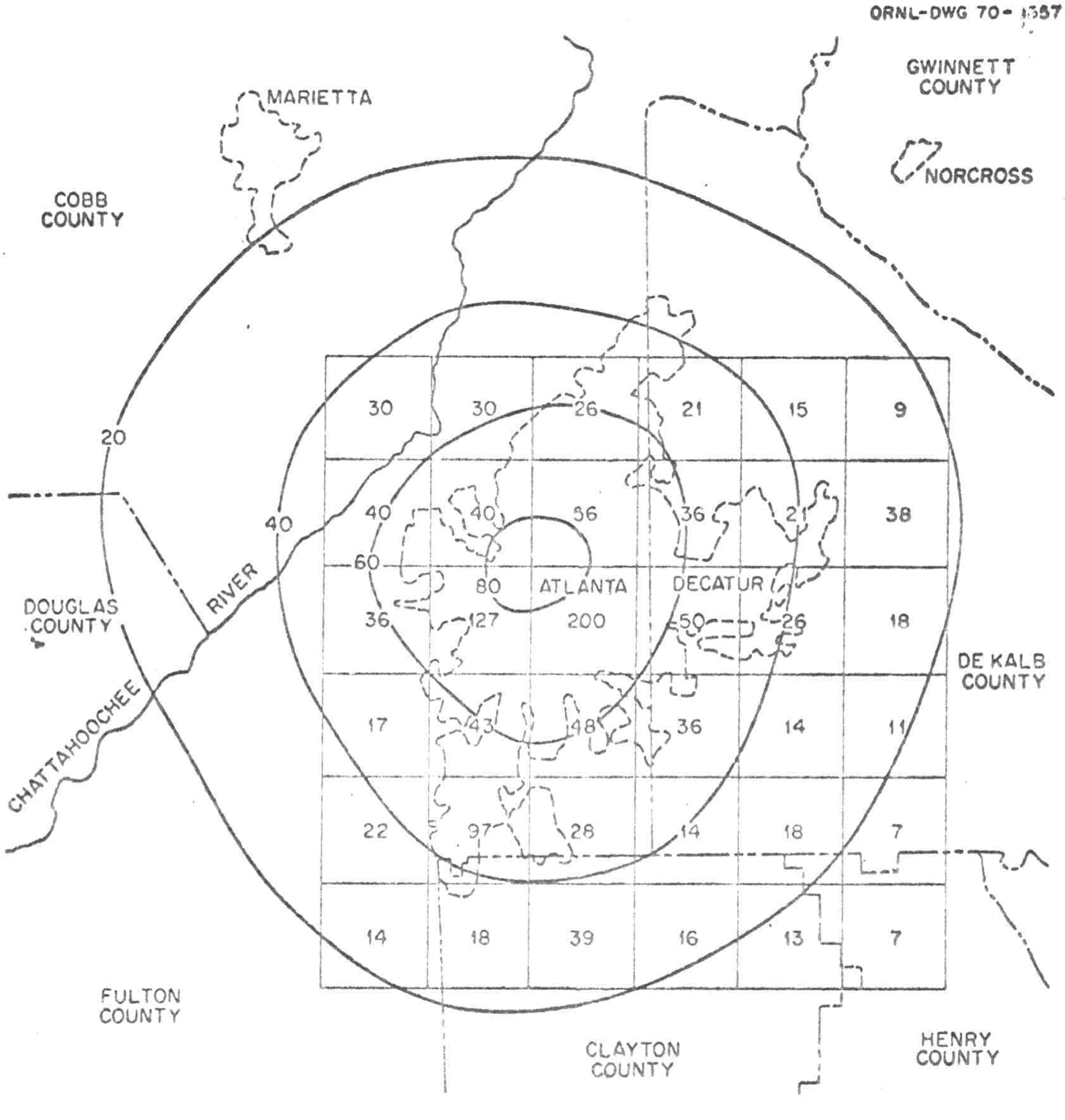

Figure 5. Calculated wintertime ground level particulate concentrations, mg/m^3, based on equation 10, for Atlanta (numbers in squares). Isopleths are the calculated values, mg/m^3, presented in reference 17.

