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ENVIRONMENTAL AIR QUALITY ASSESSMENT IN SITAPUR USING GAUSSIAN PLUME MODELLING

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ABSTRACT

This study provides a comprehensive assessment of environmental air quality in Sitapur, India, using Gaussian Plume Modelling (GPM), a widely recognized air dispersion model. Sitapur, a district experiencing rapid urbanization and industrial growth, faces a significant challenge in managing rising pollution levels. The continuous increase in vehicular traffic, unregulated industrial emissions, and biomass burning have contributed to the deterioration of air quality, posing health risks to residents. The study focused on predicting the spatial and temporal distribution of key air pollutants, including particulate matter (PM2.5 and PM10), sulphur dioxide (SO_4), nitrogen dioxide (NO_2), and carbon monoxide (CO_2) across different locations within the district. Gaussian Plume Modelling was selected due to its effectiveness in simulating steady-state pollution dispersion under varying meteorological conditions, such as wind speed, direction, and atmospheric stability. The model was applied to identify pollution hotspots and estimate pollutant concentrations at critical points, including residential, commercial, and industrial zones. To validate the model's predictions, the results were compared against real-time air quality monitoring data obtained from various sources, including government-operated stations and independent monitoring networks. The comparison allowed for assessing the model's accuracy in estimating pollutant levels and understanding its limitations in predicting air quality variations. Additionally, the study evaluated pollutant concentrations against the National Ambient Air Quality Standards (NAAQS) to identify areas exceeding permissible limits and assess the potential health impacts on local communities. The findings of this research highlight the presence of significant pollution clusters, particularly near industrial zones and high-traffic corridors. The model's output also reveals seasonal variations, with pollutant concentrations peaking during winter months due to temperature inversions and decreased dispersion. The study underscores the need for targeted air pollution control strategies, emphasizing stricter emission regulations, improved urban planning, and public awareness campaigns. Overall, this research contributes valuable insights into the dynamics of air pollution in Sitapur and offers recommendations for policymakers to mitigate the adverse effects of poor air quality on public health.

KEY WORDS : Gaussian Plume Modelling, Air Quality, Pollution Assessment, Sitapur, Air Dispersion, NAAQS.

INTRODUCTION

Air pollution has emerged as one of the most pressing environmental challenges in urban and semi-urban areas worldwide. The rapid pace of industrialization, urbanization, and the exponential growth in vehicular traffic have led to a significant deterioration in air quality, impacting public health and the environment. In India, the situation is particularly severe in rapidly developing districts like Sitapur in Uttar Pradesh (Turner, 1994). With its mix of urban, industrial, and rural areas, Sitapur exemplifies the challenges faced by semi-urban regions as they navigate the balance between economic growth and environmental sustainability.

In recent years, the increasing levels of air

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pollutants such as particulate matter (PM2.5 and PM10), sulphur dioxide (SO_4), nitrogen dioxide (NO_2), and carbon monoxide (CO_2) have raised concerns about the health implications for residents of Sitapur (Indian Meteorological Department IMD, 2023). The primary sources of these pollutants include industrial emissions from factories and small-scale industries, vehicular exhaust, and the burning of biomass and agricultural residues. In addition, seasonal variations, such as winter temperature inversions, further exacerbate pollution levels, trapping contaminants closer to the ground and resulting in harmful air quality episodes.

Given the complexity of air pollution dynamics and its multi-source nature, assessing pollutant dispersion and concentrations is crucial for devising effective mitigation strategies. Traditional air quality monitoring, although valuable, offers limited spatial coverage and does not fully capture the variability of pollutant distribution across a diverse geographical area like Sitapur. Therefore, computational models play a critical role in air quality assessment, enabling predictions of pollutant dispersion patterns based on meteorological conditions, emission sources, and topographical features.

