Caeli

Cleaner air & healthier cities

The role of satellite data in air quality monitoring

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Summary

This whitepaper underscores the importance of monitoring and improving air quality for human health and environmental sustainability using advanced satellite technology. It details key pollutants such as nitrogen oxides (NO_x), ammonia, ozone, carbon monoxide, sulfur dioxide, and particulate matter (PM_{10} and $PM_{2.5}$), influenced by human activities and natural processes. By leveraging innovative solutions for accurate air quality assessment, it aims to support informed decision-making by policymakers, researchers, and the public to foster healthier and cleaner cities.

Health impacts of air pollution
Exposure to fine particulate matter ($PM_{2.5}$) is linked to respiratory diseases, cardiovascular issues, lung cancer, and premature death. Nitrogen dioxide (NO_2) exposure can lead to respiratory problems, cardiovascular diseases, hindered lung development in children, and increased susceptibility to infections. These pollutants contribute significantly to premature deaths across Europe.

Major sources of air pollution include road transport, energy supply, and industrial processes. Effective control measures involve setting emissions standards, promoting clean energy, and implementing urban planning strategies to reduce traffic congestion.

Air quality guidelines and compliance
Adhering to European Union (EU) and World Health Organization (WHO) air quality guidelines is crucial. The EU's Zero Pollution Action Plan aligns with WHO guidelines to improve air quality by 2030. Advanced technologies like satellite data and artificial intelligence are vital for accurate monitoring and compliance.

The TROPOMI instrument on the Sentinel-5P satellite plays a pivotal role in monitoring air pollutants. Advanced algorithms process satellite data to map pollution accurately. Continuous machine learning training ensures precise and reliable air quality assessments.

Benefits of localized air quality data
Access to real-time, localized air quality data allows residents to make informed decisions about their activities, minimizing exposure to pollutants. Policymakers can develop targeted, effective policies to address pollution in specific areas. Machine learning models enhance data accuracy, supporting thorough decision-making for healthier communities.

In conclusion, leveraging satellite technology and advanced algorithms for air quality monitoring provides crucial insights for creating cleaner, healthier cities. This integrated approach ensures comprehensive air quality management, fostering a better environment for all.

1 Introduction

The insights of this whitepaper will provide a comprehensive overview of air quality, highlighting its importance for human health and the environment. This document aims to inform readers about the current possibilities of air quality monitoring, emphasizing the role of advanced satellite technology in providing accurate data. By detailing the innovative solutions available for air quality assessment, including comprehensive algorithms and the use of machine learning, it illustrates how satellite data can be leveraged to create healthier and happier neighborhoods. The goal is to raise awareness and encourage informed decision-making among policymakers, researchers, and the general public to improve air quality at both local and global levels.

Figure 1: A city enveloped in smog due to PM pollution.

2.1 What is air quality?

Air quality refers to the degree of air pollution in our atmosphere. It is determined by the concentration of pollutants present, which can vary due to human activities and natural processes, affecting the air we breathe.

Key gaseous air pollutants

Gaseous air pollutants include nitrogen oxides (such as NO_2), ammonia, ozone, carbon monoxide, and sulfur dioxide. These pollutants play a crucial role in determining air quality, interacting with other atmospheric components and affecting the overall concentration of pollutants in the air. While some of these gases are naturally present in the atmosphere in small amounts, human activities significantly increase their levels, making them major contributors to air pollution.

Particulate Matter

Particulate matter (PM), on the other hand, consists of tiny particles and liquid droplets suspended in the air. Unlike gaseous pollutants, PM can include a variety of substances such as dust, soot, and smoke, and is categorized based on particle size, including PM_{10} and $PM_{2.5}$.

Significance of NO_2 and PM

Among these pollutants, nitrogen dioxide (NO_2) and particulate matter (PM) are two significant culprits that heavily influence overall air quality. NO2 and PM play a major role in determining the quality of the air we breathe. Maintaining good air quality is essential for ensuring a sustainable and healthy environment, highlighting the importance of monitoring and controlling these pollutants.

Monitoring air quality helps identify pollution sources, understand pollution trends, and assess the effectiveness of regulations and interventions. Control measures, such as emissions standards for vehicles and industrial processes, the promotion of clean energy sources, and urban planning strategies to reduce traffic congestion, are vital in reducing pollutant levels and protecting public health.

By understanding the sources, effects, and control measures for key air pollutants like NO_2 and PM, we can better manage air quality and work towards a cleaner, healthier environment for all.

