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Real-time Read and Analysis of Air Pollution Produced from Private Electrical Generators in Mosul City using LoRaWAN

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Abstract - This study presents a novel, site-specific deployment of a Long Range Wide Area Network (LoRaWAN)-driven air pollution monitoring network specifically for the Iraqi city of Mosul, which is beset by widespread power outages and extensive utilization of decentralized diesel generators. While these generators mitigate electricity shortages, they are enormous contributors to urban air pollution, emitting high levels of CO_2 and particulates. As opposed to previous studies, which concentrate on affluent urban areas, this research addresses a very deprived locale using an extensible low-power, low-cost LoRaWAN network and high-precision CO_2 sensors (Sensirion SCD30 and MH-Z19) and The Things Network (TTN) for real-time data aggregation. With geo-referenced generator mapping integrated into the system, systematically distributed sensor nodes, and spatial interpolation via Geographic Information System (GIS), the system acquires seasonally varying emissions and identifies hotspots of pollution. Temperature and humidity data are incorporated to calibrate sensors so that the emission models are improved. Furthermore, the study conducts an operational evaluation of the LoRaWAN network over Mosul's urban densification, investigating link stability, RSSI, latency, and packet loss to verify network performance in actual conditions. The results highlight strong seasonal correlation between generator working and CO_2 flux, reinforcing the climate-energy-emission nexus. Practically, LoRaWAN's infrastructure-independent and long-range design would be particularly apt to Mosul's connectivity-deficient terrain, serving as a robust platform for environmental monitoring and planning regulation. This research makes a significant contribution to the field by proposing an open, reproducible IoT-based framework for urban air quality control in energy-constrained regions and outlines future directions encompassing multi-pollutant sensing, mobile sensor nodes, and blockchain-secured data communication for enhanced trust and system reliability.

Keywords— LoRaWAN, Air Quality Monitoring, CO_2 Emissions, Diesel Generators, IoT, The Things Network, Mosul, Smart Cities, Environmental IoT.

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1. INTRODUCTION

1.1 Background and Historical Context

Iraq's power sector remains buried under a chronic crisis, an outcome of decades of war, infrastructural wear, and institutional turbulence. Paralyzing effects from the 1991 Gulf War and resulting economic sanctions stunted the power generation infrastructure in the country and stopped grid modernization [1]. The war in 2003 hastened further decline, and essential infrastructure—power stations, transmission lines, and substations—became defunct due to war damages and prolonged lack of maintenance [2]. Despite post-war reconstruction, Iraq's electricity supply woefully falls behind demand. Peak demand in 2019 was 26 GW, more than double the grid's 16 GW capacity, a deficit that persists to this day [3]. Summer peaks exacerbate this deficit: summer peak demand is more than 35 GW, more than 10 GW above supply [4]. In Mosul, the conditions are critical. The city's power grid, already compromised, was further ravaged under ISIS rule (2014–2017), stifling recovery and forcing near-total reliance on private diesel generators [5]. These localized units, while a short-term solution, take disastrous environmental and economic toll—a survivability versus sustainability dilemma [6].

1.2 Environmental and Health Impacts of Diesel Generators

The dominance of diesel generators with more than 1000 sites with generators installed has rendered Mosul's cityscape an emissions-heavy urban city as shown in Figure 1, with devastating impacts on air quality and the public's health. Diesel generators emit CO_2, NO_x, SO_2, and PM2.5/PM10 at thousands of times more than safety levels, particularly within dense generator suburbs [7]. Epidemiological studies link prolonged exposure to elevated CO_2 and PM2.5 levels with respiratory disease, cardiovascular morbidity, and early mortality [8]. Compounding this, the absence of enforceable emissions regulations allows generators to operate freely in residential areas, increasing health risks [9].

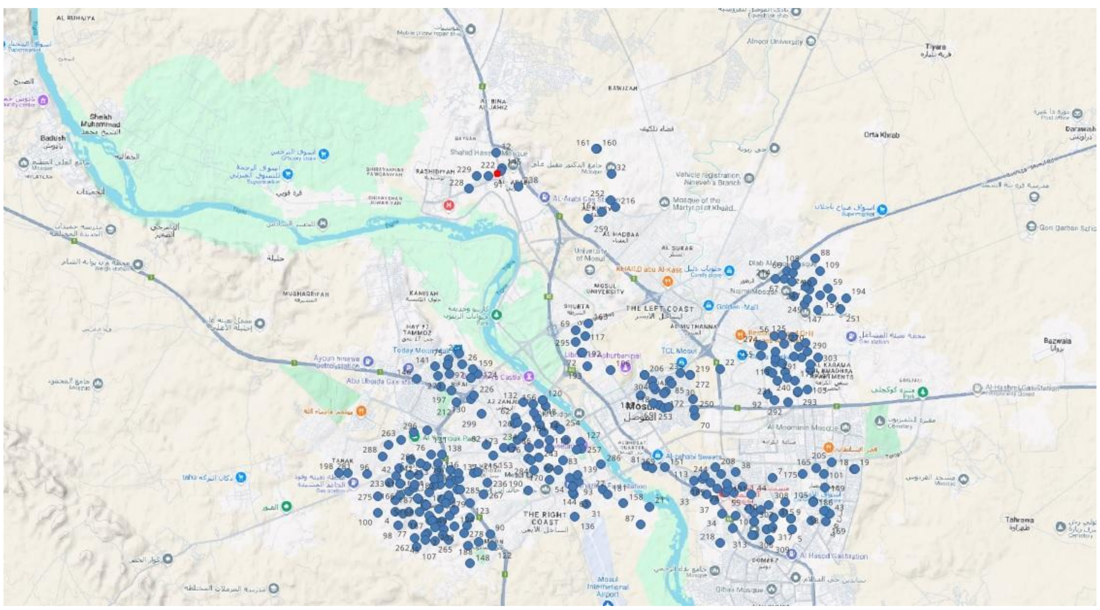

Figure 1. Geographical Distribution of Deisel Electrical Generators Across Mosul City

Three systemic failures underline this crisis:

- **Lack of Real-Time Monitoring** - Iraq lacks infrastructure to monitor air quality, concealing pollution trends and health impacts [1].
- **Regulatory Vacuum** - There is no policy to regulate the use of generators, with no penalty for their excessive emissions [10].
- **Public Dependence** - Lack of alternatives and a lack of awareness place citizens in a cycle of addiction to emitting technologies [11].

This problem trinity has demanded IoT-based solutions for policymaking and measuring emissions.

1.3 Technological Intervention: LoRaWAN for Air Quality Monitoring

Recent IoT architecture, LoRaWAN, offer the revolutionary solution of urban environmental sensing as can be seen in Figure 2. LoRaWAN's unique strengths—multi-kilometer range low-power connectivity, ultra-low consumption, and expandable topology—are particularly suitable for cities like Mosul city [12], [13] as shown in Figure 3. In this study, we implemented a real-time air quality monitoring system by deploying a LoRaWAN-based sensor network that integrates advanced CO_2 sensors, specifically the Sensirion SCD30 and MH-Z19, through TTN infrastructure. The proposed architecture emphasizes three core design principles: spatiotemporal resolution, achieved through high-density placement of sensors strategically positioned around clusters of diesel generators; energy efficiency, enabled by low-power nodes capable of operating on battery power for multiple years; and cost-effectiveness, by leveraging unlicensed frequency bands to significantly reduce operational and communication overhead [14]. This configuration ensures scalable, sustainable, and precise environmental monitoring in urban landscapes affected by pollutant sources.

