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Estimating Urban Air Quality Using Remote Sensing and Geographic Information Systems: A Study to Compare Satellite and Ground Measurements

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Abstract:

Urban air quality is one of the greatest global issues that affect human health, environmental sustainability, and economic development. In light of this, the aim of this review paper is to describe the latest advancements in air quality monitoring technologies, the use of Geographic Information Systems (GIS) in air quality assessment, and the effectiveness of several methods in understanding and mitigating urban air pollution. Traditional air quality monitoring, which relies on FRM and FEM equipment, provides high-quality data but suffers from high costs, limited flexibility, and spatial coverage gaps. Mobile air quality monitoring and low-cost sensors offer greater spatial resolution but face challenges in data accuracy and temporal coverage. Satellite-based monitoring complements ground-based systems, providing a broader geographic perspective but with limitations in accuracy and temporal resolution. GIS plays a vital role in air quality assessment by conducting spatial analysis, tracking emission sources, and creating complex maps of air quality detail to inform urban planning or policy development. This report also covers the integration with real-time monitoring data and whether it can be used toward decision-making in urban air quality management. This review emphasizes the possible potential of a more inclusive and dynamic approach in urban air quality management that might contribute to healthier and sustainable cities. It ends the paper with the challenges and future directions in the case of urban air quality monitoring such as the need for an easily accessible, scalable, and accurate monitoring system with respect to the increasing urban problem of pollution.

Keywords: Geographic Information Systems, Urban Air Quality, Air Quality Monitoring, Low-Cost Sensors, Satellite Monitoring

1. INTRODUCTION

Urban air quality is one of the critical issues related to public health, environmental sustainability, and well-being of the urban population. These are affected by pollutants of both natural and human origin such as industrial emissions, vehicular exhaust, construction activities, and energy production [1]. The most common pollutants are particulate matter, nitrogen dioxide, sulfur dioxide, ozone, carbon monoxide, and volatile organic compounds. Poor air quality can cause short-term health problems, such as asthma attacks and bronchitis, long-term health issues, including chronic respiratory diseases, lung cancer, and cardiovascular diseases, and also contributes to global climate change by releasing harmful emissions [2]. Economically, poor air quality carries huge healthcare costs, loss of productivity, and environmental degradation. In terms of urban air quality globally, there are variations with developing countries having the most severe pollution, as it is attributed to rapid industrialization and unregulated urban growth. There is still complexity in monitoring and managing air quality due to the limited capacity of current systems, institutional and technological barriers, and the fast rate of urbanization [3]. The issue of climatic change related to urban air pollution becomes an emerging challenge as frequency and intensity of extreme weather events raise the effects of urban pollution.

Table 1: Research Study Data

References	Topic Covered	Research Study	Title
Ghazwan et al., (2023) [4]	Land Surface Temperature (LST) Monitoring	Seasonal variations of LST using GIS and R.S techniques in Babylon City	" Monitoring Babylon City's Land Surface Temperature (LST) Using GIS and R.S. Techniques During Various Seasons"
A. F et al., (2020) [5]	Solar Radiation Mapping	Mapping solar radiation in Iraq using observational data and Angstrom model	" Development and Configuration of Iraqi Solar Radiation Maps Using Data Observation and Angstrom Model in

			July 2017"
Ebtesam et al., (2020) [6]	Greenhouse Gases and Weather Mapping	Mapping greenhouse gases and weather elements for Baghdad using GIS	" Create greenhouse gas maps for Baghdad City using data observation and arc-GIS techniques, adding certain weather elements. "
Eman et al.,(2023) [7]	Spectral Reflectivity Analysis	Evaluation of spectral reflectivity in Baghdad City using R.S and GIS	" Assess Baghdad City's Spectral Reflectivity for Various Bands Using R.S. and GIS Methods "
Eman et al.,(2023) [8]	Spectral Reflectivity Changes and Atmospheric Elements	Monitoring changes in spectral reflectivity and the impact of atmospheric elements on Baghdad City	" Using R.S. and GIS, track variations in Baghdad City's spectral reflectivity and the effects of atmospheric factors on it "
Haya et al.,(2023) [9]	Land Surface Temperature Monitoring in Oil Fields	Monitoring land surface temperature in the Al-Ahdab oil field using R.S and GIS	" Using R.S. and GIS techniques to monitor the land surface temperature for Al-Ahdab Oil Field in 2022"
Ebtesam et al., (2020) [10]	Pollutant Concentration Distribution	Using GIS for spatial analysis of pollutant concentrations in Shatt al-Arab waters	" In November 2015, maps showing the distribution of pollutant concentrations in Shatt al-Arab waters were created using spatial analysis techniques."

