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AIR POLLUTION DISPERSION MODELS AS USED IN POLAND IN REGIONAL DEVELOPMENT PLANNNING

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Preface

This report is one of a series describing a multidisciplinary multinational IIASA research study on the Management of Energy/Environment Systems. The primary objective of the research is the development of quantitative tools for regional energy and environment policy design and analysis--or, in a broader sense, the development of a coherent, realistic approach to energy/environment management. Particular attention is being devoted to the design and use of these tools at the regional level. The outputs of this research program include concepts, applied methodologies, and case studies. During 1975, case studies were emphasized; they focused on three greatly differing regions, namely, the German Democratic Republic, the Rhone-Alpes region in southern France, and the state of Wisconsin in the U.S.A. The IIASA research was conducted withing a network of collaborating institutions composed of the Institute fuer Energetik, Leipzig; the Institute Economique et Juridique de l'Energie, Grenoble; and the University of Wisconsin-Madison.

Other publications on the management of energy/environment systems are listed in the Appendix at the end of this report.

W.K. Foell
January, 1977

ABSTRACT

This paper discusses air pollution models as used in regional development planning in Poland. After outlining the institutional structure and legislature dealing with air pollution control, the paper describes the air quality standards currently in effect. Dispersion models used in predicting air pollution concentrations are then detailed. Finally the application of air pollution modelling to urban design is discussed.

INSTITUTIONAL STRUCTURE FOR AIR POLLUTION CONTROL

Estimation of concentrations of air pollution is one element of environmental policy in Poland. Particularly, any new source of emission cannot be built without a forecast of ambient concentrations of air pollution. First of all this concerns the coal-based power plants which are main sources of air pollution in Poland.

With respect to the institutional structure for environmental management in Poland, this is centralized as in most socialist countries. The Council of Ministers has responsibility for policy making, planning and management of all pollution control activities. Two supporting institutions are the Ministry of Health and Social Care and the Ministry for Administration, Communal Economy and Environmental Protection. The Ministry of Health and Social Care defines the tasks of setting ambient standard values and proposes these standards in cooperation with the State Institute of Hygiene. It also has responsibility for developing a nation-wide pollution monitoring system which is realized by the State Sanitary Inspection. The Ministry for Administration, Communal Economy and Environmental Protection is responsible for implementation standards, and for coordination of all agencies at the voivodships' level. The agencies are responsible for pollution control in the region, for fixing thresholds of emission for individual plants in cases where standards can not be met because of great density of industry in the region, and for executing penalties when emissions from a particular plant exceed the permissible amount.

LEGISLATURE DEALING WITH AIR POLLUTION CONTROL

The first Polish law concerning protection of the atmosphere against pollution was established by the Seym (the Polish parliament) in 1966 (9). The aim of this act was to reduce the high level of pollution through setting up air quality standards which - as a rule - should not be exceeded on Poland's territory. The act points out that to avoid high concentrations of pollution the decrease of emission as well as the approprite planning of new investment locations are necessary. Since 1966, the maximum permissible ambient concentrations for different pollutants have been successively set up, covering at present 185 chemical substances (6,8,10). The standards for particularly protected regions (e.g. hospitals, health resorts, national parks, nature reservations) are much more rigorous than for protected areas, i.e. the rest of the territory. A separate act provides punitive measures for disciplining plants exceeding permitted levels of emissions (7); this concerns however, only particulate matter emission. Emission levels for individual plants are set up by regional agencies for environmental protection in cooperation with sanitary inspection in the region. Punitive fines are proportional to the volume of emission above the permitted level and vary from approximately $US2 - 4 when permitted emissions (in kilograms per hour) are exceeded by 50 to 100 per cent*. Penalty increases threefold when permitted emission is chronically violated. Additionally, a plant's manager can also be punished up to $200. Fines are subtracted from the factory's final product value and thus have an influence on salaries of the personnel and decrease the social budget of a given plant. As a result, a stress from employees on managers and on local authorities exists for installing anti-pollution devices. This feedback usually leads to improvement of air quality in the region. However, legislators foresee occasions when social or other economic concerns may have higher priority than pollution control.

Penalties from factories and plants are included in the regional administration income, but are not necessarily used for improving environmental quality. This is a matter of central planning at the level of ministries.

AIR QUALITY STANDARDS

Air quality standards in Poland refer to concentrations of gas pollutants and particulate matter of diameter less than 20 μm with averaging time of 20 minutes (D_{20}), 24 hours (D_{24}) and 1 year (D_a) - Table 1. Also, dust fallout cannot exceed the value of 250 tons per square kilometer in protected regions and 40 tons per square kilometer in particularly protected regions (6).