Figure 2: *Road traffic is the largest contributor to NO_2 emissions.*

Sources of air pollution

The primary source of nitrogen oxides (NO_x)[1] emissions is the road transport sector, including internal combustion engines in vehicles. Other significant contributors include the energy supply sector from fossil fuel combustion in power plants. Additionally, emissions from industrial processes in the manufacturing and extractive industries also contribute significantly to NO_x levels.

The largest contributor to $PM_{2.5}$ emissions is the residential, commercial, and institutional sector. This is primarily due to energy consumption from burning solid biomass and fossil fuels for residential heating. The manufacturing and extractive industry sector and road transport also contribute significantly, with emissions arising from industrial activities, internal combustion engines, and tyre and brake wear. For PM_{10}, clearly the residential, commercial, and institutional sector remains the main source.

Air pollution mainly comes from road traffic and the residential, commercial, and institutional sectors. These sources, including vehicles on the road and heating systems in homes, are present in our daily lives. This widespread pollution affects everyone and significantly impacts our health, which can lead to serious issues.

Main emission sources in the EU, 2021

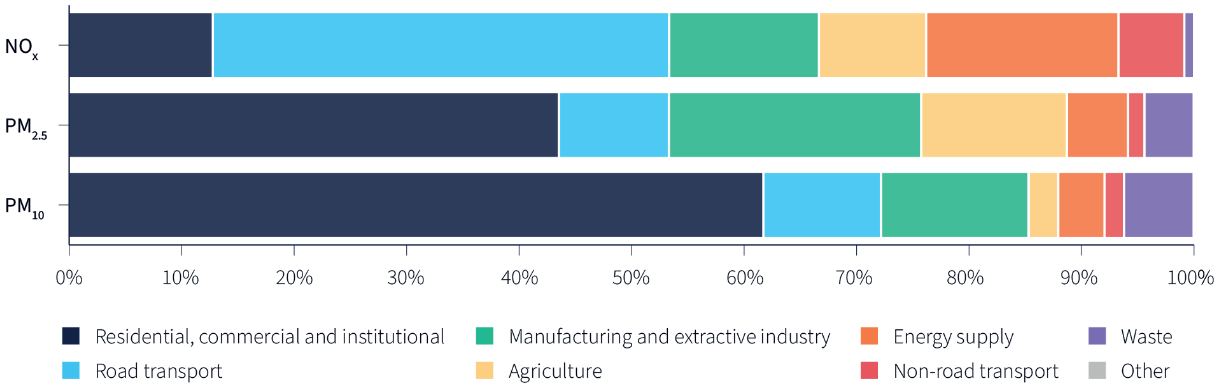

Figure 3: *Main emission sources for NO_x, $PM_{2.5}$ & PM_{10} in the EU-27 Countries (European Environment Agency 2023)*

1. NO_x (nitrogen oxides) refers to NO (nitric oxide) and NO_2 (nitrogen dioxide). NO_2, a major component, is primarily responsible for the health effects of NO_x pollution

2.2 Effects of air pollution on human health

Air pollution significantly impacts human health, contributing to various health issues. Understanding specific pollutants is crucial for improving public health. Two key pollutants, particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2), are particularly harmful due to their widespread presence and effects.

Health effects of Particulate Matter

Fine particulate matter ($PM_{2.5}$) is one of the most dangerous air pollutants due to its small size, which allows it to penetrate deep into the respiratory system and even enter the bloodstream. The widespread presence of these sources means that $PM_{2.5}$ pollution is a pervasive issue, affecting millions of people across Europe. Exposure to $PM_{2.5}$ has been linked to a range of serious health problems:

1. **Respiratory diseases:** Exposure can worsen asthma, bronchitis, and other chronic respiratory conditions and increase the risk of lung infections.
2. **Cardiovascular diseases:** Long-term exposure to $PM_{2.5}$ is associated with an increased risk of heart attacks, strokes, and other cardiovascular problems.
3. **Lung cancer:** $PM_{2.5}$ is a known carcinogen and contributes to the development of lung cancer.
4. **Premature death:** The most severe consequence of $PM_{2.5}$ exposure is an increased risk of premature death. This pollutant contributes significantly to mortality rates, especially among vulnerable populations such as children, the elderly, and those with pre-existing health conditions.

Particulate Matter pollution is responsible for a substantial burden of premature deaths across Europe. Countries in Eastern and Central Europe, such as Poland and Italy, are particularly affected due to factors like industrial emissions, residential heating using solid fuels, and vehicular traffic. Addressing $PM_{2.5}$ pollution is crucial for improving public health and reducing mortality rates.