2. ADVANCEMENTS IN AIR QUALITY MONITORING TECHNOLOGIES

Advancements in air quality monitoring have introduced diverse methods, including high-precision FRM/FEM equipment, mobile monitoring that provides spatial flexibility, and low-cost stationary sensors for scalable networks [11]. Satellite-based monitoring supplements the ground-based methods but offers wide-area coverage for a comprehensive view of matters. These innovations address concerns in data resolution, accessibility, and deployability, enhancing our potential to monitor air quality, integrating these technologies into greater insights while balancing cost and precision with geographical reach.

- **Conventional FRM and FEM equipment-based air quality monitoring**

The standard for scientific research Federal reference grade air quality monitors, or FRMs and FEMs, are used by the government. In general, state and federal decision-makers utilize scientific reference-grade monitoring systems, such as the Federal Reference Method and Federal equivalent method monitors, to aid in policy-making, air quality attainment, and regulatory standard evaluation. The equipment's measuring performance will be subject to stringent requirements [12]. FRM devices are tailor-made to meet the stringent criteria established by regulatory bodies such as the USEPA. While various technologies could be incorporated into FEM monitors, it is essential that they meet or exceed government criteria, such as those specified by the US Environmental Protection Agency (EPA). To evaluate other monitoring technologies, including inexpensive sensors, we can look upon FRM and FEM monitors as a benchmark due to their high data quality. There are stringent operational requirements for characteristics like accuracy, precision, measurement range, and drift, among other things, because crucial regulatory action and decision-making rely on air quality data from FRM and FEM equipment.

Figure 1: In the United States, environmental agencies operate (FRM) or (FEM) air quality monitors to track regional air quality and gather information for policy and benchmarking purposes. [13]

FRM and FEM monitors are the "gold standard" in air quality monitoring due to the high performance and data quality requirements. However, they carry a very high operating cost and require temperature-controlled environments, not to mention skilled technicians for calibration and maintenance. They do not allow for much flexibility in siting decisions or deployment, and thus result in regional air quality measurements with significant data gaps at the local or neighborhood level.

- **Mobile monitoring of air quality**

When compared to more traditional, fixed methods, mobile air quality monitoring has the advantage of being able to evaluate the air quality in more places for longer periods of time. In contrast, air quality monitors that are permanently installed, such FRM/FEM and inexpensive stationary sensors, usually mount their hardware on or inside a vehicle. Using this strategy, one can get a dataset that is diverse in space but limited in time; it is like taking a picture of the air quality in a region at a specific instant. Mobile monitoring has the potential to offer a more complete view of changes in air quality over many geographic areas than do stationary monitors, which can only give data at specific sites .

Figure 2: Mobile air quality monitors capture snapshots of air quality across the monitoring zone for a given point in time but often cannot provide a complete picture of air quality trends or hotspots, which can change rapidly [14].

Mobile air quality monitoring offers very high spatial resolution for measuring air quality, which captures information at locations that are rarely covered by the traditional FRM/FEM networks. Due to variable data quality, mobile monitors are inappropriate for regulatory purposes. The information from the mobile monitoring could be less informative than from stationary networks, as they might not capture pollution hotspots or local trends due to constant movements. Although mobile monitoring collects data at higher spatial resolution, it does not guarantee meaningful capture of local air quality events; thus, the understanding of air quality trends over time will be limited. Thus, while mobile monitoring offers a potential solution for monitoring air quality, it should be used with caution.

- **Stationary monitoring with low-cost air sensors**

Low-cost, fixed air quality sensors fall somewhere between mobile and traditional monitoring methods in terms of spatial and temporal resolution. However, the category is broad because there are many inexpensive sensors with a wide range of performance. Some inexpensive sensors are best suited for individual consumer use at home and are advertised for both indoor and outdoor use [15]. Other inexpensive sensors, like the ones we provide at Clarity, include not only the sensing technology itself but also the related services that ensure success. Air quality monitoring will be more precise, effective, and user-friendly with the calibration of all deployed devices, integration with a cloud platform, and scalability in the building network.