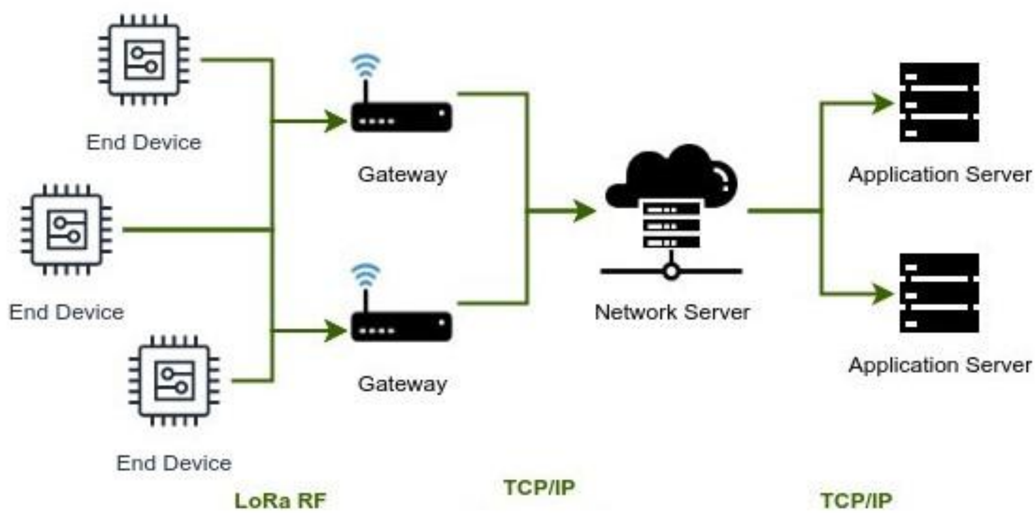

Figure 2. LoRaWAN Communication Architecture

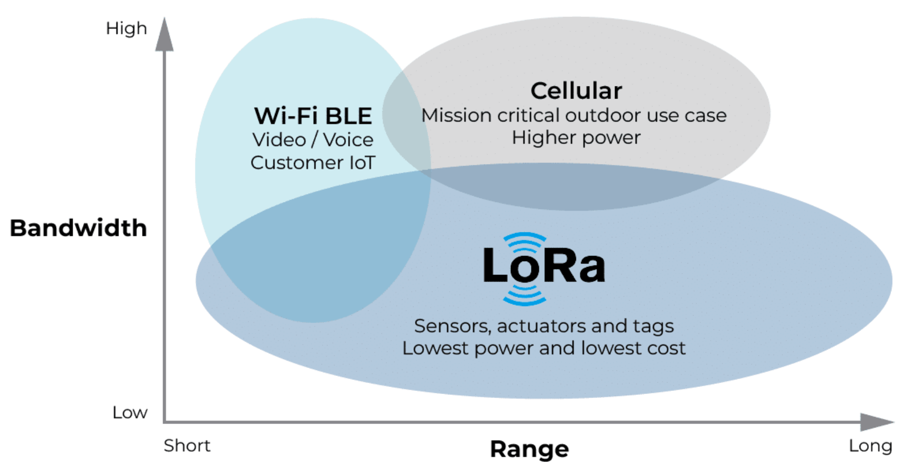

Figure 3. Comparative Spectrum of Wireless IoT Technologies Based on Range and Power Consumption

1.4 Research Objectives

This research is in remembrance of the strategic design and execution of a complex LoRaWAN-capable air quality monitoring network in the city of Mosul with specific focus given to the struggle against pollution through decentralized diesel power plants. The primary objective is to establish a robust, real-time sensor system capable of incessantly tracking CO_2 concentrations within urban environments most affected by emissions from generators. Through precise spatial analysis, the system will map the spatial clustering of diesel generators and connect these to emerging emission hotspots, giving meaningful insight into patterns of environmental degradation. The study will also monitor and analyse seasonality in CO_2 levels, shedding light on the cyclical relationship between air pollution and seasonal variations in energy demand. One of the techno pillars of the research is comparative performance benchmarking of LoRaWAN communications protocols, intensively tested applying rigorous metrics such as RSSI (Received Signal Strength Indicator), packet delivery rate, and end-to-end delay. Finally, this research will try to make scientific evidence meet action by way of opening opportunities for evidence-driven environmental policy action aimed at reducing harmful emissions as well as providing protection to vulnerable urban communities' public health.

1.5 Significance of the Study

This research stands at the intersection of environmental science, IoT-enabled engineering, and evidence-based policymaking, offering a game-changing system for urban air quality management in cities choked by diesel-driven emissions. By its leveraging of real-time CO_2 data mined from a hardened LoRaWAN network infrastructure, the research has immediate relevance to public health enhancement through enabling real-time awareness and pro-active intervention that can minimize population exposure to harmful pollutants [11]. Beyond its public health relevance, the network is a model for smart urbanism, demonstrating the potential for low-power wide-area networks to enable scalable, affordable environmental monitoring in resource-constrained cities [15]. Furthermore, the study offers empirical leverage for regulatory reform by offering actual, localized data to support the enforcement of emissions standards — in alignment with recommendations by international development agencies such as the UNDP [15]. Most significantly, the platform modularity allows for long-term scalability, with simple extension to additional pollutants, e.g., NO_2 and PM2.5, and replication in various urban geographies, thereby increasing its value as a catalytic tool for sustainable urban governance and environmental justice.

2. LITERATURE REVIEW

New IoT and LPWAN technologies have transformed air quality measurements in recent years by enabling the real-time capture of data with unprecedented temporal and spatial resolution. The new technologies are unprecedentedly energy-frugal, cost-effective, and scalable — making them perfectly adapted for implementation in cities with energy shortages and ecological deserts [1], [2]. This research combines cutting-edge research in three highly interconnected fields: (i) IoT-enabled use of infrastructure as a sensor of pollution, which provides decentralized sensing along with edge-level analytics capability [3]; (ii) LoRaWAN networks for environmental monitoring, renowned for their extended range of communication as well as zero energy consumption profile [4], [5]; and (iii) research that assesses the environmental as well as the public health impacts of exhaust emissions from diesel generators, particularly in sensitive energy infrastructures where exponentially growing off-grid power source demands exist [6], [7]. By the coming together of these streams of work, the research emphasizes the paramount significance of scalable, real-time, and policy-targeted monitoring infrastructures in fragile urban environments. While all these disciplines have progressed together, literature has not yet been able to comprehensively discuss integrating these technologies into Mosul-like fragile urban infrastructure or using them for long-term monitoring of decentralized source emissions such as diesel generators.

