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GIS Application for Nitrogen Dioxide Pollution Monitoring in Moscow, Russia

Maria V. Privalsky
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GIS APPLICATION FOR NITROGEN DIOXIDE POLLUTION MONITORING IN MOSCOW, RUSSIA

by

Maria V. Privalsky

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Arts
Department of Geography

Western Michigan University
Kalamazoo, Michigan
August 1994
ACKNOWLEDGMENTS

This project could not have been fulfilled without the help of many people, and I would like to acknowledge my gratitude.

First, I would like to thank Professor Mary Dillworth, the head of my Master’s committee, for sharing with me her experience in Geographic Information Systems and for her extreme patience.

Second, I want to thank Professor Joseph Stoltman, who took great care of me during my stay in Kalamazoo and while attending Western Michigan University. His help in preparation of this project was enormous.

Third, special thanks go to Professor Michael Stoline from the Department of Mathematics and Statistics, who took the trouble of looking into what GIS was about and helped me in the statistical analysis of my data.

And I am also indebted to Professor David Dickason for the many valuable hints and advice he gave me during my work on this project.

Maria V. Privalsky
GIS APPLICATION FOR NITROGEN DIOXIDE POLLUTION MONITORING IN MOSCOW, RUSSIA

Maria V. Privalsky, M.A.
Western Michigan University, 1994

The focus of this study was nitrogen dioxide pollution monitoring in Moscow, Russia. ERDAS GIS was used to create maps of nitrogen dioxide distribution on the territory of the city for the years from 1983 to 1991.

A special model was written to compare the consecutive pairs of years in respect to the nitrogen dioxide pollution change. Results of model application were analyzed in order to determine the territories that experienced maximum changes during the study period.

Relationship between street density as a measure of car flow and nitrogen dioxide pollution was estimated. Two measures of the relationship were used: (1) correlation coefficient (Pearson’s r); and (2) chi-square statistic. The results showed that there was a positive relationship between street density and nitrogen dioxide pollution.
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CHAPTER I

INTRODUCTION

Environmental problems are now the most acute issues in the domestic policy of Russia. Years of complete negligence of the environment brought the country to the brink of an ecological catastrophe. Thus, the necessity for truthful information on the conditions of the environment is especially great.

There were no summarized data on the environmental hazards before 1987. The first ever report on environmental conditions in the USSR was issued by Goskompriroda (the State Committee on the Environment) in 1989. The Law on Environmental Protection, adopted in December 1991, now provides publishing of an annual report on the environment in the country.

While there are several organizations that participate in the above publication, there is little interaction between them. One of the causes of this problem is the absence of any common data format which could allow for data sharing. Computers are not very common in governmental organizations yet; maps and tables are stored on paper. This creates huge problems for data usage and update. The budget for an ecological information system
in Russia in 1991 was only 0.8% of the total budget of the Russian Ecological Fund, which was not sufficient for necessary equipment and personnel training (State Report, 1992).

In many countries geographic information systems (GIS) are adopted as a tool for environmental control and data processing. The purpose of this project is to apply some of the existing GIS techniques to the environmental problems of Moscow, Russia, in particular, to nitrogen dioxide (NO$_2$) pollution.

Nitrogen dioxide is a reddish-brown-orange gas with a characteristic strong odor. It is corrosive and highly oxidizing, and may be physiologically irritating and even toxic in large concentrations (NATO, 1973). It is a major factor in the formation of photochemical smog and of tropospheric and stratospheric ozone (Bridgman, 1990).

The objectives of this project are: (a) to create a geo-referenced database on NO$_2$ concentration in Moscow for the period from 1983 to 1991; (b) to estimate the differences in NO$_2$ increase over the years in the areas of the city with different street densities; and (c) to determine if there is a relationship between NO$_2$ concentration and the street density.
CHAPTER II

LITERATURE REVIEW

Air Pollution Measurement and Monitoring

The problem of NO\textsubscript{2} air pollution has been studied for many years by various organizations in the world. One of the most thorough analyses has been performed by the NATO Committee on the Challenges of the Modern Society (NATO, 1973). The results are updated every year, and reports are published in special issues. Similar reports are prepared for such pollutants as carbon monoxide, sulfur dioxide, nitrogen oxides, etc.

Fuel combustion is considered the main source of emissions of nitrogen oxides (NO\textsubscript{x}). Depending on the transportation network and the number of vehicles, transportation accounts for up to 55 percent of the NO\textsubscript{x} pollution (NATO, 1973; Thom, 1976; State Report, 1992).

Few countries have a better organized pollution monitoring network than the United States. The network is operated under the United States Environmental Protection Agency and estimates the air quality based on such major pollutants as sulfur dioxide, carbon monoxide, various nitrogen oxides, and ozone.
The average maximum level of 0.1 mg/m$^3$ was established as a primary standard of NO$_2$ concentration in the United States in 1975 by the Clean Air Act (U.S. EPA, 1992). NO$_2$ is measured on the annual basis, and reports of its concentration and distribution are published by various organizations.