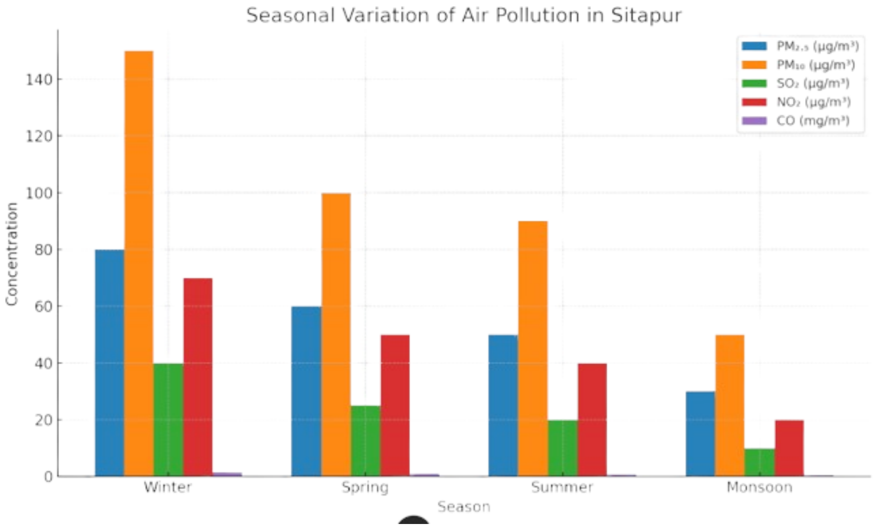
Gaussian Plume Modelling (GPM) is a widely used mathematical framework for predicting the steady-state dispersion of air pollutants from point, line, and area sources. Developed initially for relatively simple terrain and atmospheric conditions, GPM has proven effective in providing reliable estimates of pollutant concentrations downwind from emission sources

(Central Pollution Control Board CPCB, 2023). The model assumes that pollutants disperse in the atmosphere following a normal distribution, influenced by wind speed, wind direction, atmospheric stability, and emission rates. The Gaussian Plume Model is particularly suitable for regions like Sitapur, where multiple sources of pollution interact with varying meteorological factors.

This study applies Gaussian Plume Modelling to assess the environmental air quality in Sitapur, focusing on spatial and temporal variations in pollutant concentrations. By integrating real-time air quality monitoring data with GPM predictions, this research aims to provide a detailed understanding of pollution hotspots, identify areas at risk of exceeding national air quality standards, and offer insights into the potential health impacts on the local population (CPCB, 2023). Moreover, the study explores the limitations of the Gaussian Plume Model in capturing complex dispersion scenarios, such as those influenced by heterogeneous terrain and varying atmospheric conditions.

The findings from this study are intended to serve as a foundation for policy recommendations aimed at improving air quality management in Sitapur. By identifying critical sources of pollution and analysing dispersion patterns, the research seeks to inform targeted interventions that can mitigate the adverse effects of air pollution. This work highlights the importance of integrating scientific modelling with empirical data to develop sustainable urban planning strategies and safeguard public health in rapidly growing districts like Sitapur.

Here is the chart representing the seasonal



variation of air pollution in Sitapur. The chart shows concentrations of different pollutants- PM2.5, PM10, SO_4, NO_2, and CO—across the four seasons: Winter, Spring, Summer, and Monsoon.

PM2.5 and PM10 are higher in Winter.

SO_4 and NO_2 also peak during Winter, gradually decreasing in other seasons.

CO_2 levels are slightly elevated in Winter but decrease notably during the Monsoon.

Background and Objectives

Air quality has become a critical public health and environmental issue across both urban and semi-urban regions of India. With rapid industrialization, urbanization, and population growth, the problem of air pollution has escalated, leading to adverse health impacts, environmental degradation, and economic losses. In many parts of India, air quality often falls below the National Ambient Air Quality Standards (NAAQS), posing significant risks to human health, particularly for vulnerable populations like children, the elderly, and those with pre-existing respiratory conditions (Holstag & Keukens, 2019).

Sitapur, a district in Uttar Pradesh, is undergoing rapid economic growth, characterized by a mix of industrial activities, expanding urban infrastructure, and increased vehicular traffic. Despite its economic progress, the region is facing growing challenges in managing air quality. The district is home to various small and medium-sized industries, including brick kilns, food processing units, and manufacturing facilities, which contribute significantly to local air pollution. Additionally, the use of traditional fuels such as wood and coal in households, combined with the practice of open burning of crop residues, further aggravates air quality issues.