EU countries with the highest number of premature deaths attributable to $PM_{2.5}$ in 2021

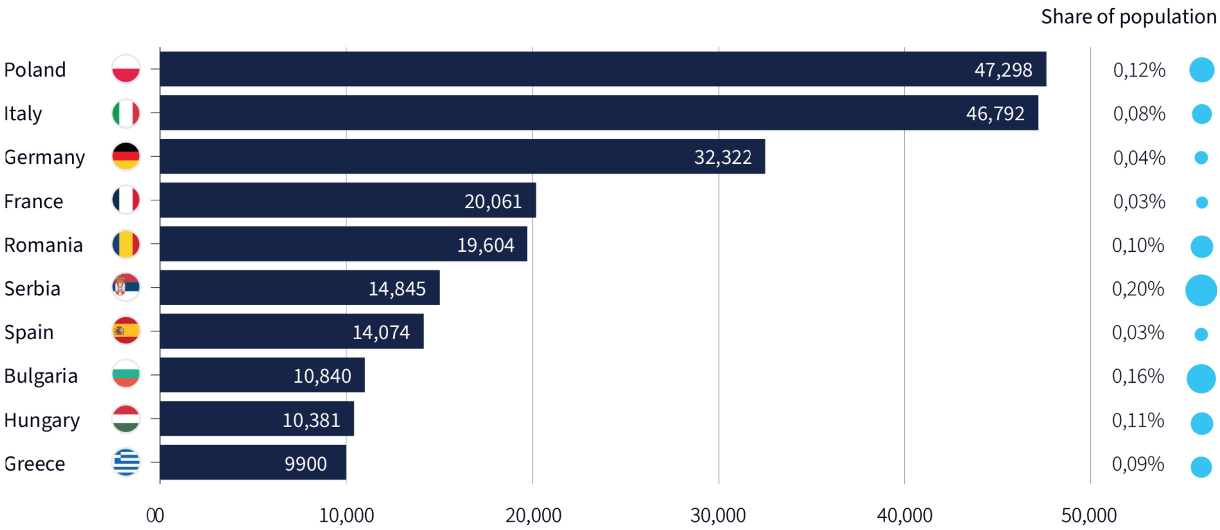

Figure 4: Top 10 EU-27 countries with estimated premature deaths attributable to $PM_{2.5}$ exposure in 2021(European Environment Agency, 2023) (Our World in Data, 2023)

Health effects of Nitrogen Dioxide

Nitrogen dioxide is a major pollutant with significant health impacts. Due to its pervasive presence in urban environments, chronic exposure to NO_2 affects millions of people. Prolonged exposure to NO_2 has been linked to a range of serious health problems:

1. **Respiratory issues:** NO_2 irritates the airways in the human respiratory system, leading to coughing, wheezing, and shortness of breath. It can exacerbate conditions like asthma and bronchitis.

2. **Cardiovascular problems:** Long-term exposure is linked to an increased risk of heart disease. It can contribute to the development of hypertension and other cardiovascular issues.

3. **Lung development in children:** Exposure can hinder lung development in children, leading to long-term health issues and reduced lung function.

4. **Increased susceptibility to infections:** NO_2 exposure can reduce the immune system's ability to fight off infections, increasing the likelihood of respiratory infections.

5. **Premature death:** High levels of NO_2 exposure are associated with an increased risk of premature death due to respiratory and cardiovascular diseases.

The impact of NO_2 pollution on health is evident in the number of premature deaths across EU countries. Countries such as Italy, Germany, and France have particularly high numbers of premature deaths attributable to NO_2 exposure. These statistics highlight the critical need to address NO_2 pollution to improve public health.

EU countries with the highest number of premature deaths attributable to NO_2 in 2021