Table 1: Highest Concentrations of Selected Pollutants Currently Permitted in Poland

Pollutant	Concentrations mg/m^3					
	Protected Regions			Particularly Protected Regions		
	D_{20}	D_{24}	D_a	D_{20}	D_{24}	D_a
SO_2	0.9	0.35	0.097	0.25	0.075	0.018
H_2SO_4	0.3	0.10	0.025	0.15	0.050	0.012
N_2O_5	0.6	0.20	0.050	0.15	0.050	0.012
Particles Ø < 20μm	0.6	0.20	0.050	0.20	0.075	0.020

According to the interpretation of the above standards by the Ministry of Health and Social Care, the D_{24} values should not be exceeded more than 5% of the time during the whole year, and the D_{20} value more than 0.5% of the time during the year (3).

New regulations are expected to be issued by the end of 1976 with more rigorous restrictions (see following sections).

* The official rate of $1 ≃ 20 zlotys (Polish currency) is used here.

DECISION MAKING IN NEW INVESTMENT LOCATION PLANNING

Generally speaking, the problem of air pollution depends on technology and appropriate locations of industrial plants. The scheme of decision making in planning locations of a new source of pollution is shown in Figure 1. The starting point is the question of whether any increase of pollution is permissible in the region under consideration (1). The answer comes from the comparison of air quality standards (2) and background concentration of pollution (3) in the region. The next step is the prediction of pollution caused by a new source (4); this may be done using mathematical models of pollution dispersion (5). Dispersion models need information on emissions and emitters (6), on technology process and type of pollutants (7), and on meteorological (8) and topographical (9) conditions of the region. Comparing the permissible increase of pollution with the predicted increase of pollution from a new source -- the decision makers can say whether the proposed plant site is reasonable.

Since meteorological conditions and topography of the region remain constant, the change in spatial pattern of concentration of pollution caused by a new investment can be only obtained through change of emission and emitter parameters, through a change of fuel technology and by installing better anti-pollution devices, or through a shift of proposed location of industrial plant. Thus the procedure of predicting the increase of pollution is repeated until a reasonable solution is obtained within the above mentioned constraints.

DISPERSION MODELS

Dispersion models being used in predicting air pollution concentrations in surroundings of emission sources are unified in the scale of the whole country [11]. Up to now, Sutton's equation is obligatory for point sources of emission, with diffusion coefficients C_y, C_z, and meteorological factor n expressed simply as a function of a surface wind speed. Holland's formula is in use to estimate an effective height of emission.

By the end of 1976 new regulations are expected with formulae for point, linear and area sources of emission [4]. Let us concentrate on these regulations. The most typcial case of the spread of gas pollutants from a point source will be considered (Figure 2). The concentreation S of a gas at x, y, z from a continuous source is given be a Pasquill equation in modified form:

$$S_{xyz} = \frac{E}{2\pi\bar{u}\sigma_y\sigma_z} \exp -\left(\frac{y^2}{2\sigma^2}\right)\left\{\exp\left[-\frac{(z-H)^2}{2\sigma^2}\right] + p_3 \exp\left[-\frac{(z+H)^2}{2\sigma^2}\right]p_2\right\} p_1$$

where E - emission rate, $\bar{u}$ - mean wind speed affecting the plume, σ_y, σ_z - horizontal and vertical standard deviations of plume concentration distribution of a Gaussian shape, $H = h + \Delta h$ is the emission effective height, and is the sum of a geometrical stack height, h, and the plume thermal and dynamic rise Δh.