Figure 3: Low-cost, stationary sensors, such as the Clarity Node-S shown above, can be placed in a range of settings and provide high spatiotemporal data resolution local air quality data collection. [16]

Low-cost sensors are not uniform in the quality of data, services, and infrastructure requirements; thus, deployment locations and conditions are affected. Self-sufficient, cellular-connected low-cost sensors can be advantageous in deploying them worldwide. They are great for constructing sensor networks in places without a reference network or for adding more data points to reference-grade monitors because of the excellent spatial data coverage they can give without missing the temporal patterns.. In building a sensor network in regions with no reference network, they have more utility than stationaries low-cost sensors by way of lower purchases and operating cost, more deployment flexibilities, and scalability. Stationary sensors vary concerning data quality that might affect a sensor, meaning there is the need for checking up the performance of a sensor intended for installation into an air quality monitoring network. The EPA has released performance targets for low-cost sensors, and calibration plays a very important role in meeting those targets.

- **Monitoring air quality using satellites**

Satellite technology with air quality monitoring is in the way of MODIS by NASA, for instance, through which one may monitor trends and events in greater scales as it deals with atmospheric chemistry. However, it lacks the ability to function in cloudy days since it needs to rely on sunlight and in its case, aerosol optical depth (AOD) measurements and ozone monitoring instrument are used. Together, ground-based and satellite measurements provide a "bigger picture" of the air quality situation. This will be useful for filling in areas where ground-based monitors aren't available, including in countries with poor infrastructure or in distant areas. Because of its low cost and wide coverage area, satellite air quality monitoring is becoming more popular. Nevertheless, its accuracy varies due to calibration biases and its operation runs at a reduced spatial and temporal resolution. Instead of replacing ground-based monitoring, ground-based models should continue to supplement it because they need to be ground-truthed.

3. GEOGRAPHIC INFORMATION SYSTEMS (GIS) IN AIR QUALITY ASSESSMENT

Geographic Information Systems (GIS) are indispensable in the assessment of air quality. It allows for the spatial analysis, mapping, and decision-making processes. How GIS is integrated into the assessment of air quality is explained here in detail [17]:

3.1.Integration of GIS in Spatial Analysis

Spatial analysis in GIS is the manipulation of geographical data to understand patterns, trends, and relationships across different spatial locations. In the context of air quality assessment, GIS integrates data from different sources such as remote sensing, ground-based monitoring stations, and weather data to perform spatial analysis. This integration allows the analysis of how air pollution levels vary across different geographic regions. The tools of GIS can process the air quality data in relation to the various environmental and human factors, which include population density, land use, traffic patterns, and proximity to industrial zones.

GIS integration in spatial analysis helps in the identification of hotspots for pollution, tracking the dispersion of pollutants, and visualizing the level of pollutants over time. The analysis thus enables understanding of the impact of air pollution in different areas of a city or region and hence forms a basis for targeted intervention and policy development.

3.2. Application in in Urban Air Quality Mapping

GIS mapping of urban air quality entails the development of high-resolution, spatially explicit maps that represent the spatial distribution of air pollutants over an urban area [18]. This kind of mapping is important in comprehending the level of air pollution over different parts of a city and identifying areas of priority concern.

Some specific applications of GIS in urban air quality mapping include:

- **Mapping pollutant concentration:** GIS can visualize air-pollutant concentration levels (e.g., PM, NO_2, SO_2) across urban regions to identify areas with extremely high levels of pollution.
- **Land use and air quality correlation:** GIS can lay down the air quality data on land use maps and identify the relationship between land use planning, industrial activities, density of traffic and green areas. For example, concentrations of pollutants might show high around highways or zones of industries.
- **Temporal monitoring:** GIS can enable the inclusion of temporal data, for example, historic air quality measurements or satellite images to develop time-series maps illustrating changes in air quality over time.
- **Source identification of pollution:** GIS can trace sources of pollution by analyzing spatial patterns of concentrations of air pollutants with regards to geographical features such as roads, power plants, or factories.