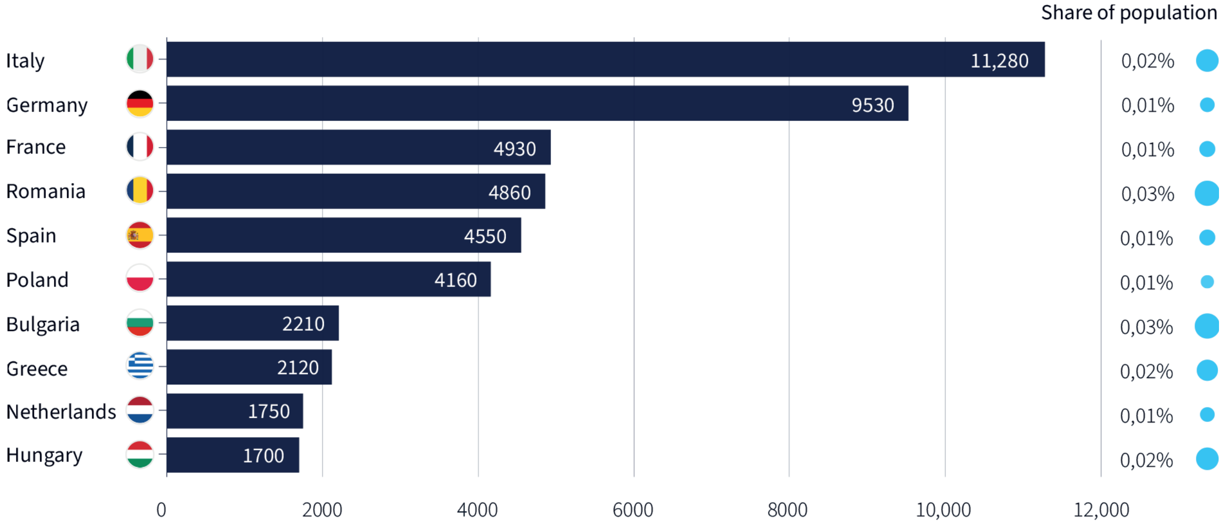

Figure 5: *Top 10 EU-27 countries with estimated premature deaths attributable to NO_2 exposure in 2021(European Environment Agency, 2023) (Our World in Data, 2023)*

2.3 Ensuring compliance with air quality guidelines

To address the challenges of air pollution, it is essential to adhere to the air quality guidelines set by the European Union (EU) and the World Health Organization (WHO). The recent revision of WHO guidelines marks a significant milestone in the global fight against air pollution and underscores the need for coordinated international action. Countries are encouraged to take ambitious measures to improve air quality and reduce exposure to pollutants to protect public health and the environment for current and future generations.

Innovative solutions play a crucial role in this effort. By leveraging advanced technologies such as satellite data and artificial intelligence, accurate and detailed information about local air quality can be provided. This data is vital for developing and implementing policies that meet WHO guidelines and EU standards.

The European Commission's Zero Pollution Action Plan, launched in May 2021, emphasizes the need to align current EU air quality standards with the new WHO guidelines. Revising the directive to focus on health benefits is essential for improving air quality. Identifying additional measures to meet the new WHO guidelines by 2030 underscores the importance of ongoing efforts to improve air quality. Effective monitoring of these air pollutants is crucial for protecting public health and ensuring a healthier environment for all citizens.

Air pollutant	WHO guideline (2005)	WHO guideline (2021)	EU guideline (Current)	EU guideline (2030)
$PM_{2.5}$	10 µg/m^3	5 µg/m^3	25 µg/m^3	10 µg/m^3
PM_{10}	20 µg/m^3	15 µg/m^3	40 µg/m^3	40 µg/m^3
NO_2	40 µg/m^3	10 µg/m^3	40 µg/m^3	20 µg/m^3

Figure 6: WHO guidelines, current EU standards, and future EU standards from 2030.

Figure 7: TROPOMI instrument on board the Sentinel-5P satellite (KNMI)

3 Techniques for air quality monitoring

Effective air quality monitoring is achieved through a combination of advanced technologies and methodologies. This chapter explores the key techniques used to gather and analyze air quality data, ensuring precise and comprehensive insights.

One of the pivotal technologies in this field is the TROPOMI (Tropospheric Monitoring Instrument), a Dutch instrument aboard the Sentinel-5P satellite. TROPOMI has been observing the Earth from space, providing invaluable data for air quality monitoring. Its advanced sensors capture detailed information on various pollutants, such as nitrogen dioxide (NO_2) and particulate matter (PM).

Detailed satellite data

The cornerstone of effective air quality monitoring lies in the utilization of detailed satellite data. Satellites equipped with advanced sensors offer extensive, real-time data on various air pollutants across vast geographic areas. This data is essential for understanding the spatial distribution of pollutants like PM and NO_2, especially in regions where ground-based monitoring is sparse or non-existent. High-resolution satellite imagery and data enable continuous monitoring and detection of pollution patterns that would otherwise remain undetected.