In general, NO$_x$ pollution levels have decreased in the United States by 190% since 1940, but only by 9% since 1970 (Bridgman, 1990). This change was due mostly to pollution control measures and technological improvements limiting emission. Still, in some cities NO$_2$ levels remain rather high. Table 1 lists the five U.S. cities with the highest NO$_2$ concentration in 1984.

Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>NO$_2$ Levels (mg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles - Long Beach, CA</td>
<td>0.1189</td>
</tr>
<tr>
<td>Denver - Boulder, CO</td>
<td>0.0984</td>
</tr>
<tr>
<td>Anaheim Area, CA</td>
<td>0.0923</td>
</tr>
<tr>
<td>Chicago, IL</td>
<td>0.0902</td>
</tr>
<tr>
<td>Boston, MA</td>
<td>0.0902</td>
</tr>
</tbody>
</table>

Usually, nitrogen dioxide is included in the overall pollution measurements, and every monitoring organization
determines its own air quality categories. Table 2 below lists several examples of such classifications (Thom, 1976).

Comparative results for nitrogen dioxide pollution in European cities show that the average concentration is 0.082 mg/m\(^3\), with higher amounts in southern European cities, such as Milan, Rome, and Athens. For China annual average NO\(_2\) ranges from 0.08 to 0.175 in northern cities and from 0.02 to 0.131 in southern cities. In Canada, the annual average NO\(_2\) was 0.049 in late 1970s (Bridgman, 1990).

The recommended level of average concentration of NO\(_2\) in Russia is 0.04 mg/m\(^3\) (Goskomgidromet, 1990). Since no quality standards exist for car fuel in the country, NO\(_2\) pollution is very high in the cities with large numbers of car owners. Moscow, with its population of approximately 15 million, is the third most polluted city in the country after Norilsk and Krivoy Rog (Goskomgidromet, 1990). The average concentration of NO\(_2\) in Russia in 1989 was 0.041 mg/m\(^3\), and in 38% of the cities the concentration exceeded this value. There was a steady increase in pollution since 1988, especially in the cities with populations over 2 million (Goskomgidromet, 1990).

Since high concentrations of NO\(_2\) can be harmful to human health and environment, it is necessary to monitor
### Table 2

Examples of Air Pollution Classification in the USA
(Thom, 1976)

<table>
<thead>
<tr>
<th>Organization</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bay Area Pollution Control District, California</td>
<td>Clean Air</td>
</tr>
<tr>
<td></td>
<td>Light Pollution</td>
</tr>
<tr>
<td></td>
<td>Significant Pollution</td>
</tr>
<tr>
<td></td>
<td>Heavy Pollution</td>
</tr>
<tr>
<td></td>
<td>Severe Pollution</td>
</tr>
<tr>
<td></td>
<td>Emergency</td>
</tr>
<tr>
<td>Department of Environmental Protection</td>
<td>Good</td>
</tr>
<tr>
<td>Air Compliance Section, Hartford, Connecticut</td>
<td>Satisfactory</td>
</tr>
<tr>
<td></td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td></td>
<td>Unhealthy</td>
</tr>
<tr>
<td></td>
<td>Harmful</td>
</tr>
<tr>
<td>Air Pollution Control District</td>
<td>Good</td>
</tr>
<tr>
<td>Jefferson County, Kentucky</td>
<td>Acceptable</td>
</tr>
<tr>
<td></td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td></td>
<td>Unhealthy</td>
</tr>
<tr>
<td>New York State Department of Environmental</td>
<td>Low Pollution</td>
</tr>
<tr>
<td>Conservation</td>
<td>Medium Pollution</td>
</tr>
<tr>
<td></td>
<td>High Pollution</td>
</tr>
</tbody>
</table>

emissions in order to determine main sources of NO₂ pollution. Most of the countries have vast programs in air pollution control, though classifications of air quality
are different not only for different countries, but also within one country, as the example of the United States shows.

Methods of Air Pollution Monitoring in the USA

Many countries have been using Geographic Information Systems for such purposes as environmental control, land use mapping, etc. Their experiences can be used by Russian scientists in developing GIS for specific conditions in the country.

For example, GIS are widely incorporated in the work of the Environmental Protection Agency in the USA. GIS are used to identify and assess environmental problems and trends. Steps have been made in the direction of integrating GIS in the work of the agency as a tool for management decisions related to environmental policies and programs (U.S.EPA, 1989).

One example of GIS application is the Air Program carried out in some EPA regions. Examples of how GIS is being used in EPA activity in air quality monitoring are the following: (a) comparing air quality data with the monitoring network to determine if the network is adequate; (b) comparing predicted trends and prognoses with the monitoring results to determine the sources of pollution not in compliance in priority areas; (c) comparing
emission data in noncompliance areas to determine additional sources of pollution and to target priority areas; and, (d) analysis of ambient air quality trends including demographic data, meteorological parameters, and emission data.

Another example of GIS application in air quality assessment is a project fulfilled by the Edwards Air Force Base Flight Test Center (Douglas, et al., 1992). The goal was to determine cancer risks from airborne emissions at the base. For this purpose the Prototype Air Toxic Hot Spots (PATHS I) system was created to allow monitoring of possible emission sources, including generating and displaying an isoline map of health risks based on a specific time period, emission concentration, climate region, and occupancy level.