These maps can be used by urban planners, policy makers, and environmental agencies to target specific areas for improvements, such as stricter regulations on industries or more green spaces.

3.3.GIS's Function in Making Decisions

The role of GIS in decision-making is significant as it allows decision-makers powerful visual tools for analyzing and interpreting data about air quality. All insights gained from such analyses would support informed decisions by city planners, public health management teams, and in matters of environmental policy. The most important roles GIS performs in decision-making are the following [19]:

- **Policy formulation and regulation:** GIS helps policymakers gain an understanding of the spatial patterns of air pollution and provide scientific inputs on regulations, zoning laws, and industrial policies. For instance, if areas with high pollution are identified, then one may formulate air quality standards or install monitoring stations there to enhance quality.
- **Urban planning:** Urban planners use GIS in designing environmentally friendly cities, which are less likely to be polluted. For example, by comparing air quality with land use maps, urban planners can identify where to restrict the urbanization of an area or where green spaces are needed to be increased in an area to reduce air pollution.

- **Health and safety assessments:** GIS will be used to assess impact on public health due to poor air quality. For example, GIS can help with correlating the prevalence of respiratory diseases with air pollution levels thereby providing evidence for health intervention or informing the public concerning health risks associated with poor quality air.
- **Emergency response planning:** In instances where air pollution spikes to high levels due to industrial accidents, wildfires, or any other environmental crisis, GIS can be used to aid in the development of emergency response plans. It enables authorities to monitor the spread of pollutants, assess vulnerable populations, and coordinate mitigation efforts.
- **Public awareness:** GIS-based maps and visualizations also prove to be useful tools for raising public awareness about air quality issues. Interactive maps can be used to provide real-time air quality data to the public, helping individuals make informed decisions about their health, such as avoiding high-pollution areas or taking preventive measures during pollution peaks.

4. COMPARISON AND VALIDATION OF SATELLITE AND GROUND-BASED MEASUREMENTS

- **Strengths**: Global coverage through satellite-based air quality measurements brings an essential benefit. Since the measurements are taken around the globe, they will allow continuous monitoring of vast and remote areas that could otherwise not be accessed, hence providing an opportunity for uninterrupted data measurement. Satellites also are cost-effective in monitoring areas with no infrastructure and would be ideal for long-term trend tracking over decades. This advantage provides valuable information about pollution trends and the resulting health and environmental impacts [20]. Then, ground-based air quality measurements offer high spatial and temporal resolution and hence real-time information of air quality from the site. It can also be applied in identifying local air quality and detecting pollutants that are challenging for satellites to measure at ground level, such as certain gases and particulate matter. Ground-based measurements are also highly accurate and are not affected by atmospheric interference, making them very important for validating satellite data and ensuring comprehensive air quality assessments.
- **Limitations**: Satellite-based monitoring suffers from a number of drawbacks. First, due to the satellite overpass schedule, temporal resolution is poor and real-time monitoring at all times becomes impossible. Spatial resolution is limited and fails to capture the small-scale variations in air quality, especially in micro-environments. Additionally, ground-level pollutants cannot be accurately captured by satellites due to interference by the atmosphere, while cloud cover or bad weather may hinder the measurement [21]. All these drawbacks become much more pronounced in highly populous urban areas. Ground-based measurements have their own set of challenges, including high deployment and maintenance costs, which are financially infeasible for large-scale monitoring. They are location-specific and cannot cover remote or inaccessible regions. Ground stations give snapshots of local air quality, not continuous monitoring that satellite systems provide. Equipment malfunctions or environmental disruptions can also cause interruptions in data collection.
- **Accuracy Challenges in Urban Settings**: In the urban environment, urban heat islands, complex land cover, and atmospheric disturbances in the form of dust and clouds create difficulties with the satellite-based measurements. Along with the problem of detecting pollutants close to ground level, this makes the use of satellites for producing the data of air quality impossible in the dense polluted areas of cities. On the other hand, ground-based measurements are often influenced by local variability in air quality, such as traffic patterns or specific sources of pollution that might not reflect broader city-wide trends. Calibration issues could arise if stations are not properly maintained, resulting in inaccurate data. The localized

nature of the ground stations also means that the air quality data may not be representative of the whole city, thus the findings may not be generalized [22].