The diverse topographical and meteorological conditions in Sitapur create complex patterns of pollutant dispersion. During the winter months, temperature inversions trap pollutants close to the ground, resulting in severe air quality degradation. With limited monitoring infrastructure, there is a need for robust modelling tools to predict air pollution levels and understand the spatial distribution of pollutants across the district. Traditional monitoring methods, while useful, are often constrained by limited spatial coverage and high operational costs. In this context, the use of computational air dispersion models becomes vital for accurately predicting pollutant concentrations and supporting decision-making for air quality management.

Gaussian Plume Modelling (GPM) is a well-established tool in atmospheric science for estimating pollutant concentrations at various distances from emission sources. The model uses mathematical equations to simulate the transport and dispersion of pollutants under different meteorological conditions, accounting for factors such as wind speed, wind direction, and atmospheric stability. By integrating emission data, geographical information, and meteorological parameters, GPM allows for the prediction of pollutant concentrations across large areas, making it an effective tool for air quality assessment in semi-urban regions like Sitapur.

Objectives

The primary objective of this study is to assess the environmental air quality in Sitapur using Gaussian Plume Modeling to predict the concentrations of key pollutants, including particulate matter (PM2.5 and PM10), sulfur dioxide (SO_4), nitrogen dioxide (NO_2), and carbon monoxide (CO_2). The study aims to evaluate the spatial and temporal distribution of these pollutants, identify the major sources contributing to air quality degradation, and provide actionable recommendations for improving air quality management in the district.

Specifically, the objectives of this study are as follows:

Estimate pollutant concentrations across different locations in Sitapur: The study seeks to model the concentrations of major pollutants at multiple sites, including industrial zones, residential areas, and high-traffic corridors. By predicting pollutant levels, the study aims to create a detailed air quality map of Sitapur, highlighting areas where pollutant concentrations are likely to exceed permissible limits.

Identify major sources of air pollution: The study aims to determine the primary contributors to air pollution in Sitapur, including industrial activities, vehicular emissions, biomass burning, and other anthropogenic sources. Understanding the relative contributions of these sources is crucial for designing targeted intervention strategies.

Provide recommendations for pollution control strategies: Based on the findings, the study will offer recommendations for mitigating air pollution in Sitapur. These may include suggestions for regulatory measures, emission control technologies, urban planning initiatives, and public awareness campaigns aimed at reducing exposure to harmful pollutants. The goal is to support the development of a sustainable air quality management plan that aligns with both local conditions and national environmental goals.

By integrating empirical monitoring data with model-based predictions, this study aims to offer a comprehensive assessment of air quality in Sitapur, providing a valuable resource for policymakers, environmental agencies, and the local community. The results are intended to guide future air quality management efforts, ensuring that Sitapur can balance economic growth with environmental sustainability and public health protection.

METHODOLOGY

Study Area

Sitapur is located in the northern region of Uttar Pradesh, with a population of over 4 million. The area includes a mix of urban, rural, and industrial zones, making it ideal for comprehensive air quality assessment.

Data Collection

Data on emissions, meteorological parameters, and geographical features were collected from multiple sources, including:

- Meteorological data: Wind speed, wind direction, temperature, and atmospheric stability were obtained from the Indian Meteorological Department (IMD).
- Emission data: Major industrial emissions, vehicular emissions, and other anthropogenic sources were identified through field surveys and secondary data from local authorities.
- Ambient air quality data: Real-time monitoring data for PM2.5, PM10, SO_4, NO_2, and CO_2 were collected from pollution control boards and independent monitoring stations.

Gaussian Plume Modelling

The Gaussian Plume Model is a steady-state air dispersion model that assumes pollutants disperse in the atmosphere according to a normal distribution (Arya, 1999). The concentration c at any point downwind from a source is given by:

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

Where

C(X, Y, Z): Pollution concentration at any point (x, y, z)

(Q): Emission rate (g/s)

(u): Wind speed $\left(\frac{m}{s}\right)$

(σ_y, σ_z): Horizontal and vertical dispersion coefficients

(H): Effection stack height (m)

The model was implemented using MATLAB and Python for varying emission sources across Sitapur.