2.1 IoT-Based Air Pollution Monitoring

The advent of inexpensive, high-resolution IoT sensors has enabled driving a paradigm change in urban air quality monitoring to lead cities out of episodic, labour-intensive sampling and onto hyperlocal, real-time observation. The same has enabled municipal governments to have real-time environmental intelligence for decision-making and action on public health. Beijing, for example, has rolled out an enormous IoT-based air monitoring network with in-built

CO_2, NO_2, and PM2.5 sensors backed by cloud analytics that recorded greater than 90% accuracy against reference stations and demonstrated the feasibility of IoT as a platform for regulatory-grade monitoring [16]. The integration of IoT components such as GPS tracking, environmental sensors, and emergency alert mechanisms within a safety system reflects the foundational principles of LoRa-based networks—enabling reliable, low-power, and real-time monitoring for critical applications across distributed smart environments [17]. In Seoul, the real-time network of IoT provided regulatory action in real-time fashion, wherein the authorities were able to cut industrial NO_2 emissions by 22% by a six-month pilot test [18]. Though valuable contributions, there is one significant research gap that has not been addressed yet: previously, research has been conducted on traffic and industrial emissions, but decentralized sources such as the widespread use of diesel generators in energy-deficient regions like Mosul have not been addressed. This work addresses this gap square on in researching LoRaWAN-enabled monitoring of CO_2 emissions from off-grid distributed power generation. By doing so, it not only extends the geographic coverage of IoT-based monitoring to post-conflict and underdeveloped settings, but also shifts attention to unregulated micro-pollution sources, which are typically inaudible in macro-level monitoring systems. The work presented in [19] shoed that the integration of blockchain platforms like Hyperledger Fabric into IoT environments aligns with the core goals of LoRa-based networks—ensuring secure, efficient, and scalable data collection and transmission through layered architectures tailored for low-power, wide-area communication systems. The structured exchange of navigation and location data through lightweight communication protocols reflects the core principles of LoRa-based networks—demonstrating how low-power, long-range communication can enable scalable data sharing within smart city and IoT frameworks [20]. Similarly, in New Delhi, researchers demonstrated that IoT streams enriched with machine learning may forecast air pollution bursts by 24 hours, complemented with the precious pre-emptive reporting of public health alerts [21].

2.2 LoRaWAN for Environmental Sensing

LoRaWAN is a de facto standard technology for large-scale environmental IoT networks because of its very low power consumption with battery longevity of up to 10 years and long range (of several kilometres), aided by the ability to achieve adaptive modulation-based flexible data rate handling. Each of these capabilities renders it a very effective solution for economically feasible, long-term sustainable air quality monitoring in cities. In Dhaka, a new deployment of a 200-node LoRaWAN network also recorded packet loss rates of under 1% at 5 km distances, even with dense urban RF interference present—verifying the resilience of LoRaWAN to real-world radio frequencies [19]. A 1-year trial in Madrid compared LoRaWAN and NB-IoT side by side for transmitting pollution data and discovered that LoRaWAN used 83% less power with no significant differences in throughput, thereby settling the power efficiency benefits beyond doubt [22]. LoRaWAN was tested in Karachi as a low-cost alternative for cellular IoT, in which a single gateway could provide 15 km^2 coverage for a tenth of the deployment cost, demonstrating its suitability for resource-constrained settings [23]. While such deployments validate the potential of LoRaWAN for ambient urban air monitoring, a critical research avenue remains uncharted—namely, source-specific emission monitoring of emissions from decentralized diesel generators. The current work fills this overlooked dimension in a simple way by leveraging LoRaWAN to establish high-resolution, real-time CO_2 emissions monitoring data from generator-dense micro-environments, namely, electricity-poor urban environments. Unlike past studies that have measured air quality as a background phenomenon in general, this approach employs LoRaWAN at the source level and offers traceable, localized measurement of distributed emitters, closing the accountability gap in urban pollution management.

2.3 Diesel Generator Pollution and Air Quality Studies

Exhaust emissions of diesel generators have been widely documented in literature as having public and environmental health implications but are under-measured during energy insecurity and infrastructural crises. Quantitative analysis of generator CO_2 emissions in Kuala Lumpur in one study found concentrations near-school and near-hospital to be 2.4 times that of urban background concentrations—referring to disproportionate risk to susceptible populations [23]. In Basra, Iraq, geospatial analysis of NO_2 concentrations accounted for 32% of high childhood asthma events to the direct effect of generator exhaust plumes and identified residential hotspots that overlapped with prolonged generator operation [24]. In Baghdad, on the other hand, Computational Fluid Dynamics (CFD) was applied in simulating PM2.5 dispersion patterns around clusters of diesel generators, and significant statistical associations between modelled levels of exposure and visits for respiratory emergency room admissions were obtained [25]. Although these findings are significant, there is a natural methodological limitation in each of the studies, i.e., their employment of short-term, hand-operated sampling techniques, which are not of sufficient temporal resolution to enable real-time observation or responsive policy action. This limitation dictates the present research's adoption of continuous, IoT-driven monitoring to deliver actionable feedback towards controlling emissions in urban environments typified by energy supply through generators [26]. By the application of a pervasive sensing infrastructure that monitors both spatiotemporal emission rates and proximate environmental conditions, this research corrects the long-standing absence of continuous monitoring systems in generator-reliant urban environments [27].

3. RESEARCH METHODOLOGY

This paper proposes a LoRaWAN-enabled air quality monitoring system tailored to Mosul, Iraq, a city experiencing widespread use of diesel generators due to chronic power grid deficiencies. The system is conceived to log real-time CO_2 emissions from strategically located sensors to enable continuous and high-granularity environmental monitoring. The approach integrates sensor-based telemetry with innovative geospatial analysis and clustering algorithms to facilitate the identification of pollution hotspots in urban micro-environments with pinpoint accuracy as shown in Figure 4. The analysis layers are designed not only to quantify the environmental externalities of decentralized power generation but also to evaluate mitigation strategies based on spatial reasoning and emission intensity. Through the leverage of the synergy among IoT infrastructure and spatial intelligence, this research delivers an operational model of scalable data-driven emissions monitoring and policy-driven urban sustainability.

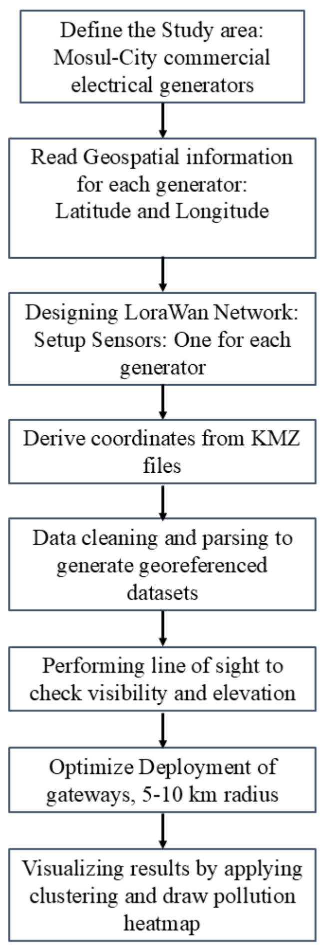

Figure 4. Research Methodology Flow Chart

3.1 Study Area and Research Design

- **Focus** - Mosul's high-density generator zones (identified via municipal geospatial data), where diesel generators are widely used due to electricity shortages.
- **Approach** - Mixed methods (quantitative sensor data + qualitative geospatial modelling).
- **Objective** - Quantify emissions, optimize sensor-gateway placement, and analyse pollution dispersion.