Implementation of GIS into air pollution monitoring in the United States allows for convenient data handling, better control over main sources of pollution, and, as a result, higher air quality.

Methods of Air Pollution Monitoring in Russia

In the process of economic changes, when the danger of further ecological decline is extremely acute, Russian state and local governments need more control over the ecological situation in the country. The more independent
from the state government the local governments become, the more they need ecological services based on their local resources.

The data should be available to health, educational, commercial and other organizations. Some commercial enterprises now try to establish ecological services, but they are not able to solve specific problems due to the absence of trained personnel and financial resources.

Nearly all ecological services in the country are provided by the state government. The network of environmental control stations of the State Atmospheric Pollution Measurement and Control Service has existed for more than 20 years now (Kalaidopulo, 1990). The network includes nearly 570 cities with a total population of more than 115 million people, and consists of approximately 1,200 monitoring stations. The program measures pollutants as dust, NO, NO₂, SO₂, CO, and more than 70 other pollutants.

Measurements for this Service are provided by several agencies: Regional Meteorological Centers of Goskomgidromet (State Committee on Hydrometeorology) (91%), Epidemiological Centers of Health Ministry (3%), and laboratories of the largest industrial complexes (6%) (State Report, 1992).

The air quality data are processed by more than 25
ministries and 20 research institutes, which prepare an annual report on the environmental conditions in the country and its regions. The main problem in compiling the report is a high level of data incompatibility in terms of format, storage methods, scale, etc. Most of the data are stored on paper, which creates certain difficulties for data analysis, such as problems with integrating the data from various sources, combining several territories, or physical damage of paper maps and tables.

Geographic Information Systems were recently introduced in Russia as a tool for environmental control. Research in this field is mostly concentrated on larger areas, such as a geographic region. A GIS for resource management, which includes air quality analysis, was designed in the Altai Laboratory for Ecology and Rational Nature Use for Altai Krai region. Another example would be "Prirodopolzovanie", a GIS developed by the Pacific Institute of Geography of the Far East sector of Russia. It is part of a program "Dalniy Vostok" started in 1981, and includes various aspects of environmental mapping and control (Koshkariov, et al., 1989).

There are several computerized systems of environmental control and analysis for smaller areas, such as a GIS "Health", which is used to determine the correlation between the pollution levels and public health in 80 ci-
ties of Russia (Goskomgidromet, 1992). A GIS for land value estimation, based on certain criteria including air quality, was designed for the city of Dnepropetrovsk in Ukraine (Portianski, 1992). The same type of GIS are now being developed in the large cities for environmental monitoring (Sokolovski, 1990). The process of development is time and labor consuming, as large amounts of data previously stored on paper must be converted to digital format.

In Moscow air quality monitoring is being done mostly by two organizations: Moscow Center of Environmental Pollution Monitoring and Control, and City Epidemiological Service. There are 23 permanent monitoring stations in Moscow that belong to the Center of Environmental Pollution Monitoring and Control, where the measurements are being done for air quality analysis. Results of the analysis are usually released as paper maps and reports, which creates problems for further updates. The same services exist in 17 other cities in the Moscow region.

The results of air quality analysis are necessary for such organizations as the Moscow Planning Institute (Mosgenplan) to plan the construction of new residential and industrial centers, and to plan the reconstruction of the existing developments. Other possible users of the results might be local (district) governments who control
land leasing and sales, and health institutions who conduct analyses of health hazards in the cities and who need to update their data constantly.

The development of a GIS for air quality estimation is one of the most interesting and urgent problems for Moscow government and research organizations. Such a system can utilize various sources of spatial and aspatial data, provide a tool for data analysis and update, and can be used in decision-making. The experience of other countries (especially the USA) in applying GIS to environmental problems can serve as the basis for developing a strategy of air quality monitoring in Russia using GIS.
CHAPTER III

DATA PROCESSING AND DISCUSSION OF THE RESULTS

Objectives

As it was stated above, this research has three major objectives. First, a geo-referenced database on NO$_2$ concentration in Moscow for the period from 1983 to 1991 will be created. Second, the differences in NO$_2$ increase over the years in the areas of the city with different street densities will be estimated. And third, the relationship between NO$_2$ concentration and street density will be examined.

GIS provides a good tool for creating a geo-referenced database which can be used for further analysis, such as applying map overlays and cross-tabulation to estimate the relationship between several phenomena. In addition, the modeling possibilities of GIS can be used to compare a number of data sets, such the NO$_2$ data for several years.

Database

Data obtained from the Moscow Center for Environmental Pollution Control were used to create maps of NO$_2$ dis-
tribution for nine years form 1983 to 1991 (see Appendix A, Table 1). Figure 1 shows the locations of the observation stations in Moscow. Out of the existing 23 stations only 17 could be used, as the data were missing for several years for the 6 other stations.

It is necessary to note that this number of stations is not sufficient for a very detailed analysis, and that the results of analysis are approximate.

ERDAS GIS was used for creation and analysis of NO$_2$ pollution maps from the data. The mapping procedures are described in the following section.