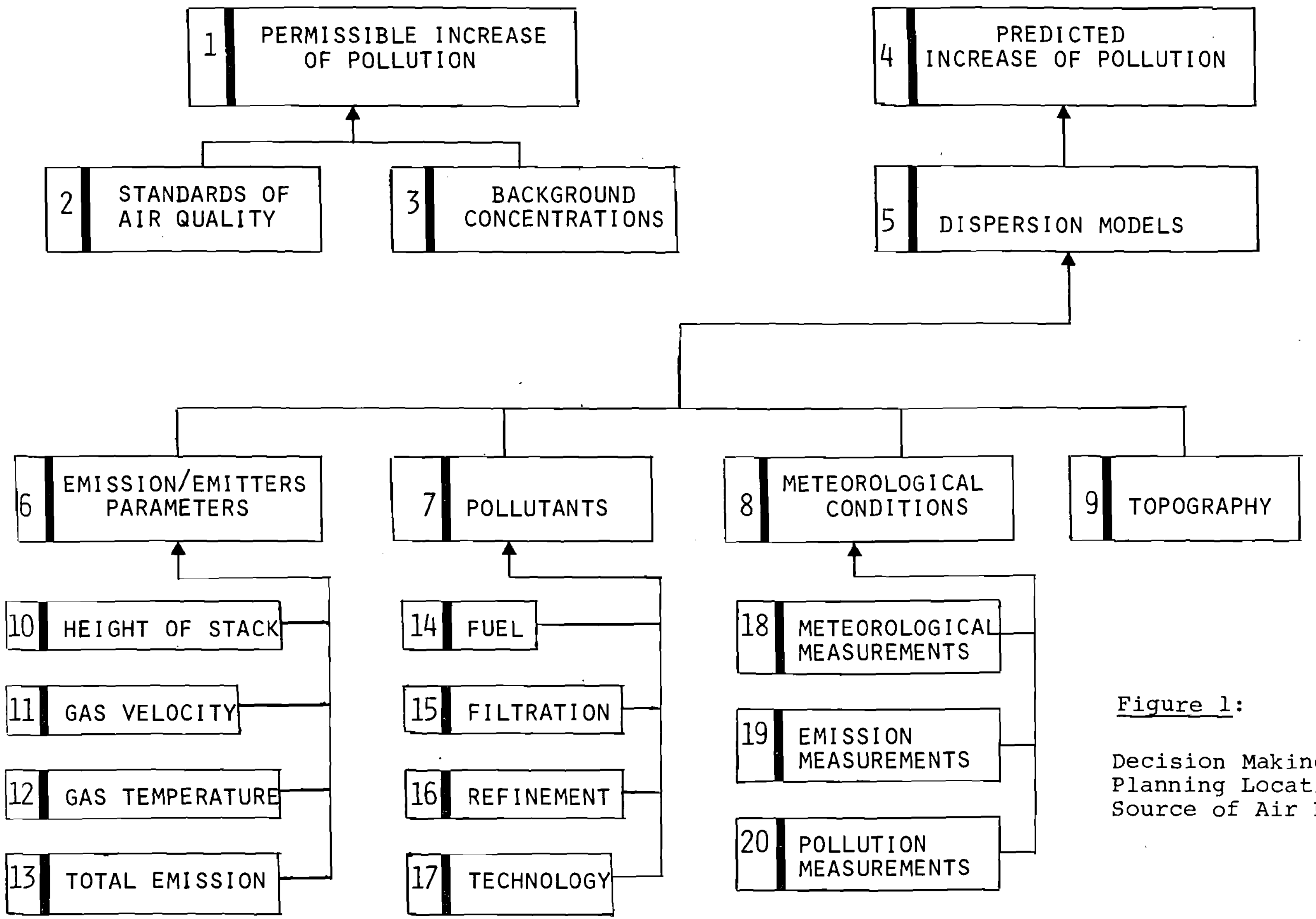
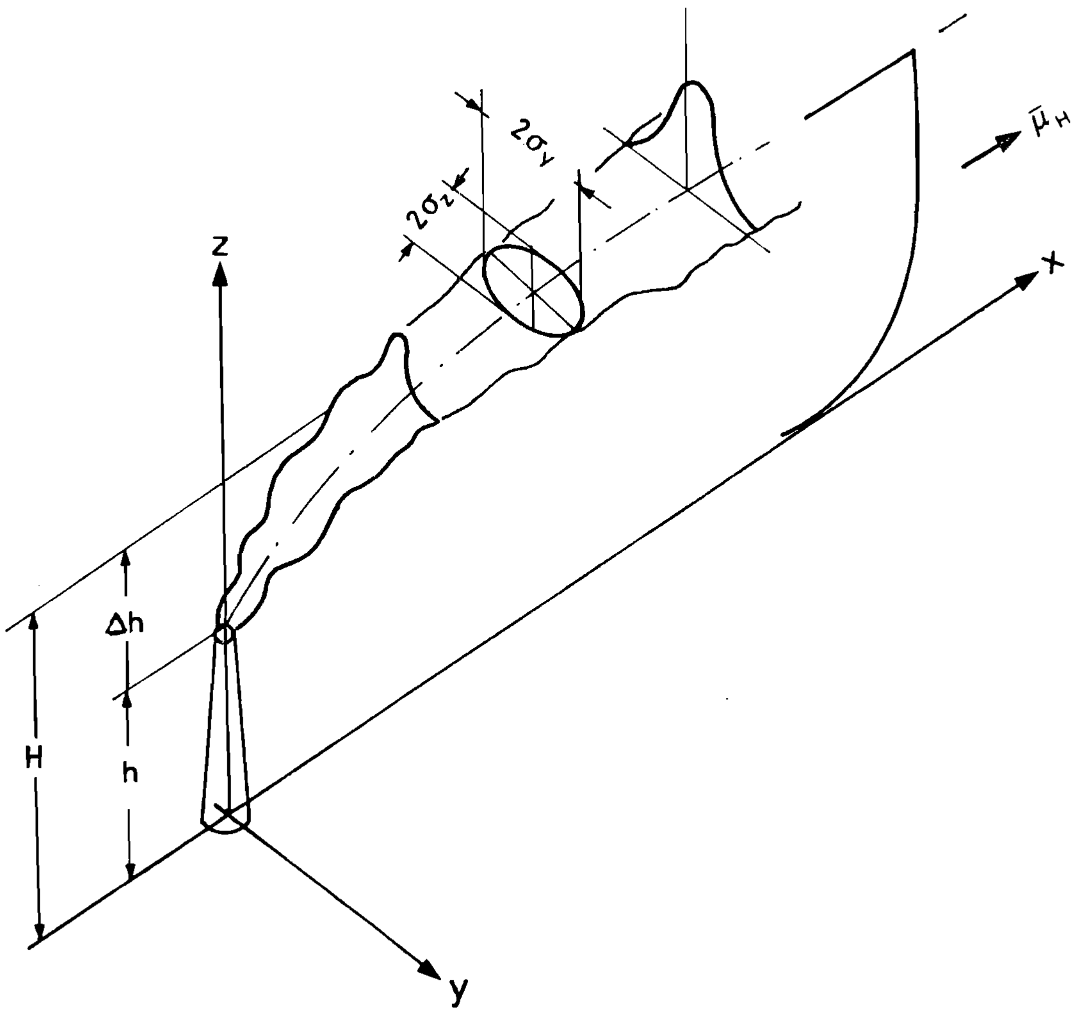