3.2 LoRaWAN System Architecture

LoRaWAN system architecture is a layered, energy-efficient communication protocol designed for LPWAN use cases within the Internet of Things (IoT) environment. Operating on top of the LoRa physical layer (PHY), LoRaWAN leverages chirp spread spectrum (CSS) modulation, a technique known for its immunity to noise and for its capability to sustain long-range transmissions at low power levels. This makes the protocol particularly well-adapted to applications with low-bandwidth, infrequent data transactions over great geographic distance conditions that are typical of urban-scale environmental sensing deployments, such as the air quality monitoring network that was deployed in Mosul. The architecture is designed with energy efficiency, signal strength, and scalability in mind, to enable reliable delivery of data in interference-dense, densely built environments. It is supportive of a star-of-stars architecture, in which sensor nodes (deployed at emission sources or monitoring points) transmit environmental data to LoRa gateways, which forward the data to centralized network servers through IP-based backhaul. The architectural system allows for real-time, low-cost, and geographically extensive environmental monitoring, paving the way for responsive and data-driven air quality action.

3.2.1 Essential Components of LoRaWAN

LoRaWAN networks are comprised of the following essential components:

- End Devices (Sensors) - These are the environmental nodes that are sent into the field to gather environmental information such as CO_2 levels, temperature, and humidity. These are sensors such as Sensirion SCD30 or MH-Z19, sent close to diesel-powered generator clusters to gauge amounts of pollution.
- Gateways are the interconnects between end devices and the central network server. Gateways are connected to the internet via fibre, Ethernet, or cellular connections. Gateways operate in non-intelligent mode, simply forwarding all the incoming LoRa packets to the network server without any pre-processing.
- Network Server - The network server supports packet duplication, device authentication (through Over-the-Air Activation (OTAA) or ABP), MAC command handling, and uplink/downlink scheduling. It ensures secure communication and controls adaptive data rate (ADR) optimization to increase energy efficiency.
- Application Server - This element processes the application-layer data transmitted by end devices. It comes pre-integrated with platforms such as TTN or proprietary LoRaWAN servers. In the Mosul air pollution project, it is utilized to produce pollution maps, detect vital zones, and activate real-time alarms if threshold pollution levels are reached.

3.2.2 Communication Model

The LoRaWAN communication model follows a star-of-stars topology, a very scalable and power-efficient architecture design that favours its application to large-scale environmental IoT deployments. In this arrangement, multiple sensor nodes transmit information directly to one or more LoRa gateways, which are non-routing intermediaries that pass on sensor data to the network server via IP-based backhaul (e.g., cellular, Ethernet, or Wi-Fi). This topology eliminates multi-hop communication at the node level, thereby radically reducing energy usage, latency, and computational overhead—parameters that are vital in sustaining battery-powered operations over a long period. In addition, the star-of-stars architecture enhances network reliability through the reduction of communication collisions as well as routing complexity. Each sensor node directly joins any in-range gateway in a manner independent of other nodes, allowing redundant coverage and ensuring reliable data forwarding in case of gateway failure or RF interference. This architecture is highly amenable to urban-scale deployments, such as Mosul's air quality monitoring network, where wide-area connectivity and low maintenance are critical to continuous, real-time pollution monitoring:

- End devices communicate with one or more gateways.

- Gateways forward messages to a central network server via IP backhaul.
- Devices are typically asynchronous and operate under Class A, B, or C communication classes:
- Class A - Used in our project, it gives the lowest power consumption by opening receive windows only after transmissions.
- Class B/C - Left for future development such as real-time control or actuations.

3.3 Security Framework

The LoRaWAN security framework is designed with dual-layered architecture that ensures confidentiality, authenticity, and integrity of data transmissions across the network. These two distinct layers—network-level security and application-level security—operate in tandem to provide end-to-end protection for IoT communications. The network security layer is responsible for verifying the authenticity of the device within the LoRaWAN infrastructure and for managing the secure exchange of messages between sensor nodes and the network server. This layer utilizes a unique network session key (NwkSKey) to safeguard communication channels and prevent unauthorized access to network-level services. Concurrently, the application security layer secures the integrity and confidentiality of the actual sensor data transmitted from the end device to the application server, using a separate application session key (AppSKey). Both keys are derived through a secure join procedure, often employing OTAA, wherein cryptographic credentials are dynamically generated rather than statically stored. This cryptographic separation of concerns ensures that compromise of one layer does not expose the other, thereby reinforcing the system's resilience against spoofing, replay attacks, and data tampering. The robust security design of LoRaWAN makes it well-suited for sensitive applications like urban air quality monitoring, where data authenticity is paramount for public health decision-making and regulatory enforcement.

- Network-level encryption (AES 128-bit) verifies the device in the network.
- Application-level encryption guards data confidentiality from sensor to application server.

Session keys (NwkSKey and AppSKey) are either pre-configured (ABP) or dynamically negotiated (OTAA). In settings like Mosul city, OTAA is used as the choice to enable dynamic re-keying and secure over-the-air provisioning for enhanced reliability.

3.4 Scalability and Deployment Strategy

In the case of urban deployment in Mosul, scalability and redundancy of the proposed LoRaWAN-based air quality monitoring system rely on a strategically planned multi-gateway architecture. The deployment utilizes a distributed topology where LoRa gateways are space-optimized based on terrain height, Line-of-Sight (LOS) study, and population density information to achieve maximum coverage with minimum infrastructure. This approach ensures that all gateways service a high number of sensor nodes with minimal packet loss and assured communication over distances of over 10 kilometres in low-interference environments. The system is scalable horizontally, and additional sensors or gateways can be easily incorporated as monitoring demand or urban expansion increases. Furthermore, the platform is supported by ADR methods, which adaptively adjust transmission power and frequency as a function of signal quality to enhance network efficiency for dense deployments. Such an extensible and modular deployment strategy ensures that the system can be upgraded together with the city's infrastructure needs as well as duplicated in other cities with similar problems of decentralized emissions and limited grid connectivity. Employing the combination of geospatial intelligence, network flexibility, and open IoT standards, this deployment provides the foundation for a scalable system for real-time urban air pollution monitoring in resource-constrained environments:

- Gateway position was optimized via viewshed and elevation analysis with the help of GIS software to supply LOS coverage to each sensor node.
- Gateways were planned to offer ranges of 5–10 km for urban and suburban areas, keeping the number of infrastructure points as low as possible.
- Bi-directional communication support is offered by the system to support future integration of actuation systems (e.g., generator cut-off mechanisms or ventilation triggers).

3.5 Geospatial Analysis for Gateway Placement

The dependability and effectiveness of an environmental monitoring network using LoRaWAN are largely dependent on the placement of gateways. In the case of cities like Mosul, where pollution monitoring has been coupled with diesel generators dispersed over varied topography, geospatial analysis forms the basis of planning the network. Ideal placement not only ensures maximum LOS coverage but also minimizes the infrastructure cost while maintaining quality data collection.