Mapping of Nitrogen Dioxide Pollution

The first step in mapping was creation of surface maps of NO$_2$ pollution for each of the nine years based on the average annual data. Flowchart 1 in Appendix B shows the steps in data input and processing.

Locations of 17 monitoring stations were digitized as single points, and average annual NO$_2$ values were assigned to the points. Resulting files were used to generate surface maps of NO$_2$ distribution between the stations.

The following algorithm was used for computation of weighting factors ($W_i$) for the pixels between the stations (ERDAS, 1991, p.23):
Figure 1. Locations of MosCERP Stations. Moscow, 1992.
where \( Q = \frac{1 - Q}{Q} \)

For interpolation of \( NO_2 \) values between stations the following algorithm was used (ERDAS, 1991, p.23):

\[
V = \frac{\sum_{i} W_i \cdot T_i}{\sum_{k=1}^{c} W_k}
\]

where \( V \) = the output data file value,
\( i \) = a point within a specified radius of the analyzed pixel,
\( W_i \) = the weighting factor of point \( i \),
\( T_i \) = topo (GIS) values of point \( i \),
\( c \) = the number of topo (GIS) values.

The range of \( NO_2 \) values in resulting surface maps for all nine years was from 0.0325 mg/m\(^3\) to 0.1450 mg/m\(^3\).

Table 2 in Appendix A illustrates the rescaling algorithm used to obtain GIS values for every pixel from the surface maps.

The resulting maps were overlaid with the map of
major streets (Figures 2 - 10). Visual analysis of the maps shows that the level of NO₂ pollution has been increasing since 1983, and in some areas reached the maximum level in 1990. Since 1983 the recommended level of concentration of 0.04 mg/m³ was exceeded on most of the city territory. From 1983 to 1986 the values never went higher than 0.07 mg/m³, but since 1987 many areas showed significant increase in concentration up to 0.1450 mg/m³.

There is no common pattern in NO₂ distribution for these years, but the central and north-east parts of Moscow showed higher levels of concentration in recent years. Two locations showed significant increases in pollution: an area in the central part, southeast from the Garden Ring (a circular streets around the center of the city), where the values increased from 0.0325 mg/m³ in 1983 to 1.1375 mg/m³ in 1990; and an area in the northwest, which experienced an increase from 0.04 mg/m³ in 1986 to 0.1075 mg/m³ in 1990.

Data obtained from these maps can be used for the further analysis, such as estimation of changes in NO₂ pollution over a period of time, or examination of relationships between NO₂ and geographic phenomena that are known to influence NO₂ distribution, such as car flow, meteorological conditions, or elevations or architectural pattern of the area.
Figure 2. Nitrogen Dioxide Pollution. Moscow, 1983.
Figure 4. Nitrogen Dioxide Pollution. Moscow, 1985.
Figure 5. Nitrogen Dioxide Pollution. Moscow, 1986.
Figure 6. Nitrogen Dioxide Pollution. Moscow, 1987.
Figure 7. Nitrogen Dioxide Pollution. Moscow, 1988.
Figure 8. Nitrogen Dioxide Pollution. Moscow, 1989.
Figure 9. Nitrogen Dioxide Pollution. Moscow, 1990.
Figure 10. Nitrogen Dioxide Pollution. Moscow, 1991.
Mapping of Differences in Pollution
Over a Period of Time

As a next step in the analysis a model was written for estimating the differences in NO₂ pollution levels between two years (see Appendix B, Flowchart 2). A positive or negative change of 0.0075 mg/m³ was used as one level. This value corresponds to the increment used for creation of original NO₂ pollution maps, and makes it possible to express the changes in NO₂ concentration as relative values, such as "2 levels increase", or "3 levels decrease" from the previous year.

Figures 11 - 18 show the results of applying the model to consecutive pairs of years. The results show that the range of changes increased with time and reached its maximum in 1990-1991 when some areas experienced up to 15 levels increase, while the pollution level in other areas gradually decreased. This phenomenon could result from more strict pollution control measures taken by the city government in some districts, or from specific meteorological conditions during 1990-1991.

The area that experienced most changes lies in the central part of the city, southeast from the Garden Ring. Unfortunately, present lack of auxiliary data makes it impossible to determine what caused those intensive changes.
Figure 11. Changes in Nitrogen Dioxide Pollution Levels in Moscow, 1983 vs. 1984

1 level = 0.0075 mg/cubic meter

- Decrease 2 levels
- Decrease 1 level
- Same
- Increase 1 level

5 km
Figure 12. Changes in Nitrogen-Dioxide Pollution Levels in Moscow, 1984 vs. 1985.
Figure 13. Changes in Nitrogen Dioxide Pollution Levels in Moscow, 1985 vs. 1986.