Figure 1:

Decision Making Process in Planning Locations of a New Source of Air Pollution



<u>Figure 2</u>: Coordinate System Showing Gaussian Distribution of a Plume in Horizontal and Vertical Planes

The modification of the above equation refers to the functions p_1, p_2, p_3. The function p_1 describes the transformation of pollution in the atmosphere, such as an oxidation of SO_2, photochemical conversion of SO_2 into H_2SO_4, etc. The above mentioned reactions take place at different rates and in the presence of secondary factors, such as washing-out of SO_2 by precipitation, or dillution of SO_2 in water. A simple proportional mechanism of transformation has been assumed

$$\frac{\partial S}{\partial \tau} = -k \cdot S$$

Given this assumption, function p_1 may be expressed in form

$$p_1 = \exp\left(-\frac{0.693\tau}{\tau_{\frac{1}{2}}}\right)$$

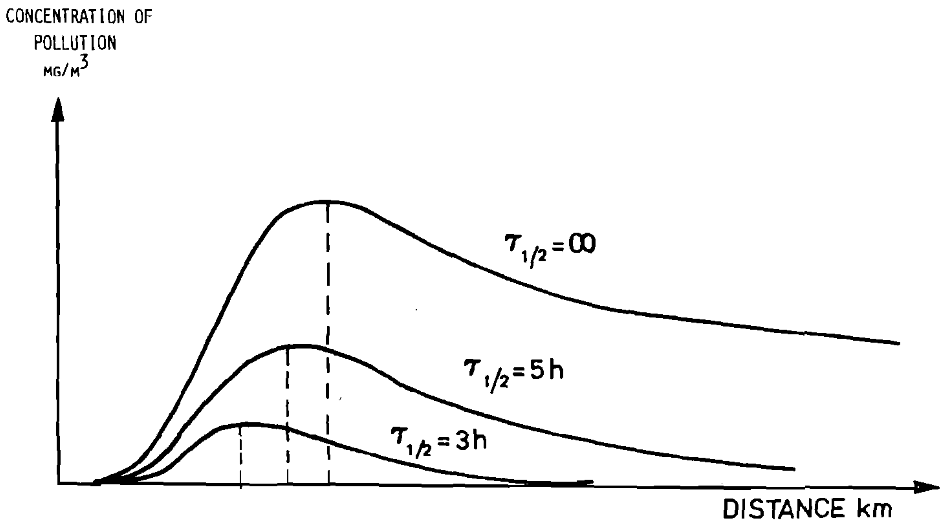
where $\tau \simeq x\sqrt{\bar{u}}$ is a residence time of pollution in the atmosphere, $\tau_{\frac{1}{2}}$ is a half-life transformation of pollutant, i.e. time after which the concentration of pollution decreases by half (Figure 3). In the case of SO_2 the values of $\tau_{\frac{1}{2}}$, given in Table 2, have been estimated.

