Design and Implementation of a Dynamic Simulation System for Air Pollutant Diffusion - A Case Study of the Fangshan District, Beijing, China

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Abstract
With the rapid development of China’s industrialization and urbanization, urban air pollution has become an urgent problem to be solved. Industrial air pollutants in local areas of cities and towns directly harm the health of residents. Under the UNEP initiative, research on urban air pollution has become a main aspect of air pollution research. This paper focuses on the study of atmospheric pollution in small urban areas using GIS spatial analysis and simulation as the methods and the improved Gaussian plume diffusion model as the mathematical principle, based on ArcGIS Engine components and C#.Net. A simulation system platform for the diffusion process of atmospheric pollutants is designed and implemented, which has various functions including dynamic simulation display expression, GIS spatial analysis, spatial data processing, attribute information extraction and simulation result thematic mapping and export. Based on the Fangshan District in Beijing as an example, the dynamic simulation and spatial analysis of pollutant diffusion were conducted using the system platform based on industrial air pollution resource data in the region. The results show that the system provides significant decision-making guidance for effective urban air pollution warnings and the improvement of urban air quality.

Keywords: Air Pollution, Simulation, Gaussian Plume Models, Arc Engine

Introduction
Since the industrial revolution, the problem of air pollution has been inherent in the development of the industrial economy, from the London smog a hundred years ago to the haze and fog of the Beijing, Tianjin and Hebei Regions today [1-4]. According to the first survey of pollution sources, China’s secondary industry has emitted most of the sulfur dioxide while promoting per capita GDP growth, which is an important cause of air pollution [5]. Air pollution has become one of the most serious environmental pollution problems in China [6]. Therefore, the search for a more efficient alternative to traditional air pollution prevention measures is no longer just about the system or the public [7, 8]. GIS, which allows for powerful spatial analysis and has intuitive and accurate visual display characteristics, complements the advantages of a Gaussian diffusion model to scientifically simulate the diffusion, spread and dilution of polluted gases in the space-time range, which will be beneficial to atmospheric environmental protection and pollution control [9].

The simulation of air pollution diffusion has been the focus of many scholars. Zhao Wei and others developed the City Air 1.0 urban air quality management system to simulate and visualize the spread of pollution [10]. Chen Hongmei and others used Fuzhou to carry out a GIS simulation analysis of urban air pollution diffusion and obtained relevant conclusions [11]. Tang et al. [12] and others used components of GIS development technology to support an R&D system and simulated the pollutant diffusion in the Liuuzhi Steel Plant in Chongqing. Zhang [13] used Net as a development tool and Arc Engine to implement concentration prediction and analysis software functions. Arystanbekova, N. K predicted air pollution based on a Gaussian model [14]. D Briggs noted that GIS technology could make a great contribution to air pollution control and conducted significant research on methods of interpolation and dynamic modeling techniques [15].

Tolga Elbir designed a system for large Turkish cities to perform basic spatial analysis [16]. Gulliver and Briggs [17] discussed a GIS system that can be used to simulate traffic-related air pollution. Kumar et al. [18] used a GIS-designed simulation system to evaluate and predict the spread of urban traffic air pollution. Kwak et al. [19] performed a simple
chemical simulation of NO₂, NO₃, and O₃ using a Gaussian smoke model and established a comprehensive urban air quality model. The research of these scholars is very representative, but additional research on air pollution at small urban scales is still needed. In this paper, software for the simulation of atmospheric pollutant diffusion is designed and implemented based on close integration of the Gaussian diffusion model, which is widely applied, and GIS. The system first establishes the model relationship between the atmospheric pollutant diffusion phenomenon and influencing factors such as wind speed and direction, then the spatial distribution of the polluting gas centered at the pollution source and the diffusion process over time can be dynamically displayed. The software is a complete system, with functions such as a GIS attribute query, spatial analysis and thematic production output.

**Gaussian plume model**

**Assumptions**

The Gaussian diffusion model, which ignores the effect of gravity or buoyancy on a gas with an average density close to that of air, is based on the hypothesis that the diffused gas concentration obeys a Gaussian distribution in an approximately uniform stable turbulent flow field, and mainly considers the turbulence leading to gas diffusion [20-22].

The hypotheses of Gaussian diffusion model are as follows:

1. The quasi-regional flow field is stable, the cutting edge of the wind field is not considered, and the underlying surface is open, uniform and flat.
2. During the diffusion period, the polluting gas should be passive and conservative. The polluting gas has no loss or conversion during the diffusion process, and the air does not move relative to each other and is reflected on the ground.
3. The diffusion process occurs in the same temperature layer, the average wind speed is greater than 1 m/s, and the diffusion description is generally less than 10 to 20 km.