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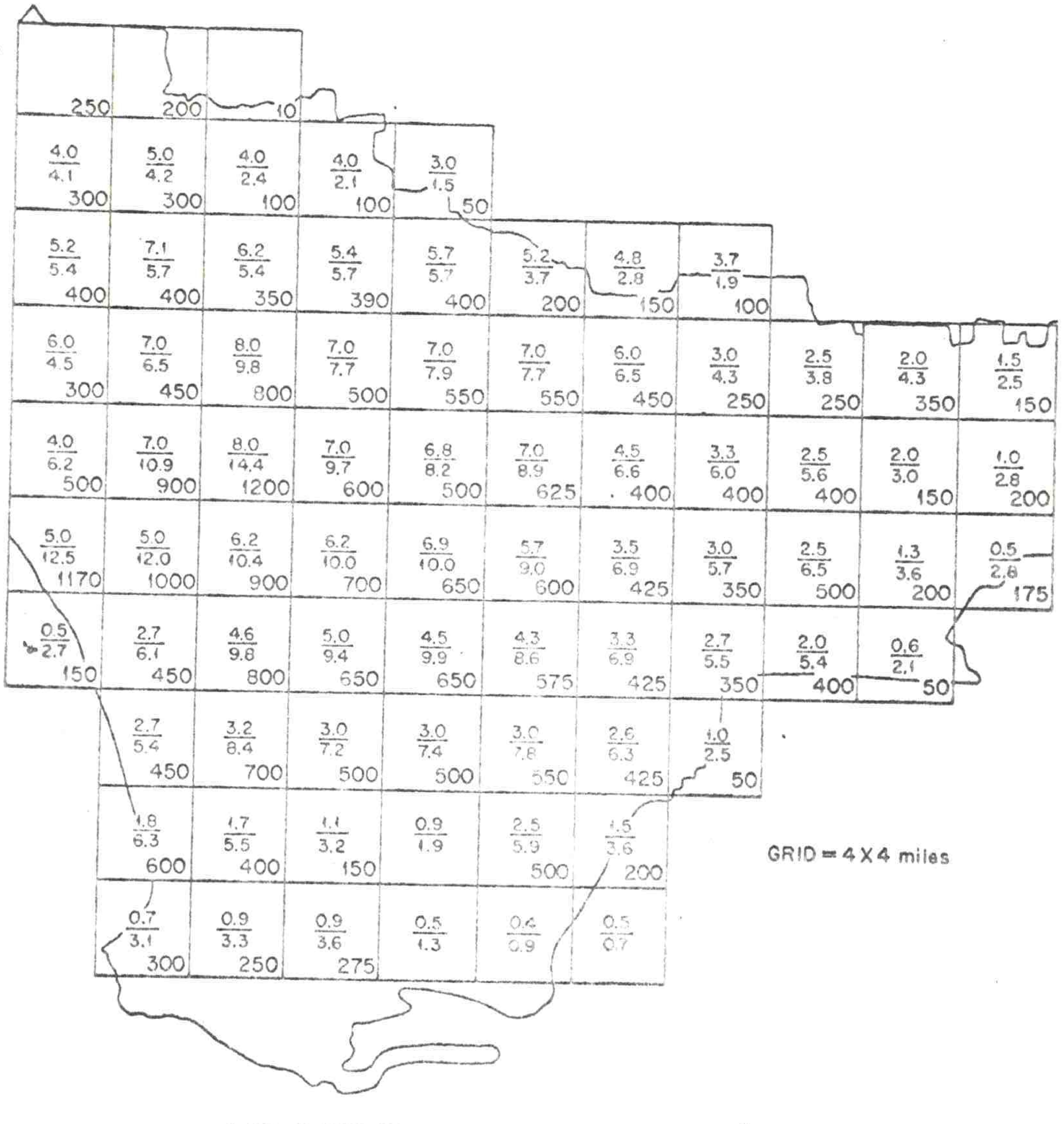
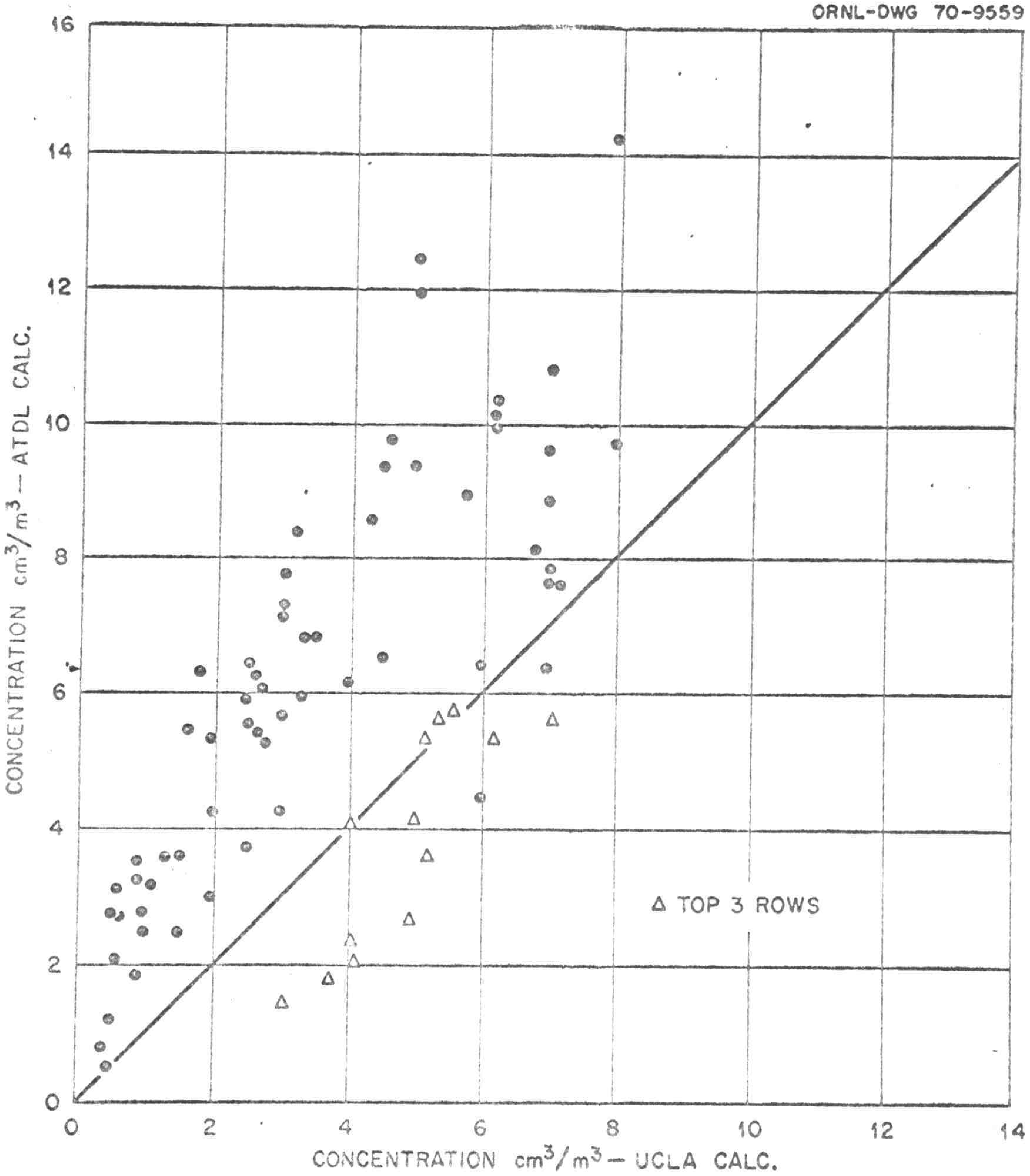


LOS ANGELES RESIDENTIAL NATURAL GAS.

Figure 6. Ground level concentrations of natural gas in Los Angeles, cc/m^3, as calculated using Lamb's model (numbers above the line) and equation (10) (numbers below the line). Source data, 10^3 ft^3/day mi^2, are indicated at the bottom of each square.



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