Advanced algorithms

Transforming raw satellite data into meaningful air quality insights requires sophisticated algorithms. These algorithms analyze satellite data while accounting for factors such as weather conditions, topography, land use, and emission sources. By integrating multiple data sources, these algorithms enhance the accumake racy of pollution mapping. They process vast amounts of data efficiently, providing near real-time updates on air quality levels and tracking changes and trends with precision, both on a monthly and annual basis.

Continuous training

Accuracy in air quality monitoring is further ensured through the continuous training of machine learning models using data from ground sensors. Ground-based sensors provide localized, high-precision measurements of air pollutants, which are crucial for calibrating and validating satellite data. Integrating sensor data into machine learning models ensures that the information provided is not only accurate but also highly detailed. This continuous training process allows models to adapt to new data and improve over time, resulting in the most reliable air quality assessments available.

Role of generative AI models

Generative AI models, such as Generative Adversarial Networks (GANs) and Convolutional Neural Networks (CNNs), play a crucial role in enhancing the resolution of satellite images. These models learn from large datasets to generate new data that isn't directly available in the original dataset. In the context of satellite imagery, AI models are trained on high-resolution images to recognize patterns and textures. When presented with low-resolution images, the AI uses its learned knowledge to predict and generate the missing details, creating higher resolution images. These details are predictions based on probabilities derived from the training data.

Monthly validations of the AI model outputs are conducted to ensure the accuracy and reliability of the generated high-resolution images. By regularly comparing the AI-generated images with new high-resolution data, the performance of the AI models is continuously evaluated and optimized.

Accurate and detailed pollutant mapping

The advanced system, supported by the expertise of a highly experienced team, provides detailed information down to the neighborhood level. This enables residents, policymakers, and researchers to understand air quality conditions with unparalleled specificity. Detailed mapping is essential for identifying pollution hotspots, assessing the effectiveness of air quality interventions, and making informed decisions to protect public health and the environment.

In summary, this approach to air quality monitoring harnesses the power of satellite data, advanced algorithms, and continuous machine learning to deliver the highest level of accuracy and detail in pollution mapping. This integrated technique ensures comprehensive air quality insights, fostering a cleaner, healthier world.

4.1 **Detailed air quality assessment**

Neighborhood-level air quality monitoring involves the collection and analysis of air quality data at a highly localized scale. This approach leverages advanced satellite data, sophisticated algorithms, and continuous machine learning to provide precise and detailed information about the air quality in specific neighborhoods. By focusing on smaller areas, this method can identify pollution hotspots and track air quality trends with great accuracy, allowing for more effective interventions and policies.

4.2 **Case study: Monitoring air quality in Apeldoorn**

In this case study, we examine the municipality of Apeldoorn in the Netherlands. The focus is on neighborhood-level air quality monitoring, which has revealed significant variations in NO_2 and $PM_{2.5}$ levels across different areas of the city.

These maps (Figure 9 to 12) show the concentrations of NO_2 and $PM_{2.5}$ across Apeldoorn neighborhoods in 2019, with color schemes based on WHO and EU guidelines. A clear breakpoint at 10 µg/m^3 for NO_2 and 5 µg/m^3 for $PM_{2.5}$ indicates areas exceeding WHO limits. The data reveals that all neighborhoods surpassed the WHO guidelines for both pollutants.

In addition to neighborhood averages, contour maps that show pollution hotspots not bound by administrative boundaries. These contour maps offer a more nuanced view of air quality, highlighting specific areas with elevated pollutant levels, which can be crucial for identifying precise sources of pollution and implementing targeted interventions.

Concentrations can also be displayed on a monthly basis with monthly averages to get insights into air quality trends throughout the year (Figure 8). This data helps in understanding seasonal variations and the impact of specific events or activities on air quality.

In Apeldoorn, neighborhood-level monitoring in 2019 revealed significant variations in NO_2 and $PM_{2.5}$ levels, with all neighborhoods exceeding WHO guidelines. Higher concentrations were observed near busy roads and industrial zones. With access to our detailed air quality data, local authorities can conduct more in-depth analyses to identify specific sources of pollution and patterns over time. This enables the implementation of targeted measures, such as traffic regulations and green buffer zones, to effectively mitigate pollution in the most affected areas. A detailed map is provided on the next page (Figure 13), where you can see the relationship between NO_2 concentrations, the city, and the highways.