1 level = 0.0075 mg/cubic meter

- decrease 4 levels
- decrease 3 levels
- decrease 2 levels
- decrease 1 level
- same
- increase 1 level
- increase 2 levels

5 km
Figure 14. Changes in Nitrogen Dioxide Pollution Levels in Moscow, 1986 vs. 1987

1 level = 0.0075 mg/cubic meter

- Decrease 1 level
- Same
- Increase 1 level
- Increase 2 levels
- Increase 3 levels
- Increase 4 levels

5 km
Figure 15. Changes in Nitrogen Dioxide Pollution Levels in Moscow, 1987 vs. 1988.
Figure 16. Changes in Nitrogen Dioxide Pollution Levels in Moscow, 1988 vs. 1989.
Figure 17. Changes in Nitrogen Dioxide Pollution Levels in Moscow, 1989 vs. 1990.
Figure 18. Changes in Nitrogen Dioxide Pollution Levels in Moscow, 1990 vs. 1991.
Further analysis of changes could include construction of time series that would allow for tracing the changes for any given point for more than two years. Unfortunately, most of GIS do not have capabilities for such procedures.

Relationship Between Nitrogen Dioxide Pollution and Street Density

It is interesting to estimate the influence of different geographic phenomena on the NO\textsubscript{2} pollution. There are certain factors that can either decrease or increase the NO\textsubscript{2} values, such as car flow through the area, meteorological conditions, architecture of the surrounding area, etc.

Unfortunately, the time limits and the budget of this project did not allow for the involvement of several such factors. This chapter concentrates on the relationship between the street density, which is one of the estimates of the car flow, and NO\textsubscript{2} values. Car flow has been steadily increasing in Moscow for the past several years.

For this purpose the street map of Moscow (1:38,000) was digitized and converted to raster format (Figure 19). Further, the territory within the city limits was subdivided into three categories - low, medium, and high density - according to the total length of streets per square
Figure 19. Moscow Street Map.
Source: Moscow Street Map, GUGK, 1992.
kilometer\(^1\). (See Appendix B, Flowchart 3 for the procedure.) Figure 20 shows the resulting map of street density. The highest street density is found within the Garden Ring and near it, and the density decreases from the center to the outskirts.

It was expected that there would be a positive relationship between street density and the values of NO\(_2\) in each street density category. Two measures of association were selected to assess this relationship: (1) a correlation coefficient (Pearson’s \(r\)), and (2) the chi-square statistic.

There are certain problems that arise when using geographic data for inferential purposes, such as difficulties with estimating the population under study, sample size, independence of the observations, normality of the distribution, etc. (Gould, 1970). As the data used for this analysis were derived by interpolation from a limited number of actual observations, and all territory of the city was used as a sample, there is no possibility of using them for inferential purposes, and correlation coefficients and contingency tables are used only as descriptive measures.

\(^1\) Because of map scale and rasterization procedure the actual unit area equalled 0.98 square kilometers.
Correlation Analysis

One of the ways to estimate the relationship between the street density and NO$_2$ value was to calculate correlation coefficients. For this purpose maps with the same unit area were generated from the original NO$_2$ maps. A covariance matrix was obtained from the NO$_2$ maps and a street density map using a preliminary procedure for the principal component analysis in ERDAS (see Appendix B, Flowchart 4). The data from the matrix were used to calculate the correlation coefficients for street density and NO$_2$ concentration. The resulting coefficients ($r$) and coefficients of determination ($r^2$) are shown in Table 3.

The results indicate that the degree of relationship between street density and pollution increased since 1987 with the maximum values in 1989 and 1991. It was not expected that the values of this coefficient would be high, as street density is not the primary factor in NO$_2$ distribution. Considering that there are many other factors

Table 3

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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>0.168</td>
<td>0.205</td>
<td>-0.071</td>
<td>0.210</td>
<td>-0.108</td>
<td>0.157</td>
<td>0.264</td>
<td>0.219</td>
<td>0.262</td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.208</td>
<td>0.042</td>
<td>0.005</td>
<td>0.044</td>
<td>0.012</td>
<td>0.025</td>
<td>0.070</td>
<td>0.048</td>
<td>0.069</td>
</tr>
</tbody>
</table>
involved in NO₂ distribution the value of 0.262 (in 1991) seems to show that there is some relationship between street density and NO₂ concentration. At the same time, the lowest correlation coefficient values for some years (1985 and 1987) might be explained by the dominance of other factors, such as meteorological conditions, over the street density (car flow) during those years.

The increase in the correlation coefficient values for most recent years indicates that a positive non-zero relationship exists and that this aspect should be studied more. For such a study, it will be necessary to make some changes in the analysis set-up, such as to include a larger number of observation stations and other characteristics of the car flow (average number of lanes for the area unit, closeness to main industrial, social or residential centers, etc).

Coefficients of determination (r²) show the percentage of variation in NO₂ values that can be explained by the differences in street density. As the results show, for most years less than 10 percent of variation in NO₂ can be explained by the variation in street density. This low level of explanation might be caused by factors mentioned above, or by the fact that street density is not sufficient enough for characterization of the car flow.
Chi-Square Analysis

Another way to estimate the degree of relationship between NO\textsubscript{2} and street density is the chi-square statistic. It allows for estimation whether there is a relationship between these two variables, or they are statistically independent. If they are independent, then the same proportions of, for example, areas with high concentrations of NO\textsubscript{2}, will occur within high street density, as occur in medium-high, medium-low, or low concentration areas. Contingency tables were constructed for the years of 1989, 1990, and 1991 (see Appendix B, Flowchart 5). The results are shown in Appendix A, Tables 3 through 5.