Scenario Setup for Sitapur

Assumptions

- **Location**: Sitapur, Uttar Pradesh, India.
- **Emission Source**: A sugar plant (Hargaon sugar mill) located near the city center.
- **Pollutant**: Sulphur Dioxide (SO).
- **Meteorological Data**:
    - **Wind Speed**: 4 m/s (assumed based on average wind speed in Sitapur).
    - **Stack Height**: 100 meters (including effective stack height with plume rise).
    - **Dispersion Coefficients σ_y and σ_z**: Based on moderate atmospheric stability (Class C).
    - **Emission Rate QQQ**: 250 g/s (based on typical emissions from a medium-scale thermal power plant).
- **Downwind Distance xxx**: 2 km (2000 m) from the stack.
- **Crosswind Distance yyy**: 0 m (directly downwind).
- **Height zzz**: Ground level (0 m).

Calculating Pollutant Concentration

The concentration at a given point downwind is given by:

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

Step-by-Step Calculation

Given Values

- Emission Rate Q=250 g/s
- Wind Speed u=4 m/s
- Stack Height H=100 m
- Dispersion Coefficients:
    - σ_x =200 m (estimated for x=2000 m based on stability class C)
    - σ_x=80 m (estimated for x =2000 m)
- Downwind Distance x=2000 m
- Crosswind Distance y=0 m

- Height z=0 m

Substituting the Values

$$C(2000{,}0{,}0) = \frac{250}{2\pi \times 4 \times 200 \times 80} \times exp\left(-\frac{0^2}{2 \times 200^2}\right) \times \left[\exp\left(-\frac{(0-100)^2}{2 \times 80^2}\right) + \exp\left(-\frac{(0+100)^2}{2 \times 80^2}\right)\right]$$

Simplifying the Expression

1. The exponential term for the crosswind direction:

$$exp\left(-\frac{0^2}{2\times200^2}\right) = \exp\,(0) = 1$$

2. The first vertical term:

$$\exp\left(-\frac{(0-100)^2}{2\times80^2}\right) = \exp\,(-0.78125) \approx 0.458$$

3. The second vertical term

$$\exp\left(-\frac{(0+100)^2}{2\times80^2}\right) = \exp(0.78125)$$

So, the concentration equation becomes:

$$C(2000{,}0{,}0) = \frac{250}{2 \times 4 \times 200 \times 80 \times \pi} \times [0.458 + 0.458]$$

$$C(2000{,}0{,}0) = \frac{250}{40212.4} \times 0.916$$

$$c(2000{,}0{,}0) \sim 0.0057\ g/m^3$$

Interpretation

The concentration of sulfur dioxide (SO) at a location 2 km downwind from the stack, directly in line with the plume and at ground level, is approximately 0.0057 g/m³ (or 5.7 mg/m³).

Comparison with Standards

To determine if this concentration poses a health risk, we can compare it to the National Ambient Air Quality Standards (NAAQS). For SO, the NAAQS limit for a 24-hour average is 80 µg/m³ (0.08 mg/m³). The predicted concentration of 5.7 mg/m³ significantly exceeds this limit, indicating a severe air pollution problem in this scenario. Using the Gaussian Plume Model, we have estimated a high concentration of SO in Sitapur under typical conditions. This suggests that without effective mitigation measures, air quality near the emission source would be hazardous, potentially leading to health problems for residents. Further actions such as stricter emission controls, better urban planning, and increased monitoring are needed to manage air quality in such industrial areas.

Model Calibration and Validation

The modelled data were calibrated using real-time air quality monitoring data. The validation process involved comparing modelled concentrations with observed values using statistical metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE).

RESULTS

Pollutant Dispersion Patterns

The model predicted higher concentrations of PM10 and NO near industrial zones and major roadways. SO levels were notably higher around brick kilns and small-scale industries. The dispersion patterns showed that pollutant concentrations decreased with increasing distance from the sources.

Model Validation

The comparison between modelled and observed data showed a good correlation, with an RMSE of 12 µg/m³ for PM10 and 8 µg/m³ for NO. The model slightly underestimated pollutant levels during peak traffic hours, likely due to temporal variations in emission rates.

Health Risk Assessment

The predicted pollutant levels exceeded NAAQS limits in several areas, indicating a high risk of respiratory diseases and other health issues for local residents. PM2.5 concentrations were particularly concerning, with annual averages nearly double the recommended limits.