3.5.1 Objectives of Geospatial Analysis

The geospatial analysis platform utilized in this research has an active role to play in relating environmental information to spatial knowledge, hence transforming raw sensor readings into actionable city-level information. The overall objectives of this module are threefold: First, to identify and define areas of high pollution within Mosul via spatial interpolation of CO_2 concentration readings collected by the distributed sensor nodes. This allows for the detection of emission clusters corresponding to diesel generator high-density zones. Second, the study aims to optimize the location of LoRaWAN gateways and sensor nodes in space through means such as LOS modelling, digital elevation models (DEMs), and viewshed analysis to ensure trustworthy communication coverage across disparate urban territories. Third, the geospatial element is designed to support clustering and zoning algorithms that reveal patterns of air pollution dispersion and generator placement, thereby optimizing mitigation targeting. More broadly, this space-based technique enables real-time visualization, policy-setting prioritization, and environmental planning required for data-driven air quality management in energy-constrained urban environments. It all can be summarized in the following:

- To ensure full coverage of sensor nodes within the effective range of gateways (optimally 5–10 km).
- To minimize signal obstruction due to terrain and city infrastructure.
- To minimize redundancy of gateways by optimizing the number and positioning of units deployed.
- To aid future scalability and resilience of the network.

3.5.2 Data Acquisition and Preprocessing

The data acquisition and preprocessing phase serves as the foundational step in establishing a reliable and spatially aware environmental monitoring framework. The analysis commenced with the extraction of geographic coordinates corresponding to diesel generator locations and prospective LoRaWAN gateway sites. These coordinates were derived from Keyhole Markup Language Zipped (KMZ) files, as illustrated in Figure 5, which were compiled through a combination of high-resolution satellite imagery interpretation and on-ground field surveys conducted in the urban districts of Mosul. This process ensured the inclusion of both verified generator hotspots and technically feasible gateway placements. The extracted spatial data was then parsed, cleaned, and converted into georeferenced point datasets, subsequently integrated into a GIS environment for further analysis. To ensure positional accuracy and eliminate redundancy, duplicate points were filtered, and elevation values were appended using a digital terrain model. This preprocessing phase established a topologically consistent and analysis-ready spatial dataset, enabling robust geospatial modelling and sensor network optimization in subsequent phases of the study. Each of these points was labelled with its function:

- Latitude and Longitude
- Altitude (through GPS or terrain DEM)
- Elevation above sea level (through DEMs)

These data were analysed and visualized using GIS software, such as QGIS, to enable high-end spatial analysis as shown in Figure 6.

3.5.3 LOS and Viewshed Analysis

To guarantee uninterrupted radio frequency (RF) communication between LoRaWAN gateways and deployed sensor nodes, a rigorous LOS and viewshed analysis was conducted as part of the spatial optimization process. This analysis utilized high-resolution DEMs to simulate terrain profiles and detect any topographical obstructions that could impede signal propagation. By computing viewsheds from each proposed gateway location, the model identified all areas within the sensor deployment zone that are visibly and electromagnetically accessible under typical urban and sub-urban propagation conditions. The analysis accounted for gateway elevation, antenna height, curvature of the Earth, and potential structural interferences, thereby ensuring that each node falls within an effective communication radius. This geospatial validation process was essential to refine gateway placement, reduce packet loss, and maintain a high packet delivery ratio (PDR) across the network. The results of the viewshed modelling provided a terrain-aware communication matrix, which was instrumental in aligning sensor node distribution with optimal coverage zones—ensuring the resilience and reliability of the LoRaWAN infrastructure under Mosul's complex urban terrain conditions.

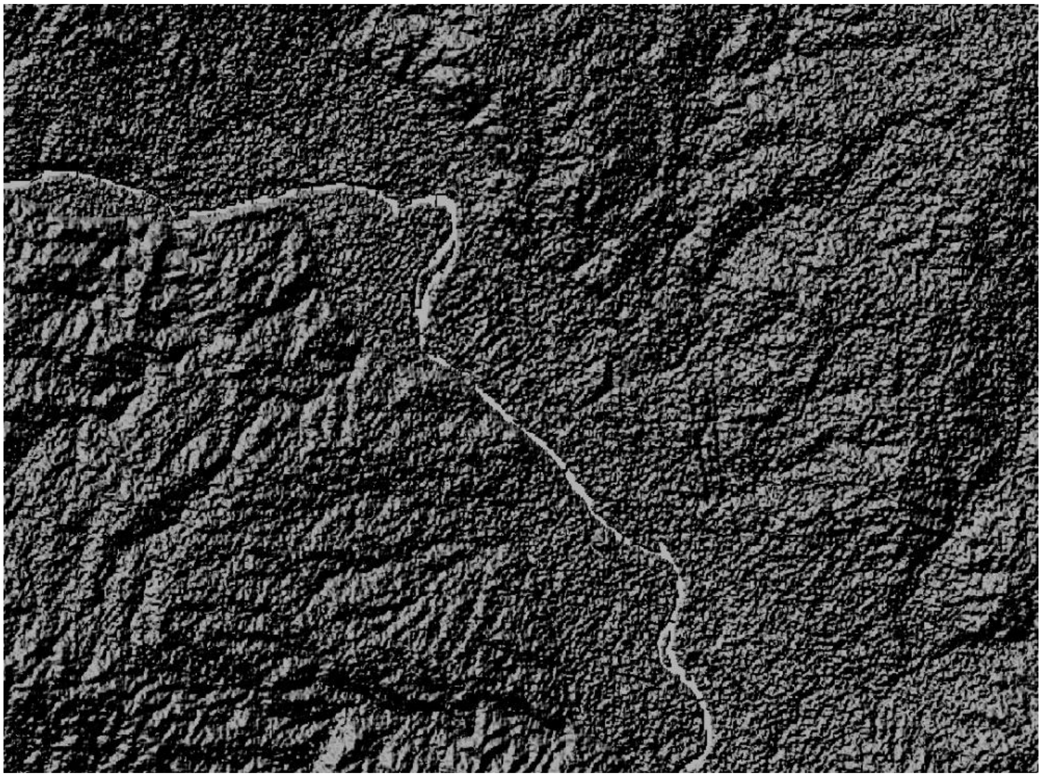

Figure 5. DEM of Mosul City for Terrain-Aware Network Planning

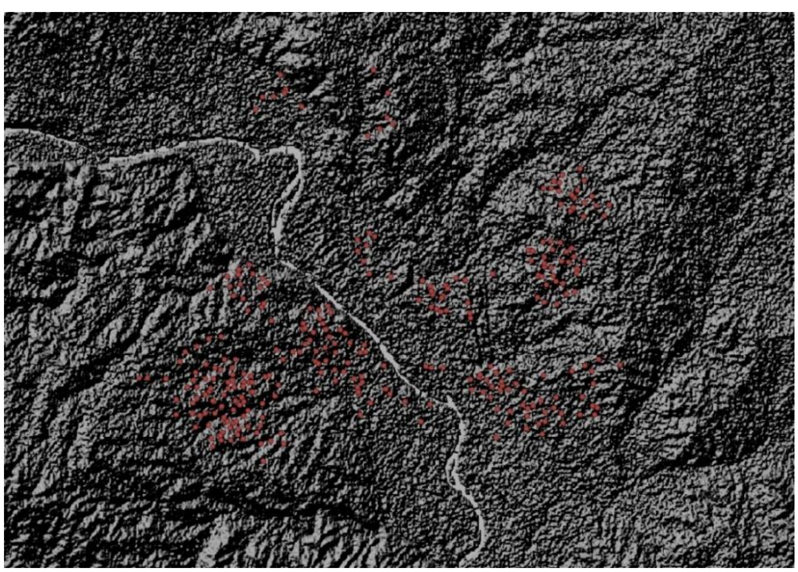

Figure 6. Spatial Distribution of LoRaWAN Sensor Nodes over Mosul's DEM

A viewed analysis was conducted:

- Visibility from every gateway to every sensor as in Figure 7 was calculated with digital terrain models, to find sensors within LOS distance.
- Elevation profiles between gateway points and sensor points were analysed to find potential obstructions as shown in Figure 8.
- The LoRa radio propagation model, including the Fresnel zone clearance, and urban clutter attenuation, was considered.