Corresponding chi-square values were calculated for each year. The formula for chi-square is shown below (Clark and Hosking, 1986, p.263):

\[ \chi^2 = \sum_{j=1}^{k} \frac{(O_j - E_j)^2}{E_j} \]

where \( O_j \) = observed frequency of NO\textsubscript{2} vs. street density,
\( E_j \) = expected frequency of NO\textsubscript{2} versus street density,
and \( k \) = number of cells in the contingency table.

However, a chi-square value does not provide us with a good measure of the degree of the relationship (Clark
and Hosking, 1986). A chi-square based measure of association (Cramer’s V) was used to determine the strength of the relationship between the street density and NO$_2$ pollution.

A formula for Cramer’s V is shown below (Clark and Hosking, 1986, p.266).

$$V = \sqrt{\frac{\chi^2}{n \times \min(r-1), (c-1)}}$$

where $n$ = number of observations, and

$$\min(r-1), (c-1) = \text{minimum value of columns or rows in the contingency table.}$$

The results of computations are shown in Table 4 and indicate that there is a positive relationship between streets density and NO$_2$ pollution, but the degree of association is not very strong. These results coincide with those obtained for correlation coefficients.

Table 4

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$</td>
<td>93.02</td>
<td>62.56</td>
<td>68.22</td>
</tr>
<tr>
<td>$V$</td>
<td>0.22</td>
<td>0.18</td>
<td>0.19</td>
</tr>
</tbody>
</table>
CHAPTER IV

CONCLUSIONS

As the result of this project the digital database was created for NO₂ pollution in Moscow, Russia, for the period from 1983 to 1991. An algorithm for change estimation between two years was developed and applied to consecutive pairs of years.

The results of the analysis showed that the level of pollution increased over 9 years. The recommended maximum concentration (0.04 mg/m³) was exceeded in most of the city territory since 1983, and continued to increase for the whole study period. At the same time, it is necessary to note that Russian standards of air quality are very strict, and in most other countries of the world the recommended levels of concentration of NO₂ can reach 0.1 mg/m³.

While many areas of Moscow, such as the outskirts, did not show much change in NO₂ concentration during the study period, the territory of the center of the city experienced a strong increase from 1983 to 1990, and some decrease in 1991.

The relationship between street density and NO₂ pollution was studied here also. Correlation coefficients
and the chi-square statistic showed that there was a positive relationship between street density and pollution, but the association was not very strong, and street density explained a very limited amount of variation in NO₂ pollution.

Further analysis should examine other factors that influence NO₂ pollution, such as meteorological conditions, architectural patterns of the district, and additional criteria of the car flow, such as an average number of lanes per area unit, and closeness to main transportation, industrial, and social centers.

Special techniques for time series analysis using the data from pollution maps could be developed to allow analysis of the changes for every point, over a given period of time.

The results of this project can be also used for such purposes as land value assessment, water quality control, estimation of the relationship between pollution and diseases in the city, etc.
Appendix A