- **Integration and Validation Methods**: Validations can be done against ground-based observations in the overlapping areas by using statistical models or machine learning to correct satellite measurements. Data fusion techniques, combining satellite data with ground-based measurements, will enhance the spatial resolution and reliability of the data particularly in urban areas where variability is large. Ground-based data forms a benchmark for validating the satellite measurements. Statistical methods such as interpolation and kriging are used to improve spatial coverage and data integration across different regions [23]. A dynamic framework for air quality management and timely intervention arises from the integration of real-time monitoring systems with satellite data.

- **Data Integration Techniques**: Satellite-derived air quality data can be easily combined with geographic variables like land use, population density, among others, with the support of Geographic Information Systems. GIS facilitates detailed spatial analysis that can lead to a better identification of hotspots and assessment of risks for exposure. Kriging spatial interpolation technique is highly effective in improving the resolution of data in regions with scarce ground-based measurements. In addition, ground-based data are combined with GIS tools that map air quality for cities' planners to have visualization spatial distribution of pollutants so decisions are made appropriately. All these integrations have to increase the precision of models satellite and also bettered the overall air quality management strategy [24].

- **Urban Planning and Policy Application**: Monitoring the trend in long-term air quality over large geographic regions, thus long-term pollution patterns across larger areas, require data obtained from satellites. In more strategic policy-making instances such as wildfires or dust storms, satellite data helps broaden these processes. Resource allocation could be steered by satellite data indicating persistence in certain patterns of pollution [25-27]. It forms a guide for national or regional policy frameworks to address poor air quality. In local policy-making, it can do little for that matter but short-term policies. It enables targeted intervention in extremely polluted areas as well as compliance monitoring, to ensure fulfillment of air-quality standards; ground-based measurement allows an immediate response to real-time problems that might imperil people's health as well as improve public health.

- **Cost-Effectiveness**: Satellite-based air quality monitoring is also cost-effective since it covers such vast areas, especially in areas where ground infrastructure is missing. It will be much cheaper to set up and deploy satellites across large areas compared to ground-based systems [28-29]. Such systems are expensive to deploy and maintain, particularly in remote locations. It requires special equipment and staff for its routine operations, thus incurring higher operating costs. This financial burden limits the scalability of ground-based systems, especially in resource-constrained settings.

- **Temporal Coverage**: Satellite-based monitoring provides frequent data availability that is satellite's pass frequency-dependent. Thus, it provides continuous air quality monitoring over long periods, allowing the data to span years and even decades. For the evaluation of environmental change and the effectiveness of policies, such long-term datasets are valuable [30]. On the other hand, ground-based stations provide real-time, continuous data collection without the dependency on when the satellites pass. However, their long-term data collection is dependent on the maintenance and calibration of the equipment, which may require replacements.

5. CONCLUSION

Urban air quality is a significant challenge with far-reaching implications for public health, environmental sustainability, and economic stability. The first sources of air pollution in urban areas are anthropogenic. This emanates from industrial emissions, vehicular exhaust, and other human activities. It is possible that sometimes natural events will enhance the level of pollution. Harmonious air quality causes serious health issues such as respiratory and cardiovascular diseases, which predominantly affect vulnerable people like children, the elderly, and persons with pre-existing diseases. Apart from health consequences, it also affects ecosystems, biodiversity, and contributes to climate change through the release of greenhouse gases. Economic cost in terms of the costs to health and lost productivity due to air pollution is considerably very high and continues to challenge cities worldwide.

Advances in air quality monitoring technologies have provided better tools to track and manage pollution. Traditional methods, such as FRM and FEM monitors, provide highly accurate data but are often expensive and not so flexible for real-time or localized monitoring. Low-cost sensors have found a perfect balance between the price to be paid and real-time data collection; it also expands the network of monitoring systems in underserved areas. GIS technologies have an integral role in the analysis of trends in pollution. By gathering various data sources such as satellite imagery, ground-based sensors, and weather data, GIS helps to identify areas of pollution, improves urban planning, and guides targeted interventions. A combined approach that uses advanced monitoring technologies and GIS-based analysis is important in effectively tackling urban air pollution, enhancing public health, and minimizing environmental damage.

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