Monthly average concentrations of NO_2 in Apeldoorn in 2019

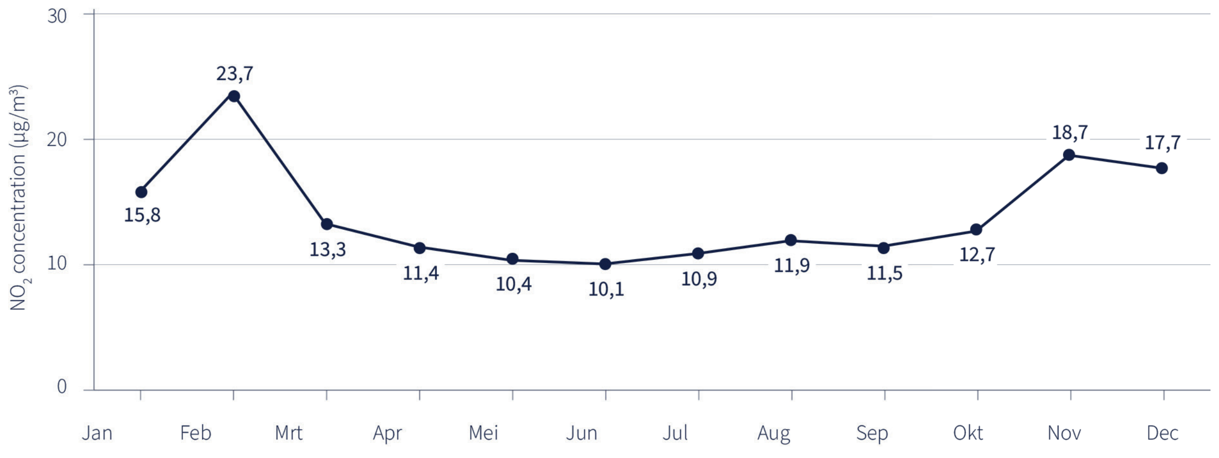

Figure 8: Trend of monthly average nitrogen dioxide concentrations in the municipality of Apeldoorn in 2019

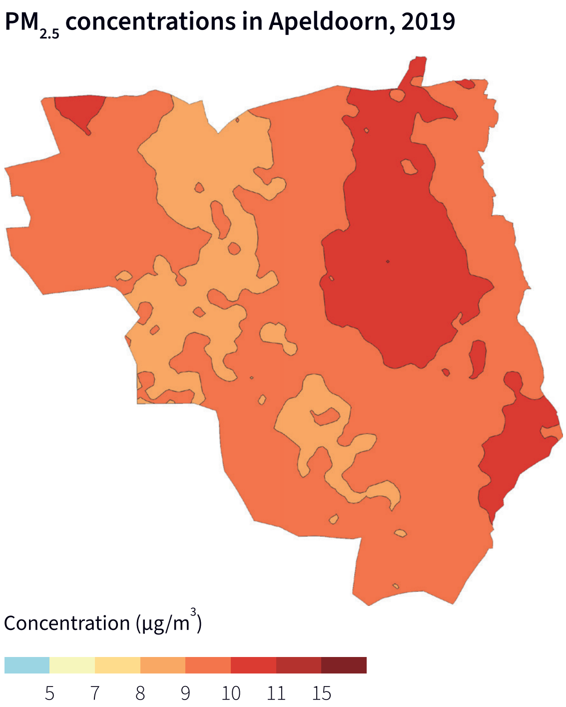

Figure 9: *Contour map of average* $PM_{2.5}$ *concentration in Apeldoorn (2019)*

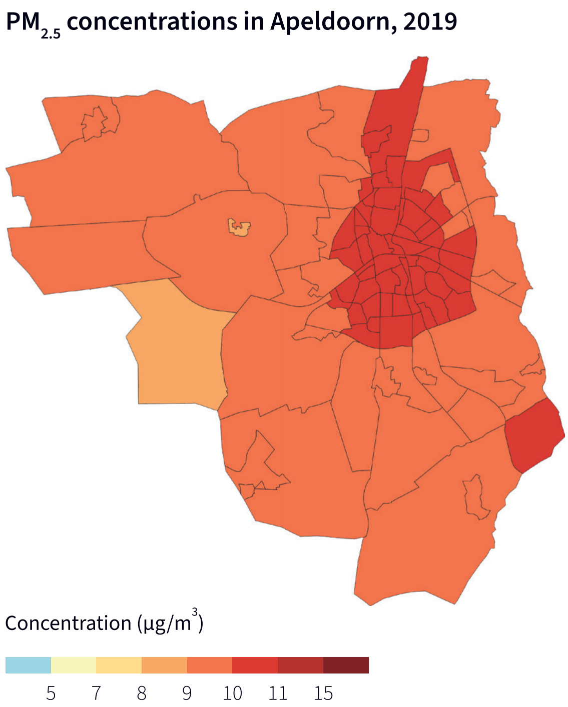

Figure 10: *Average* $PM_{2.5}$ *concentration in Apeldoorn neighborhoods (2019)*