Tables
Table 1

Annual Average NO₂ Pollution Levels for 17 Observation Stations in Moscow

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>st. 1</td>
<td>0.0408</td>
<td>0.0525</td>
<td>0.0442</td>
<td>0.0375</td>
<td>0.0358</td>
<td>0.0592</td>
<td>0.0517</td>
<td>0.0500</td>
<td>0.0633</td>
</tr>
<tr>
<td>st. 2</td>
<td>0.0600</td>
<td>0.0600</td>
<td>0.0500</td>
<td>0.0558</td>
<td>0.0675</td>
<td>0.0967</td>
<td>0.1075</td>
<td>0.1017</td>
<td>0.0942</td>
</tr>
<tr>
<td>st. 3</td>
<td>0.0492</td>
<td>0.0467</td>
<td>0.0567</td>
<td>0.0450</td>
<td>0.0458</td>
<td>0.0683</td>
<td>0.0692</td>
<td>0.0683</td>
<td>0.0633</td>
</tr>
<tr>
<td>st. 4</td>
<td>0.0692</td>
<td>0.0630</td>
<td>0.0508</td>
<td>0.0417</td>
<td>0.0408</td>
<td>0.0625</td>
<td>0.0592</td>
<td>0.0483</td>
<td>0.0933</td>
</tr>
<tr>
<td>st. 5</td>
<td>0.0517</td>
<td>0.0617</td>
<td>0.0400</td>
<td>0.0625</td>
<td>0.0575</td>
<td>0.0642</td>
<td>0.0467</td>
<td>0.0850</td>
<td>0.0925</td>
</tr>
<tr>
<td>st. 6</td>
<td>0.0475</td>
<td>0.0492</td>
<td>0.0509</td>
<td>0.0567</td>
<td>0.0858</td>
<td>0.1017</td>
<td>0.0625</td>
<td>0.0675</td>
<td>0.0783</td>
</tr>
<tr>
<td>st. 7</td>
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<td>0.0533</td>
<td>0.0592</td>
<td>0.0792</td>
<td>0.1017</td>
<td>0.0950</td>
<td>0.1025</td>
</tr>
<tr>
<td>st. 8</td>
<td>0.0533</td>
<td>0.0608</td>
<td>0.0533</td>
<td>0.0417</td>
<td>0.0492</td>
<td>0.0758</td>
<td>0.1033</td>
<td>0.0975</td>
<td>0.0875</td>
</tr>
<tr>
<td>st. 9</td>
<td>0.0325</td>
<td>0.0400</td>
<td>0.0508</td>
<td>0.0391</td>
<td>0.0492</td>
<td>0.0825</td>
<td>0.0608</td>
<td>0.0608</td>
<td>0.0625</td>
</tr>
<tr>
<td>st. 10</td>
<td>0.0475</td>
<td>0.0517</td>
<td>0.0575</td>
<td>0.0464</td>
<td>0.0560</td>
<td>0.0742</td>
<td>0.0950</td>
<td>0.1100</td>
<td>0.1042</td>
</tr>
<tr>
<td>st. 11</td>
<td>0.0400</td>
<td>0.0450</td>
<td>0.0525</td>
<td>0.0450</td>
<td>0.0558</td>
<td>0.0767</td>
<td>0.0642</td>
<td>0.0717</td>
<td>0.0617</td>
</tr>
<tr>
<td>st. 12</td>
<td>0.0683</td>
<td>0.0592</td>
<td>0.0467</td>
<td>0.0467</td>
<td>0.0558</td>
<td>0.0658</td>
<td>0.0667</td>
<td>0.0508</td>
<td>0.0667</td>
</tr>
<tr>
<td>st. 13</td>
<td>0.0425</td>
<td>0.0408</td>
<td>0.0608</td>
<td>0.0458</td>
<td>0.0575</td>
<td>0.0767</td>
<td>0.0658</td>
<td>0.0750</td>
<td>0.0758</td>
</tr>
<tr>
<td>st. 14</td>
<td>0.0383</td>
<td>0.0358</td>
<td>0.0642</td>
<td>0.0383</td>
<td>0.0467</td>
<td>0.1108</td>
<td>0.1342</td>
<td>0.1433</td>
<td>0.0608</td>
</tr>
<tr>
<td>st. 15</td>
<td>0.0409</td>
<td>0.0450</td>
<td>0.0500</td>
<td>0.0417</td>
<td>0.0592</td>
<td>0.0817</td>
<td>0.0900</td>
<td>0.1058</td>
<td>0.1042</td>
</tr>
<tr>
<td>st. 16</td>
<td>0.0517</td>
<td>0.0550</td>
<td>0.0575</td>
<td>0.0417</td>
<td>0.0492</td>
<td>0.0658</td>
<td>0.0500</td>
<td>0.0650</td>
<td>0.0725</td>
</tr>
<tr>
<td>st. 17</td>
<td>0.0357</td>
<td>0.0508</td>
<td>0.0533</td>
<td>0.0408</td>
<td>0.0608</td>
<td>0.0600</td>
<td>0.0583</td>
<td>0.0625</td>
<td>0.0925</td>
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</table>
Table 2
Algorithm for Rescaling NO*.lan Files into NO*.gis Files

<table>
<thead>
<tr>
<th>GIS value</th>
<th>NO$_2$ value (mg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>background</td>
</tr>
<tr>
<td>1</td>
<td>0.0325 - 0.03999</td>
</tr>
<tr>
<td>2</td>
<td>0.0400 - 0.04749</td>
</tr>
<tr>
<td>3</td>
<td>0.0475 - 0.05499</td>
</tr>
<tr>
<td>4</td>
<td>0.0550 - 0.06249</td>
</tr>
<tr>
<td>5</td>
<td>0.0625 - 0.06999</td>
</tr>
<tr>
<td>6</td>
<td>0.0700 - 0.07749</td>
</tr>
<tr>
<td>7</td>
<td>0.0775 - 0.08499</td>
</tr>
<tr>
<td>8</td>
<td>0.0850 - 0.09249</td>
</tr>
<tr>
<td>9</td>
<td>0.0925 - 0.09999</td>
</tr>
<tr>
<td>10</td>
<td>0.1000 - 0.10749</td>
</tr>
<tr>
<td>11</td>
<td>0.1075 - 0.11499</td>
</tr>
<tr>
<td>12</td>
<td>0.1150 - 0.12249</td>
</tr>
<tr>
<td>13</td>
<td>0.1250 - 0.12999</td>
</tr>
<tr>
<td>14</td>
<td>0.1300 - 0.13749</td>
</tr>
<tr>
<td>15</td>
<td>0.1375 - 0.14500</td>
</tr>
</tbody>
</table>
### Table 3

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium-Low</th>
<th>Medium-High</th>
<th>High</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>387</td>
<td>157</td>
<td>3</td>
<td>3</td>
<td>550</td>
</tr>
<tr>
<td>Medium</td>
<td>160</td>
<td>153</td>
<td>10</td>
<td>4</td>
<td>327</td>
</tr>
<tr>
<td>High</td>
<td>18</td>
<td>31</td>
<td>8</td>
<td>0</td>
<td>57</td>
</tr>
<tr>
<td>Total</td>
<td>365</td>
<td>341</td>
<td>21</td>
<td>7</td>
<td>934</td>
</tr>
</tbody>
</table>