The Gaussian diffusion model is derived from a large number of actual measurement studies and analyses, mainly for the spread of pollutants from elevated point sources. The model assumes that the pollutant concentration in the uniform turbulent atmosphere obeys a positive distribution, but the actual atmospheric conditions are very complicated and varied. Therefore, in practical applications, the Gaussian model holds in a small area where the underlying surface is approximately uniform, and the airflow is relatively stable. In diffusion studies, the calculated value is more relevant than the real value, and the simulation effect is good [23, 24].

**Model calculation**

Continuous leakage of elevated point source pollutants occurs when aspects such as the wind direction, wind speed, and atmospheric stability do not change over a certain period of time. Due to the complexity and diversity of the objects on the ground, the simplest study is idealized and only the plume is considered. It is completely reflected on the ground and is not absorbed by the ground. The reference source method is used to treat the gas concentration at any position as the concentration of the position when there is no ground and the concentration of the pollutant when the ground is present [20]. Then, the model of the downdraft to any point of polluting gas concentration C(x, y, z) is calculated as follows (Yuan J, 2016):

\[
C(x, y, z) = \frac{Q}{2\pi \sigma_x \sigma_y \sigma_z} \exp\left(-\frac{x^2}{2\sigma_x^2}\right) * F
\]

\[
F = \exp\left(\frac{(z - He)^2}{2\sigma_z^2}\right) + \exp\left(\frac{(z + He)^2}{2\sigma_z^2}\right)
\]

where \( x \) is the distance between the calculated wind direction and the downwind direction (m); \( y \) is the distance between the calculated position and the location of the source of the wind (m); \( z \) is the height of the calculated position from the ground (m); \( Q \) is the pollution source Or release rate (mg/s); \( U \) is the average wind speed at the source of the pollution (m/s); \( He \) is the geometric height at which the source leaks from the ground (m); \( \sigma_x, \sigma_y, \sigma_z \) are horizontal and vertical diffusion parameters, respectively (m); \( \sigma_x, \sigma_y, \sigma_z \) is a function of the ground roughness, the calculated position distance from the downwind position \( x \) between the pollution source, and the atmospheric stability.

**Model parameter calculation**

Based on the two kinds of nighttime cloud volume design, three different daytime insolation and five different ground wind speeds designed by Pasquill-Gifford, the description of atmospheric stability is divided into six types. Stabilization includes stability and stability, and instability includes strong instability, instability, slight instability, and neutrality. The types are represented by the letters A to F, from strong instability to neutral to stable [25]. The Chinese national standards, “Technical Principles and Methods for Establishing Local Air Pollution Emission Standards” (GB3840-83) and “Technical Principles for Environmental Impact Assessment” (HJ/T2.1-93) are mainly based on the improved Pasquall stability classification method, in which the first simulation step is based on the cloud amount and solar elevation angle; the corresponding solar radiation levels are shown in Table 1. In the second step, the number of solar radiation levels obtained in the first step and the ground wind speed value in the simulation area at the corresponding simulation time is queried in (Table 2) and the number of stability levels is determined. The Chinese national standards, “Technical Principles and Methods for Establishing Local Air Pollution Emission Standards” (GB3840-83) and “Technical Principles for Environmental Impact Assessment” (HJ/T2.1-93) are mainly based on the improved Pasquall stability classification method, in which the first simulation step is based on the cloud amount and solar elevation angle; the corresponding solar radiation levels are shown in Table 1. In the second step, based on the number of solar radiation levels and the ground wind speed in the simulation area at the corresponding simulation time that were obtained in the first step are queried to determine the
stability grade. The diffusion parameter $\sigma_y$, $\sigma_z$ is a function of atmospheric stability and the distance $x$, which is a variable and a function of wind speed and time, between the calculated position and the leaking source. As follows (Yuan J, 2016):

$$\sigma_y = P_y X^q_y, \quad \sigma_z = P_z X^q_z. \quad (3)$$

Based on the calculation of the diffusion coefficient of the elevated point source diffusion in the large roughness of the simulated area recommended by the International Atomic Energy Agency (IAEA), the corresponding coefficient is obtained from (Table 3) according to the pollutant release height and atmospheric stability, and the model diffusion parameter can be obtained by calculation.