Gateways with the most visible sensor connections were preferred first. This solution is particularly vital in Mosul's intricate topography, with riverbanks, crowded neighbourhoods, and higher elevations as can be seen in Figure 9.

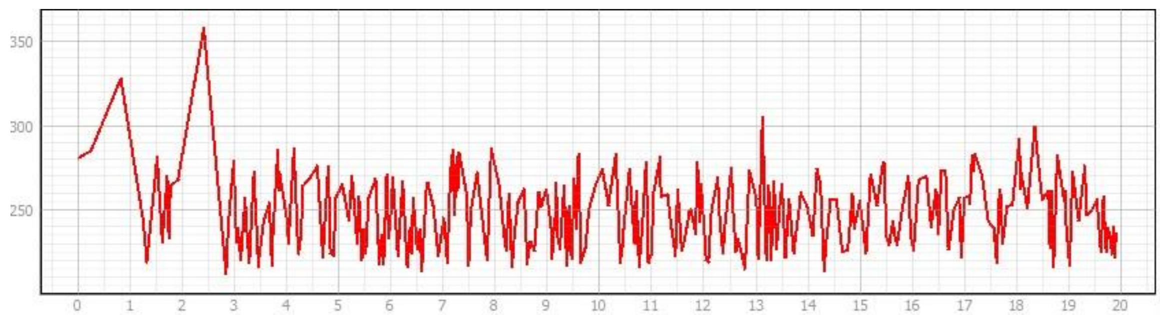

Figure 7. Altitude distribution of LoraWan Sensors over Mosul City

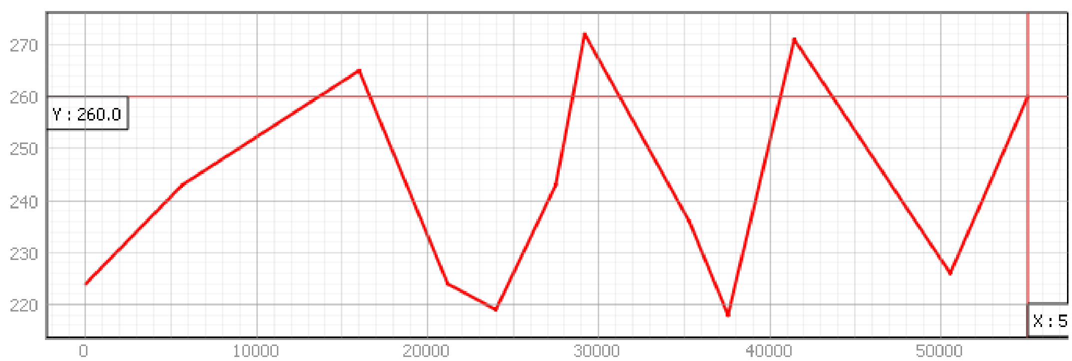

Figure 8. Gateways Altitude Distribution over Mosul City

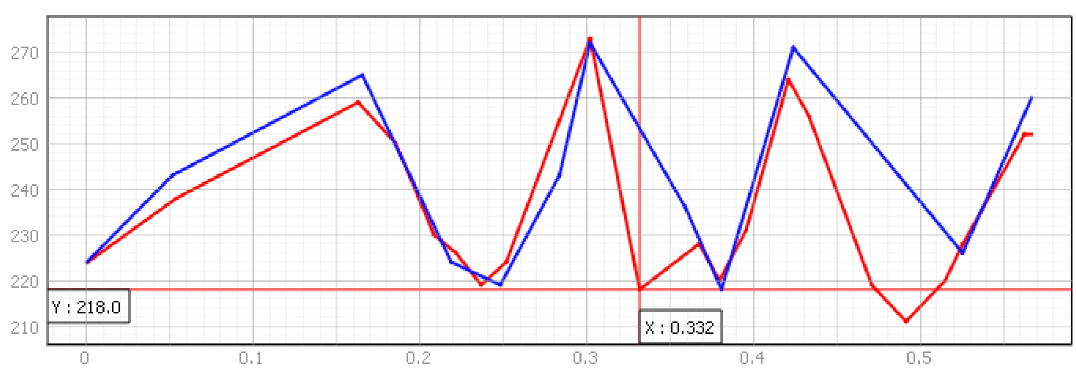

Figure 9. Gateways with Most Visible LoRaWAN Sensors

3.5.4 Coverage Optimization

For effective spatial coverage and reliable communication within the LoRaWAN-based monitoring system, a double distance threshold-based coverage optimization scheme was implemented. The scheme optimizes transmission reliability against infrastructure cost-effectiveness through gateway range adaptation based on urban morphology and signal propagation conditions within the study area. A 5 km threshold was employed in dense urban regions or highly interfered areas with widespread structural obstructions, where it is crucial to maintain a high rate of packet delivery success. This protective boundary minimizes data loss and ensures stable connection even in communication-starved neighbourhoods. A 10 km threshold was instead applied in open or less obstructed suburban locations, where LOS conditions are superior and environmental noise is inferior. This increased radius enables fewer gateways to be deployed without sacrificing data integrity and hence with reduced capital and maintenance costs. Dynamic placement of the gateways based on localized topography and building population allows the system to achieve optimal coverage, energy efficiency, and scalability, enabling the system to be deployable in a wide range of urban and semi-urban environments.

3.5.5 Visualization and Results

A suite of static and interactive geospatial visualizations was generated to support the spatial analysis, system validation, and communication performance assessment of the deployed LoRaWAN air quality monitoring network. These maps were developed using GIS platforms and web-based visualization tools to provide both macro- and micro-level insights into network performance and pollution distribution. The visual outputs include: (1) sensor-to-gateway connection maps, illustrating the communication links and distances between CO_2 sensor nodes and their nearest gateways; (2) LOS and viewshed overlays, depicting areas of clear radio visibility from each gateway based on elevation data; (3) coverage maps for both 5 km and 10 km transmission thresholds, highlighting optimal and suboptimal coverage zones; and (4) pollution heat maps, spatially interpolating CO_2 concentration values to reveal emission hotspots across Mosul's urban fabric. These visualizations not only served as analytical tools during deployment but also as decision-support interfaces for policymakers and urban planners. The integration of both static maps and interactive web layers ensures that results are accessible, interpretable, and operationally actionable for future planning, regulatory enforcement, and public health interventions. Static and interactive maps were generated showing:

- Sensor-to-gateway connections by range and visibility as depicted in Figure 10.
- Terrain maps with viewshed overlays.
- Gateways' coverage zones by buffer computation and LOS corridors.
- Identification of uncovered sensors, which prompted strategic relocation or insertion of gateways.