Region	$\tau_{\frac{1}{2}}$
Highly polluted (urban/industrial)	2-3 hours
Less polluted (suburban)	5 hours
Non-polluted (rural	8-10 hours

Table 2: Half-Life Transformation of SO_2

Function p_2 refers to the reflection of pollution at the inversion layer (Figure 4). The value of p_2 depends on the sign of (z - H); thus

$$p_2 = \begin{cases} 0 & \text{if } Z<H \\ \exp\left[-\frac{(z-H+2Z)^2}{2\sigma_z^2}\right] + p_3 \cdot \exp\left[-\frac{(z+H+2Z)^2}{2\sigma_z^2}\right] + \\ + \exp\left[-\frac{(z-H-2Z)^2}{2\sigma_z^2}\right] + p_3 \cdot \exp\left[-\frac{(z+H-2Z)^2}{2\sigma_z^2}\right] & \text{if } Z>H \end{cases}$$



$$\frac{\partial S}{\partial \tau} = -K \cdot S$$

$$P_1 = \mathrm{EXP} - \frac{0.693\tau}{\tau_{1/2}}$$

$\tau \cong x\sqrt{\bar{u}}$ – A RESIDENCE TIME OF POLLUTION IN THE ATMOSPHERE

$\tau_{1/2}$ – A HALF-LIFE TRANSFORMATION OF POLLUTANT

AREA	$\tau_{1/2}$
HIGHLY POLLUTED (URBAN, INDUSTRIAL)	2-3 HOURS
LESS-POLLUTED (SUBURBAN)	5 HOURS
NON-POLLUTED (RURAL)	8-10 HOURS

<u>Figure 3</u>: Decrease of Pollution Concentration Due to Transformation in the Atmosphere

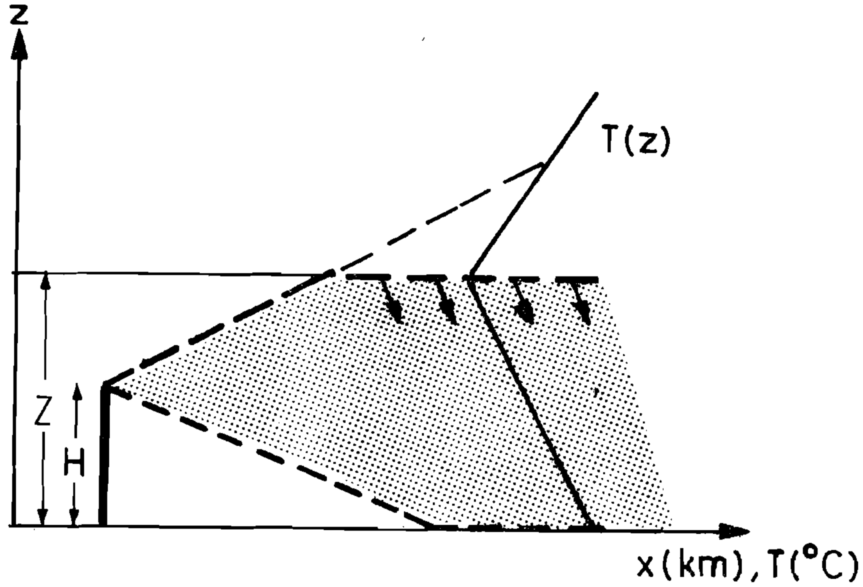


Figure 4: Simplified Model of Influence of Temperature Inversion on Concentration of Pollution

The function p_3 describes the reflection of pollutants at the earth's surface. The value of the function varies from +1 (total reflection at the earth's surface) to -1 (total absorption by the surface). So far no detailed information on the values of p_3 is available in case of partial absorption of a gas, so that usually $p_3 = 1$ is assumed in the model. For particulate matter the value $p_3 = 1$ is recommended if surface wind speed $u_o \leq 7$ m/s and $p_3 = u_o/7$ if $u_o > 7$ m/s.