System design and implementation

Main data processed by the system

The data processed by the system designed in this paper has three main parts: the pollution source data of industrial enterprises in the Fangshan District of Beijing, the vector data of the administrative area map of the Fangshan District and the model parameter data input by the user. The industrial enterprise pollution source data include tabular data related to the name of the company, the person in charge, the industry and address of the company, and point-like vector layer data describing the location of each pollution source. The administrative area vector layer data describes the basic area of the Fangshan District and the county boundaries of the district to define the approximate spatial extent and structure of the Fangshan District. The main data framework is shown in (Figure 1).

Demand analysis

In response to the demand for air pollution control and the needs of environmental management personnel in the Fangshan District, managers and decision makers can input actual conditions of the environment including meteorological data and other parameters into the system designed in this paper. The system diffusion model uses a GIS spatial analysis function to simulate the diffusion and dilution of pollutants discharged by factory enterprises over a certain period of time, which is useful for managers to conduct pollution prediction, monitoring, pollution simulation analyses, early warning and forecasting, pollution emergency plans and environmental management decisions. User requirements are shown in Figure 2.
Functional framework of the system

System architecture design

The system was built with .Net technology and adopts a three-layer architecture design, namely, a presentation layer, a business logic layer and a data access layer [26]. The presentation layer is the system interface layer: the system is based on a user-friendly design of relevant pollution source characteristics and environmental meteorological parameter input and a function button interface. The design of the business logic layer comprises the atmospheric pollutant diffusion simulation. The data access layer main design includes the detailed industrial enterprise data in Microsoft Office Access, displayed in the front-end interface, and accesses and inputs the local Fangshan space map data into the system for processing. The overall architecture design is shown in Figure 3.

Functional framework of the system

According to the previous demand analysis and overall architecture design, the system’s functions can be divided into an atmospheric pollutant diffusion simulation module, a GIS basic function module and a data addition and deletion module. The core module of the system is the air pollutant diffusion simulation module, including the main industrial enterprise pollution source information view, model parameter input, dynamic and static simulation display, dynamic simulation time input and simulation result output [27, 28]. The functional framework is shown in Figure 4.
Model simulation process

The functions of the system include basic data processing, core atmospheric pollutant diffusion simulation and integrated GIS basic spatial analysis, query, processing and output. The simulation process is shown in Figure 5.

Model parameter input interface

The system diffusion simulation interface consists of three main parts. The first is to select the pollution source of different pollution source layers and display the basic information of the pollution source through the interface. The second part is the input of several analog parameters, including the solar radiation level of the simulation area, intensity of the pollution source, wind direction, wind speed, release height of the polluted gas, and the calculated height. The third part is based on the simulated time and time interval of the inputs for dynamic simulation. In addition, the Track Bar, which is one of the Windows Forms controls, can be used to adjust the display frame-by-frame. Parameter input interface is shown in Figure 6.

Simulating the spread of atmospheric pollution in the Fangshan District

The simulation data was obtained from the Fangshan District Environmental Protection Bureau of Beijing and includes the basic attributes and spatial information of industrial factories and enterprises in the Fangshan District from 1969 to 2015, as well as administrative maps of the streets and towns in the district.

Distribution of atmospheric pollution sources in the Fangshan District

The simulation data is characterized by the distribution of industrial sources in Fangshan District. The northwestern region is dominated by bituminous coal anthracite mining, lime and gypsum manufacturing and bottled/canned water manufacturing, and the southeast region is dominated by cement manufacturing and metal structure manufacturing. In general, most industrial pollution sources in the region are densely distributed in the southeast, as shown in Figure 7. The polluting gases emitted by industrial enterprises are mainly sulfides, nitrogen oxides and particulate matter. This paper focuses on the pollution diffusion simulation of $SO_2$. 

Simulation process and results

The pollution source layer of the Fangshan Industrial Enterprise was input into the system for simulation effect display. After the layer data was input into the system, the atmospheric pollutant diffusion simulation function menu is selected and the model parameter input window is called to define the parameters. For example, a source of pollution called Beijing Saint-Gobain Glass Fiber Co., Ltd. in Fangshan District was selected. The system displays basic information such as the name, industry, person in charge and address of the company. Then, based on the locations of the pollution sources of enterprises in the Fangshan District, the cloud amount and solar elevation angle at the simulation time and the corresponding solar radiation level are determined. In this simulation, the total traffic volume and low cloud volume are less than or equal to 4 and sunny, respectively. The solar radiation level of the altitude angle between 35 degrees and 65 degrees is +2. It is assumed that the release rate of the polluting gas from the pollution source is 500 mg/s. The wind direction at the pollution source is at an angle of 45 degrees clockwise with an east wind direction, the wind speed is 5 m/s, and the pollutants are released at a height of 50 m from the ground. The system simulates the diffusion of pollutants from the ground at a height of 200 m. The parameter input is...
Figure 5: Model simulation process.