These graphical tools were indispensable in validating assumptions, communicating designs to stakeholders, and adjusting the deployment strategy in real time.

3.5.6 Real-World Impact

The operation of this geospatially optimized LoRaWAN network in Mosul demonstrates the real-world viability of low-power, high-resilience IoT infrastructure for environmental sensing in energy-constrained city environments. With well-calibrated sensor location and terrain-conditioned placement of gateways, the system was able to collect CO_2 emission data continuously and reliably from high-emitting diesel generators—acting as the operational basis of a real-time urban air pollution monitoring system. Not only was it an environmental governance feat of technology for the city but also an energy-efficient, scalable platform capable of accommodating other smart city applications. The modularity of the network architecture lays the foundation for merging traffic flow analysis, public health early warning, and emergency response coordination platforms seamlessly. Through its intersection of IoT engineering with geospatial intelligence, this project sets up a replicable model of city resilience that establishes Mosul as an incubator of sustainable, evidence-based smart infrastructure for post-crisis, resource-limited urban environments.

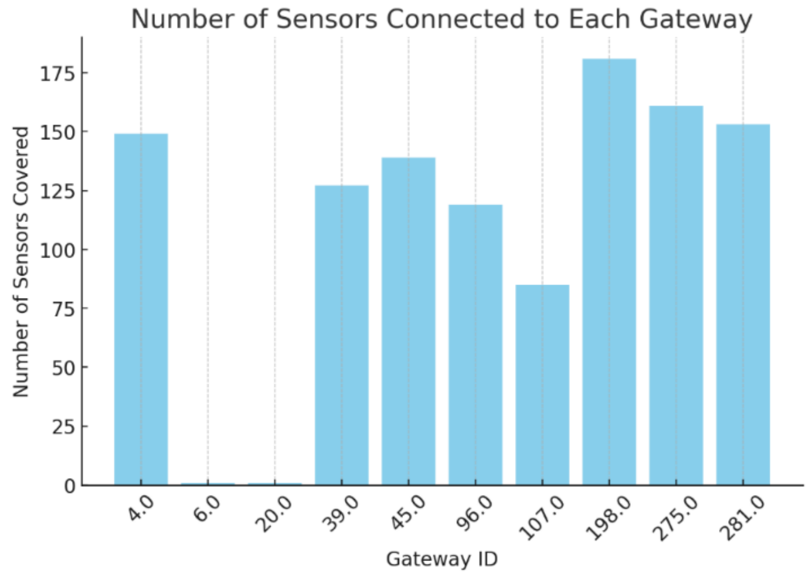

Figure 10. LoRaWAN Sensors Distribution Among Gateways

3.5.7 Gateway Placement Results

This section illustrates the result of gateway location analysis conducted during the LoRaWAN deployment plan for air quality monitoring in Mosul. Best gateway locations were calculated using a mix of DEMs, LOS simulations, and coverage threshold modelling for best coverage of sensors, minimum signal obstructions, and best utilization of network resources. The deployment process was regulated by both geospatial factors (e.g., terrain elevation, urban populace, visibility areas) and communication quality metrics (e.g., RSSI, packet delivery rate). The results discussed herein comprise complete maps of target gateway locations, their corresponding coverage areas, and sensor-gateway mapping analysis, facilitating the validation of an extendable and reliable LoRaWAN network for environmental monitoring in complex urban environments. The effectiveness of the selected gateway placements was further evaluated through a coverage efficiency heatmap as shown in Figure 11, which visualizes the spatial distribution and strength of LoRaWAN signal reach across the study area. This heatmap highlights zones of optimal coverage, identifies marginal signal regions, and guides future infrastructure scaling. To validate the LOS predictions, a series of field tests were conducted using GPS-enabled waypoints, allowing for real-world verification of gateway-to-sensor visibility and communication integrity. These field observations confirmed the accuracy of the viewshed-based LOS models, reinforcing the reliability of the geospatial methodology used in planning the network. Together, the visual and empirical outputs provide a robust confirmation of the network's spatial configuration, ensuring it is both theoretically optimized and practically deployable in Mosul's complex urban terrain.

3.5.8 Data Collection and Preprocessing

The usefulness of an LoRaWAN-enabled environmental monitoring network relies not only on architectural resilience and optimal gateway placement strategy but also on the accuracy, granularity, and integrity of environmental data collected by it. Preprocessing and data collection were an important foundation of the system's analytical power and operational reliability in this study. The main data sets were geolocated generator positions—offering latitude, longitude, and altitude—and in-situ real-time CO_2 concentration data gathered from fielded monitors, and estimated emissions computed at a default rate of 500 grams per hour per generator, and with a daily runtime of 15 hours. High-fidelity data was obtained through a rigorous cleaning pipeline involving noise filtering, outlier removal, and cross-source consistency checks. These pre-processed datasets were then loaded into QGIS and spatially joined to pollution intensity zones to develop high-resolution geospatial models. Preprocessing served a critical role in transforming raw telemetry into actionable environmental intelligence, which provided the analytical backbone of the real-time pollution monitoring system implemented in Mosul.

3.6 Pollution Estimation and Modelling

The prediction of the spatial and temporal trends of air pollution due to widespread diesel generator use is a central element of urban environmental risk analysis and policymaking in energy-poor cities like Mosul. The study follows a hybrid modelling methodology that integrates real-time data gathering using LoRaWAN-connected CO_2 sensors, geospatial mapping of generator points, and predictive spatial interpolation techniques for visualization and quantification of the diffusion of pollutants within the city. There were two complementary models. First, a baseline model was created from static estimates of known fuel consumption rates of generators and hours of operation—simulating pre-LoRaWAN conditions. Second, a real-time pollution model was created by combining sensor-based measurement of CO_2 with GIS-based heatmap visualization to enable dynamic exploration of the emission intensities of high-density generator zones. Collectively, they provide both a retrospective archive and a forward-looking analytical tool, facilitating continuous pollution monitoring, impact prediction, and evidence-based environmental management.