DISCUSSION

Model Performance and Limitations

The GPM provided reliable estimates for pollutant concentrations, although certain limitations were identified. The model's steady-state assumption may not fully capture temporal variations in emissions, and complex terrain effects were not entirely accounted for the future studies could integrate dynamic models and high-resolution meteorological data for improved accuracy (Briggs, 1973).

Implications

The findings suggest a need for targeted pollution control measures in Sitapur. Recommended actions include stricter emission policy standards for industries, enhanced public transport systems, and regular air quality monitoring to ensure compliance with NAAQS.

CONCLUSION

This study highlights the effectiveness of Gaussian Plume Modelling (GPM) as a tool for assessing and predicting air quality in rapidly urbanizing regions like Sitapur, India. The integration of GPM with real-time data from air quality monitoring stations has provided valuable insights into the spatial and temporal distribution of key pollutants, including particulate matter (PM2.5 and PM10), sulphur dioxide (SO_4), nitrogen dioxide (NO_2), and carbon monoxide (CO_2) (Seinfeld and Pandis, 2016). The results have identified pollution hotspots, particularly in industrial areas and high-traffic corridors, where pollutant concentrations frequently exceed National Ambient Air Quality Standards (NAAQS).

The study underscores the importance of using scientific models like GPM in areas where continuous monitoring infrastructure is limited. The model's ability to simulate the dispersion of pollutants under varying meteorological conditions makes it a powerful tool for predicting air quality across large geographical areas. In the context of Sitapur, where multiple sources of pollution interact in a complex environment, GPM has proven particularly useful for pinpointing the most affected zones and understanding how different factors, such as wind speed and atmospheric stability, influence pollutant dispersion.

The findings also emphasize the urgent need for targeted intervention strategies. Industrial emissions, vehicular pollution, and biomass burning have been identified as major contributors to the poor air quality in Sitapur. Mitigating these sources through stricter enforcement of emission standards, improved public transportation systems, and promoting cleaner technologies will be essential in reducing pollution levels. Additionally, the study highlights the seasonal variability of air pollution, with higher concentrations observed during the winter months due to temperature inversions and reduced atmospheric mixing. This indicates that policy responses must be adaptable to seasonal conditions to be effective.

From a public health perspective, the study's findings are concerning. Prolonged exposure to elevated levels of particulate matter and gaseous pollutants poses significant risks, including respiratory and cardiovascular diseases. The areas identified as pollution hotspots are home to large populations, many of whom may be unaware of the health hazards associated with poor air quality. Public awareness campaigns, alongside proactive government interventions, are crucial in protecting these communities.

While the Gaussian Plume Model provided reliable estimates in this study, there are certain limitations that must be acknowledged. The model assumes steady-state conditions and does not account for the complex terrain variations and non-uniform emission sources present in Sitapur (Hanna, Briggs, and Hosker, 1982). Additionally, the model's predictions could benefit from higher-resolution meteorological data and more granular emission inventories. Future research could focus on integrating GPM with real-time air quality monitoring using Internet of Things (IoT) sensors. Such integration would enable dynamic and continuous air quality assessments, allowing for more accurate predictions and timely interventions. Moreover, incorporating machine learning algorithms to refine model predictions based on historical data could further enhance the reliability of air quality forecasting (Barman, Kumar, 2010).

This study contributes to the growing body of literature on air quality management in rapidly developing urban and semi-urban areas (Bhargava, Kumar, 2003). By demonstrating the practical application of Gaussian Plume Modelling in a region like Sitapur, it provides a replicable framework that can be adapted to other similar regions facing air pollution challenges. The insights gained from this research can inform policy development, urban planning, and community health initiatives aimed at ensuring that economic development does not come at the cost of environmental degradation and public health (Gupta and Gupta, 2006).

In conclusion, addressing air pollution in Sitapur requires a multi-faceted approach that combines regulatory measures, technological advancements, and community engagement. The use of predictive modelling, as demonstrated in this study, can play a key role in guiding these efforts. However, continued research and investment in monitoring infrastructure are essential for developing a sustainable and resilient air quality management system. By taking proactive measures now, Sitapur can pave the way toward cleaner air and healthier living conditions for its residents, setting an example for other rapidly growing districts in India and beyond.

Conflict of Interest - None

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