Figure 6: Model parameter input interface.
shown in Figure 8. Finally, “Execute Calculation” is selected to make the system calculate and display the simulation. The simulation effect is shown in Figure 9.

In the dynamic simulation, within 60s of the release of the simulated pollutants, the diffusion result is taken as a frame every 15s. The “Apply Parameters” button is selected to prompt the system to simulate the model of different frame positions. The parameter definition is shown in Figure 10. “Start System” is selected to stream the simulation animations frame-by-frame.

**Discussion**

First, the effect of the model simulation is discussed. In this paper, the Gaussian diffusion model is used to simulate the point source pollution diffusion of industrial enterprises in the Fangshan District. The simulation effect depends on the model assumptions, the relevance of the input meteorological
parameters and the actual situation. However, the situation in the simulated area is complex and fluctuating. For example, the model assumes that the pollutants are diffused under constant wind speed and atmospheric stability. However, the wind speed and atmospheric stability are not in a completely constant state for any period of time, and are continually changing. Therefore, the system model simulates the diffusion under ideal conditions. We can continuously correct the input parameters or models according to the situation to be as close as possible to the actual diffusion so that the simulation is as accurate as possible. Therefore, the model simulation effect and actuality cannot be ignored. There are some deviations and it is necessary to consider the actual situation of the simulation area and the system simulation. Simulation of the same effect as the actual diffusion situation requires additional study.

Second, the development of the GIS components is discussed. In this paper, the components of the GIS method are used to design and implement the simulation system, which allows for the advantages of component GIS, such as easy development, strong embedding and powerful functions. However, with the continuous rapid development of Internet technology, technical methods of cloud computing, cloud platforms, the Internet of Things, distributed-grid computing, big data, and mobile and wireless networks, data sharing and interoperability between the concepts of platform and collaborative computing are becoming increasingly popular and GIS software is bound to be further upgraded. Although component GIS has great advantages, in the context of the growing maturity of Internet technology, GIS software requires an Internet-based approach to make GIS functions more flexible, convenient, efficient, and low-threshold. This is how WebGIS came into being. WebGIS has improved the deficiencies of component GIS in many aspects. Component GIS is not as powerful as a cross-platform capability or as useful as data sharing via the Internet. It is better for users to employ GIS without other complicated installations. The functional convenience is not as good, as its huge mobile application is based on a mobile network. With the future development of the Internet and related technologies, the development of component GIS is full of unknowns.

Finally, the pollutant diffusion simulation system designed and implemented in this paper is based on a two-dimensional angle. However, in practice, pollution diffusion is three-dimensional. The diffusion of pollutant gas is a two-dimensional motion process that includes fluid dynamics at different heights and complex processes such as gravity. Simulating the diffusion of atmospheric pollution in three-dimensions will more accurately simulate the diffusion of pollutants, rationally and scientifically. This presents a prospect for further improvement of the simulation model of atmospheric pollutant dispersion. Many of the present models for simulating diffusion are too idealistic or demanding, and the model was improved so that the application conditions are reasonable and true and the simulation results are real and reliable.

**Summary**

Studying urban air pollution is related to urban health and the development and progress of human civilization. The
simulation software for atmospheric pollutant diffusion in urban small areas that is designed and implemented in this paper is based on previous scholars’ research, and more fully combines GIS spatial analysis and simulation technology to produce vivid and convenient spatial simulation display. Studying urban air pollution is related to urban health and the development and progress of human civilization. The simulation software for atmospheric pollutant diffusion in urban small areas that is designed and implemented in this paper is based on previous scholars’ research, and more fully combines GIS spatial analysis and simulation technology to produce vivid and convenient spatial simulation display. In the system, the simulation results of different heights are realized dynamically on a frame-by-frame basis. The system is more flexible than those of previous scholars through the use of user-defined parameters such as source intensity of pollution. In summary, the research in this paper is based on GIS technology using the improved Gaussian model under ideal conditions and, considering the public atmosphere health of urban residents, it focuses on simulation and analysis of the diffusion of atmospheric pollution in small urban areas.

References
4. Dai H (2014) Talking about controlling urban air pollution Yangtze River delta energy forum. [View Article]


27. Li H (2010) Simulation of air pollution diffusion in Huizhou City. Central South University, China. [View Article]