### Table 4

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium-Low</th>
<th>Medium-High</th>
<th>High</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>306</td>
<td>231</td>
<td>11</td>
<td>2</td>
<td>550</td>
</tr>
<tr>
<td>Medium</td>
<td>99</td>
<td>202</td>
<td>22</td>
<td>4</td>
<td>327</td>
</tr>
<tr>
<td>High</td>
<td>20</td>
<td>34</td>
<td>3</td>
<td>0</td>
<td>57</td>
</tr>
<tr>
<td>Total</td>
<td>425</td>
<td>467</td>
<td>36</td>
<td>6</td>
<td>934</td>
</tr>
</tbody>
</table>
Table 5

Observed Frequencies (in Pixels) of NO₂ Concentration (Columns) vs. Street Density (Rows) in 1991

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>Medium-Low</th>
<th>Medium-High</th>
<th>High</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>270</td>
<td>273</td>
<td>7</td>
<td>0</td>
<td>550</td>
</tr>
<tr>
<td>Medium</td>
<td>99</td>
<td>218</td>
<td>10</td>
<td>0</td>
<td>327</td>
</tr>
<tr>
<td>High</td>
<td>2</td>
<td>55</td>
<td>0</td>
<td>0</td>
<td>57</td>
</tr>
<tr>
<td>Total</td>
<td>371</td>
<td>546</td>
<td>17</td>
<td>0</td>
<td>934</td>
</tr>
</tbody>
</table>
Appendix B

Flowcharts
FLOWCHART 1
Nitrogen Dioxide Pollution Maps
Files NO83.gis through NO91.gis

<<DIGSCRN>> ---► STATIONS.dig

<<EDIT>>

* NO₂ values are assigned
to the stations as record
numbers

NO*.dig

<<SORT>>

* search radius = 18,000 m

NO*.blk

<<SURFACE>>

* search radius = 18,000 m

NO*.lan

<<RESCALE>>

* see Appendix A, Table 2
for rescaling algorithm

NO*.gis

* Additional programs used: <<COLORMOD>>, <<BSTATS>>, <<ANNOTAT>>, <<CPYSCR>>

Here and in the following flowcharts:

STATIONS.dig - file name
<<RESCALE>> - program in ERDAS
<EXPORT> - program on C-MAP
FLOWCHART 2

Nitrogen Dioxide Pollution Change Maps

Files IND83-84.gis through IND90-91.gis

NO*.gis

<<GISMO>> * see model below

IND*.gis

* Additional programs used: <<COLORMOD>>, <<BSTATS>>, <<ANNOTAT>>, <<CPYSCR>>.

Increase/Decrease_Index

data
input NO2_1 file ask "input first";
input NO2_2 file ask "input second";
output target file ask "output";
start
  target = conditional
              { (NO2_2 eq NO2_1) 16;
                (NO2_2 eq (NO2_1+1)) 17;
                (NO2_2 eq (NO2_1+2)) 18;
                ...
                (NO2_2 eq (NO2_1+15)) 31;
                (NO2_2 eq (NO2_1 - 1)) 15;
                (NO2_2 eq (NO2_1 - 2)) 14;
                ...
                (NO2_2 eq (NO2_1 - 15)) 1);
FLOWCHART 3
Moscow Street Density Map.
File DENS3.gis

DIGITIZE ARCS → MOS.arc

EXPORT  → MOS.dig

DXIN  → MOSCOW.dig

GRIDPOL  → MOSCOW.gis

SCAN  → TOTAL33.gis

RECODE  → DENS.gis

AGGIE  → DENS3.gis

* option [total] was used
box dimensions = 33, 33

* recoding algorithm:
classes 1 - 123 as 1;
124 - 267 as 2;
over 268 as 3.

* box dimensions = 33, 33

* Additional programms used: <<COLORMOD>>, <<BSTATS>>, <<ANNOTAT>>, <<CPYSCR>>.
FLOWCHART 4
Correlation Coefficients.

NO*.gis
<<AGGIE>>
* box dimensions = 33, 33

AGGR*.gis
<<FIXHED>>

AGGR*.lan
<<SUBSET>>
* AGGR83.lan as band 2,
* AGGR91.lan as band 10

DENS3.gis
<<COPY>>
<<MAKEFIL>>
<<FIXHED>>

* 10 bands

DENS3.lan
<<SUBSET>>
* as band 1

NOCOR.lan
<<PRINCE>>
print-out of the covariance matrix
FLOWCHART 5

Contingency Tables for Years 1989 through 1991

AGGR*.gis

<<SUMMARY>>

DENS3.gis

print-out
BIBLIOGRAPHY


Gould, Peter. "*Is Statistix Inferens the Geographic Name for a Wild Goose?*" *Economic Geography*, vol. 46, no. 2 (supplement), June 1970.


Thom, Gary C., Wayne R. Ott. *Air Pollution Indices*. Ann