The values $p_1 = 1$, $p_2 = 0$, $p_3 = 1$ mean that neither transformation of pollution nor reflection at the inversion nor absorption at the earth's surface are considered and then Pasquill's equation takes its primary form.

The model has been verified with results differing from measured concentrations on the average by 15% within the area of the highest pollution, and on the average by 50% at greater distances from the source of emission. At the same time the predicted direction of the highest concentrations did not coincide exactly with the direction of the measured maximum concentrations. A turn to the left varying from 10^o to 40^o was observed which probably results from the action of a wind shear at above-surface altitudes while only surface wind data were introduced into the model.

CRITERIA FOR SITING A NEW POLLUTION SOURCE

As was mentioned previously, air quality standards in Poland refer to concentrations of pollution with averaging time of 20 minutes (D_{20}), 24 hours (D_{24}), and 1 year (D_a). Thus if corresponding predicted (calculated from the model) values are S_{20}, S_{24}, S_a, then the following criteria for siting a new pollution source should be fulfilled.

(a) Predicted mean annual value, including background concentration, cannot exceed 80% of the standard concentration of a given pollutant, i.e.

$$S_a \leq 0.8\ D_a$$

(b) D_{24} standard value is not to be exceeded on more than eight days, that is 2.2% of time during the year, i.e.

$$100.0\% - F(D_{24}) \leq 2.2\%$$

where $F(X) = P(Z \leq x)$ is the D_{24} concentration probability cumulative distribution;

(c) D_{20} standard value is not to be exceeded on more than 12 hours during the whole year, i.e.

$$100.0\% - F(D_{20}) \leq 0.14\%$$

(d) If more than one gas is emitted into the atmosphere then an additional index must be evaluated, namely the annual dose of pollution. The dose of pollution is a conventional measure of environmental impact defined as:

$$d_p = \sum_{i=1}^{n} S_i \cdot k_i$$

where n is the number of pollutants emitted into the atmosphere, S_i is the concentrations of individual pollutants, and k_i is the toxic coefficient for any individual pollutant. The toxic coefficient is related to the toxicity of SO_2 in the following way:

$$k_i = \frac{\text{standard annual mean value of } SO_2 \text{ concentration}}{\text{standard annual mean value of a given pollutant}}$$

Toxic coefficients for different pollutants are given in Table 3. The computed annual dose of pollution cannot exceed the standard mean annual SO_2 concentration by more than 50 percent, i.e.

$$d_p \leq 1.5D_{aSO_2}$$

Pollutant		k_i
Sulphur dioxide	SO_2	1.0
Sulphuric acid	H_2SO_4	3.9
Nitrogen oxides	N_2O_5	1.9
Carbon monoxide	CO	0.4
Chlorine	Cl	13.9
Fluorine	F_2	48.5
Sulphuretted hydrogen	H_2S_2	19.4

Table 3: Toxic Coefficients for Selected Pollutants

The final results obtained from the model are presented in form of maps with isolines of:

- mean annual concentrations of pollution (Figure 5);
- frequencies of exceeding D_{20} and D_{24} standard values (Fig. 6);
- annual dose of pollution.

The calculations should cover the area within the radius of

$$r = 107h^{1.43}$$

where h is the geometrical height of a stack in meters.

It is worthwhile to mention that effective height of emission in the above model is estimated from Holland's formula for stack height, $h \leq 30$ meters, and from Concave's formula for stack height, $h > 30$ meters. Diffusion coefficients are defined as