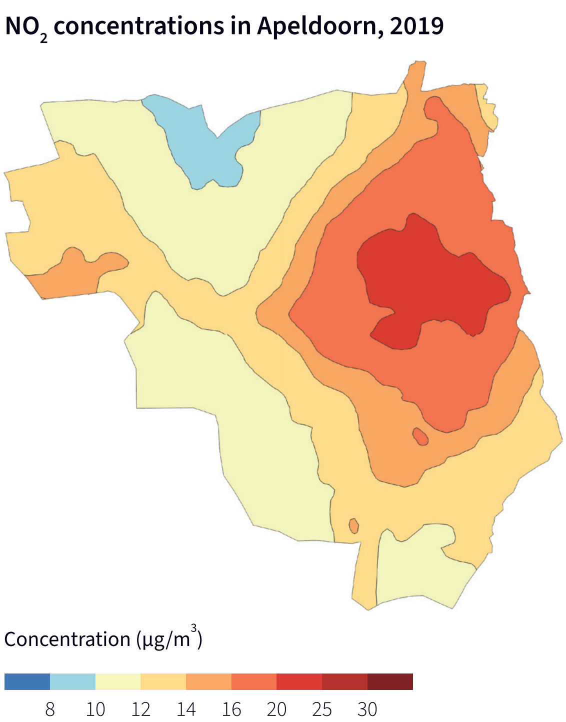

Figure 11: *Contour map of average* NO_2 *concentration in Apeldoorn (2019)*

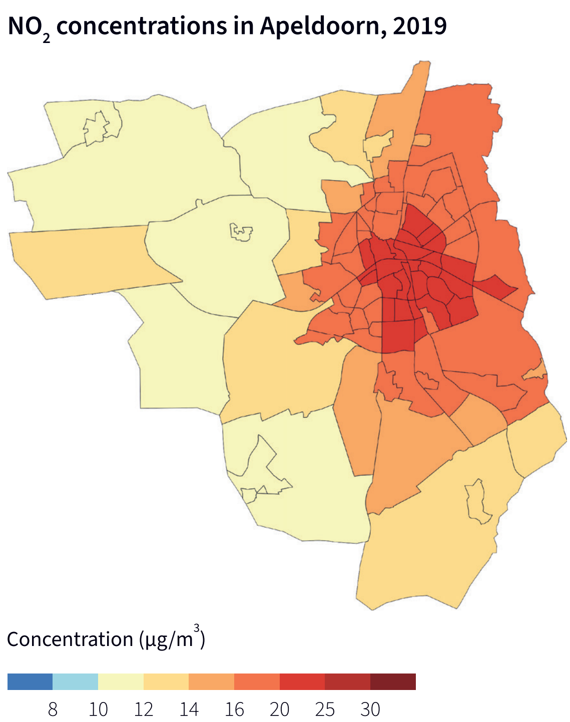

Figure 12: *Average* NO_2 *concentration in Apeldoorn neighborhoods (2019)*

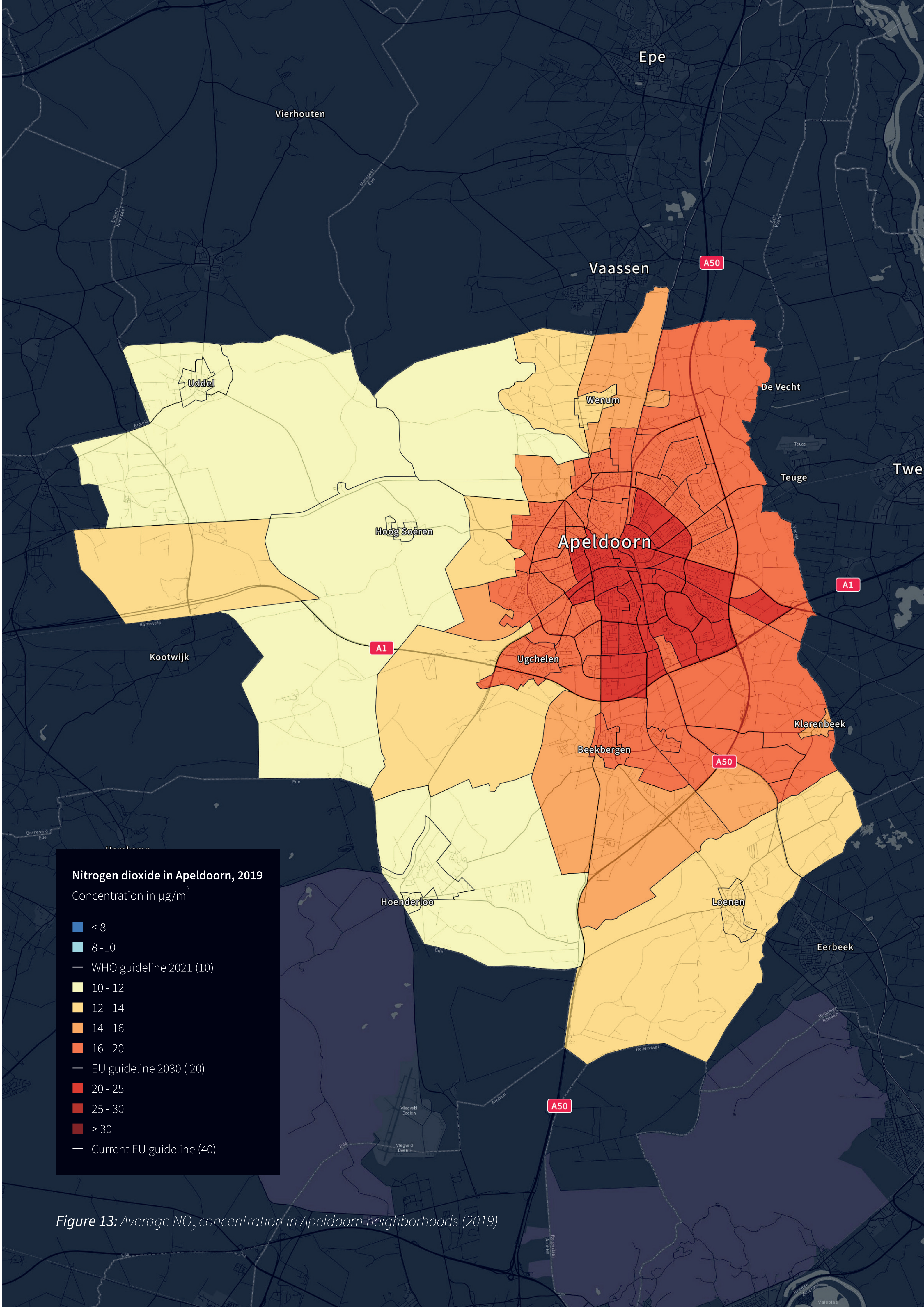

Figure 13: Average NO_2 concentration in Apeldoorn neighborhoods (2019)

Figure 14: Example of Caeli's Air Quality Monitor

4.3 Benefits of localized data

The availability of localized air quality data offers numerous advantages for both residents and policymakers, enhancing the ability to make informed decisions and implement effective measures.

For residents:

- Access to real-time air quality information enables individuals to make informed decisions about their daily activities, such as outdoor exercise or travel routes, to minimize exposure to pollutants.

- Increased awareness of air quality issues fosters community engagement and advocacy for cleaner air initiatives.

For policymakers:

- Detailed air quality data supports the development of targeted, effective policies aimed at reducing pollution in specific areas.

- Policymakers can use this data to inform mayors and aldermen of municipalities, ensuring that local leaders are well-equipped to address air quality challenges.

- Accurate, localized data helps in writing precise policy plans that address the unique needs and conditions of different neighborhoods.

The role of machine learning and algorithms

With the approach of machine learning (ML) and the use of advanced algorithms, obtaining localized and detailed air quality data is not only possible but also highly effective. Machine learning models continuously learn and improve from the data collected by ground sensors and satellites, ensuring that the information provided is both current and highly accurate. This level of detail and precision is essential for making thorough decisions about the environment and neighborhoods, ultimately leading to healthier and more sustainable communities.

The Air Quality Monitor by Caeli provides a comprehensive solution for monitoring and improving air quality. By leveraging advanced satellite data and machine learning algorithms, it delivers real-time, high-resolution air quality information. This tool helps both residents and policymakers make informed decisions to create healthier and more sustainable communities.

(www.caeli.nl/aqm)

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If this whitepaper has sparked your interest in our products, including our described Air Quality Monitor, or if you have any questions or need more information, please feel free to reach out to us.

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