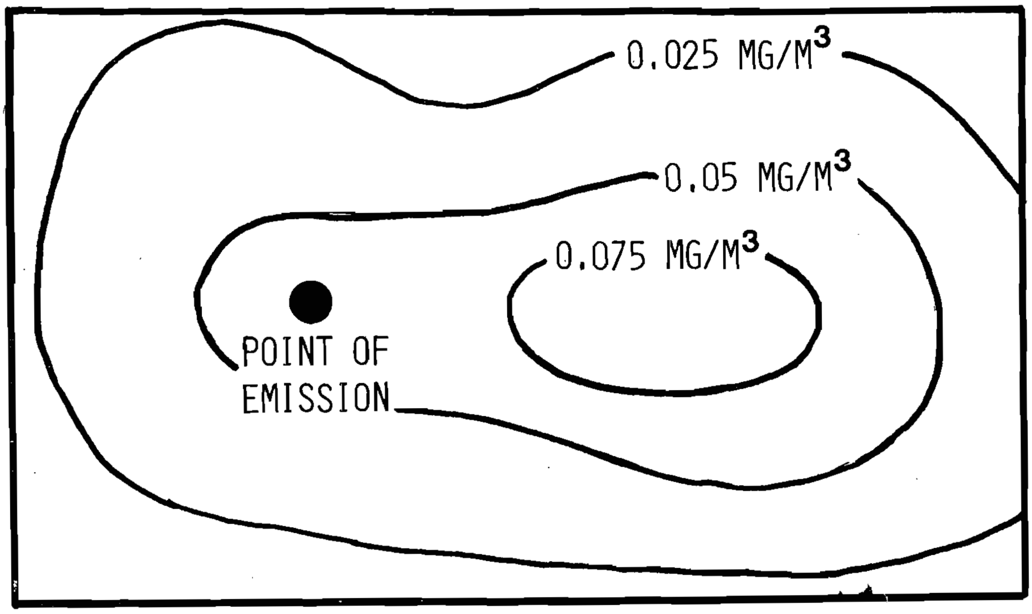


Figure 5: Spatial Distribution of Predicted S_{aSO_2} Concentrations: $D_{aSO_2} = 0.097\ mg/m^3$.

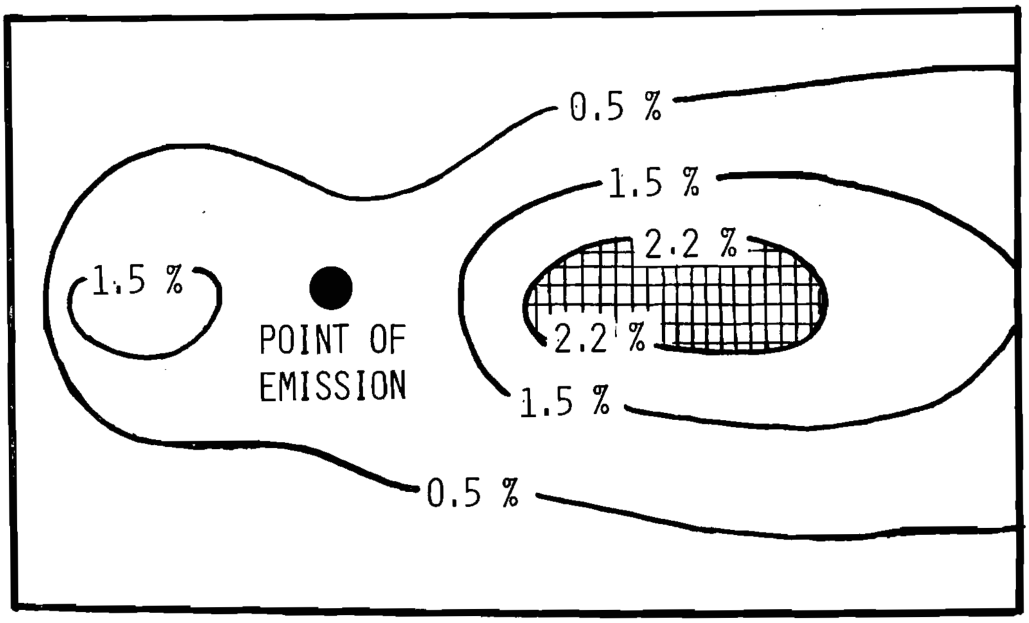


Figure 6: Spatial Distribution of the $P(S_{24SO_2} > D_{24SO_2})$ Probabilities; $p(D_{24SO_2}) \leq 2.2\%$.

$$\sigma_y = A \cdot x^a$$

$$\sigma_z = B \cdot x^b$$

where x is a downwind distance from the source of emission, and A, B, a, b are coefficients defined empirically by Nowicki [5] as the functions of roughness parameter z_o, height above ground level z, and meteorological factor m dependent on stability class of the atmosphere. The factor m has the same meaning as a power in a wind profile power formula.

The formulas for calculating air pollution concentrations caused by linear and area sources of emission are found in [4].

APPLICATION OF AIR POLLUTION MODELLING TO URBAN DESIGN

Let us present an example of using air pollution models for comparing theoretical urban designs from the point of view of air pollution protection from industrial plants sited within the towns. The comparison deals with the concepts of concentric town models, linear models, and satellite ones (Figure 7). The following assumptions have been taken under consideration [2]:

(a) The number of inhabitants in a newly designed town does not exceed 200,000;

(b) Population density is approximately 10,000 persons/km^2. According to this assumption, the area of each town is equal to 20 km^2;

(c) The area of the town has been covered by a grid with 20 grid points, each representing the area of 1 km^2;

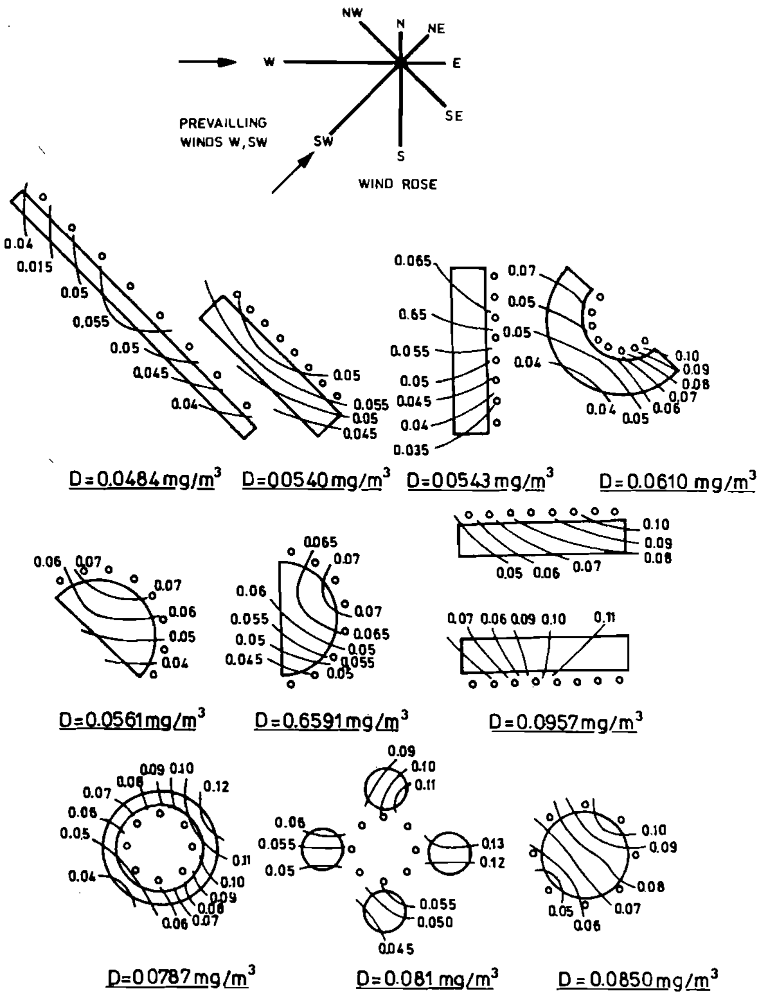
(d) The pollution dose has been evaluated at these points, and then the value was averaged over the whole area;

(e) Within the town there exist eight large industrial plants emitting various pollutants into the atmosphere; the emmission rate for every source, related to SO_2, is 1000 g/s. The emission height is 100m, gas output velocity at the temperature 400°K is 25m/s;

(f) Industrial plants are sited at the same distance 500 meters from inhabited suburbs;

(g) Meteorological conditions are unified for each urban area with prevailing winds from SW and W.

Pollution doses averaged over the town areas are shown in Table 4. One can see from the data that the most comfortable conditions exist in towns of linear shape, perpendicular to the prevailing winds. This is the argument against the concepts of the concentric urban models which were strongly advocated in the past. However, all advantages resulting from the linear models can be negated by inappropriate location of industrial plants. This may



DISTRIBUTION OF DOSE OF POLLUTION AT DIFFERENT THEORETICAL TOWN MODELS

Figure 7: Distribution of Pollution Dose At Different Theoretical Urban Models

URBAN MODEL	AVERAGED DOSE OF POLLUTION MG/M^3
LINEAR 20x1 KM 	0.0484
LINEAR 10x2 KM 	0.0540
LINEAR 10x2 KM 	0.0543
SEMICIRCULAR 	0.0561
SEMICIRCULAR 	0.0591
HORSESHOE 	0.0610
LINEAR 10x2 KM 	0.0708
ANNULAR 	0.0787
SATELLITE 	0.0810
CONCENTRIC 	0.0850
LINEAR 10x2 KM 	0.0957

Table 4: Comparison of Theoretical Models in Aspects of Air Protection Against Pollution

be seen when comparing the linear models with industrial plants located along the N- or the S-edge of the city. This last case is the worst among all the urban models, including the concentric ones.

The three concentric urban models subject to examination seem to be of equal rank. Particularly uncomfortable conditions exist in the satellite model where pollution dose varies from 0.05 mg/m^3 (S suburb) to 0.13 mg/m^3 (E suburb).

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APPENDIX

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