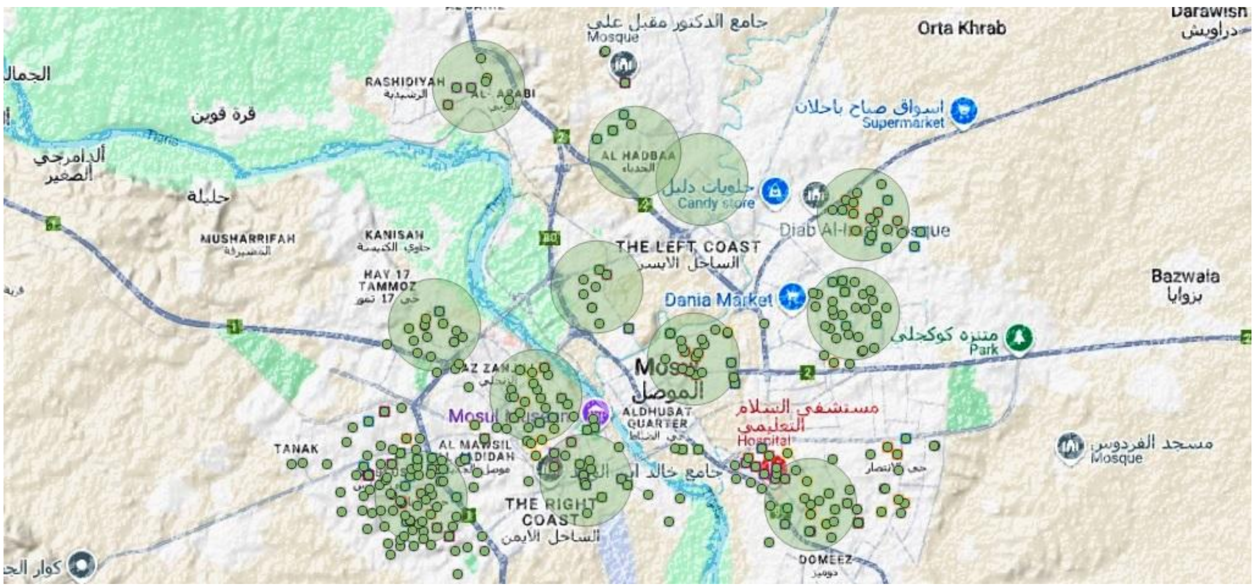

Figure 11. Spatial Distribution and Coverage Zones of LoRaWAN Gateways and Sensors in Mosul City

3.7 GIS Visualization and Clustering

GIS was a staple in the spatial optimization and analytical validation of the LoRaWAN-enabled pollution monitoring network deployed across Mosul. With GIS's robust mapping, layering, and clustering capabilities, the study was able to successfully visualize sensor node covers, delineate gateway coverages, and spatially plot CO_2 pollution levels versus diesel generator density. The system's clustering algorithms were specially calibrated with a 1 km radius, optimized to record the typical dispersion range and clustering propensity of generator-based emissions within densely populated urban areas. This visual and spatial analysis not only provided a clear picture of real-time environmental patterns but also enabled scenario modelling and coverage optimization with respect to terrain variability and urban form. Lastly, GIS integration facilitated evidence-based decision-making in both environmental monitoring and intelligent city infrastructure planning, serving as a strategic tool in the transformation of raw geospatial data into decision-ready information for sustainable city planning.

3.8 Spatial Mapping and Elevation Analysis

Spatial mapping and elevation modelling made up an important analytical part in planning and execution of a terrain-based LoRaWAN communication network for air quality monitoring in Mosul. Both candidate gateway coordinates and sensor nodes were successfully imported into a QGIS-based GIS platform, initially georeferenced to the WGS 84 global datum and subsequently systematically reprojected into UTM Zone 38N coordinates to enable accurate distance measurement and elevation-based modelling. This geospatial transformation was done to align the spatial reasoning of the network to real terrain heterogeneity. DEMs of high resolution were integrated to carry out a topographic effect analysis on LoRa signal propagation at high resolution, with specific focus on LOS visibility, signal attenuation, and terrain-based dead zones. Sophisticated viewshed analysis techniques were employed to simulate the electromagnetic fields of visibility from each gateway, enabling optimal placement configurations to be optimized for maximum coverage with minimum redundancy. This analysis not only gave optimum RF performance but also revealed key elevation barriers—like ridgelines, urban agglomerations, and natural slopes—that would otherwise have introduced discontinuities to effective communication. By incorporating elevation cognition into the network design at the outset, the study ensured a structurally resilient, topography-adaptive, and high-fidelity LoRaWAN deployment capable of sustaining long-range, low-power data transmission over Mosul's challenging cityscape.

3.9 Pollution Heatmap Visualization

The generation of pollution heatmaps was at the centre of spatially estimating the density and distribution of CO_2 emissions across the urban fabric of Mosul. Each sensor node deployed was mapped to a pollution value in accordance with its proximity to one or more diesel generators, following the emission estimation presented in Equation (1). This equation determined total emissions as a function of the normalized emission rate and operation time on a per-generator basis, allowing for the generation of a quantitative spatial dataset representing emission variability at high resolution. Interpolated surface models were then generated from this dataset within the GIS environment, producing heatmaps describing the spatial concentration gradients of pollution. These heatmaps made it possible to identify areas of high risk, which were generally associated with concentrations of dense generator clusters and poor urban ventilation. Additionally, the visual outputs made real-time comparisons of pollution levels across neighbourhoods possible, allowing mitigation efforts to be prioritized and providing a visual record to inform urban environmental policy. The heatmaps were not only analytical instruments but also decision-support layers for stakeholders who wish to integrate environmental intelligence into smart city governance systems.

$$Total\ Emissions\ (g/day) = Emission\ Rate\ (500\ g/hour) \times Operating\ Hours\ (15\ hours) \tag{1}$$

To establish a reference foundation for spatial emissions modelling, a baseline pollution level of 7,500 grams a day, corresponding to the average estimated emission of nearby diesel generators, was assigned to every sensor node. Pollution levels were then spatially interpolated over the study region using two advanced geostatistical techniques: Inverse Distance Weighting (IDW) and Kriging. Both methods were applied in the GIS environment to generate continuous pollution surfaces, with IDW favouring proximity-based influence and Kriging employing spatial autocorrelation for enhanced accuracy. The result was a series of smooth and topologically consistent heatmaps that conveyed the underlying spatial gradients of CO_2 concentration throughout Mosul. These maps, exemplified by Figure 12, enabled the identification of prominent emission hotspots and offered intuitive visual cues for high-pollution zones. By transforming discrete sensor readings into continuous spatial phenomena, this approach offered a strong rationale for urban environmental risk assessment, infrastructure planning, and targeted emission reduction efforts.

3.10 Clustering and Hotspot Detection

Clustering analysis was one of the pillars of this research's spatial intelligence model, employed to uncover the pattern behind sensor deployment and pollution intensity in Mosul's complex urban setting. To derive decision-relevant knowledge from space-based data, various clustering algorithms were utilized—each selected due to its potential to identify characteristic spatial phenomena and guide network optimization. K-Means Clustering was employed as a baseline method to cluster sensor nodes into distinct groups according to the geographical proximity and estimated emission size, thus demarcating areas of equal pollution load. To identify the non-linear and irregular pattern of distribution commonly created by clusters of diesel generators in high-density informal settlements, the study leveraged the advanced capabilities of DBSCAN (Density-Based Spatial Clustering of Applications with Noise). This method was instrumental in highlighting organically generated, high-density hotspots that conventional techniques could overlook, numerous which were very strongly correlated with hotspots of high generator use and population exposure. Hierarchical clustering also facilitated multi-scalar classification of zones of pollution, both detecting nested micro-hotspots—valuable for targeted intervention—and larger macro-clusters indicating systemic urban emission issues. The outputs of these tiered clustering models were not only descriptive but operationally strategic, directly informing the precise placement of LoRaWAN gateways to offer robust data coverage over the most polluted regions.

This clustering-based deployment strategy enhanced the system's environmental responsiveness, network efficiency, and policy utility, further solidifying its role as a central tool for real-time emission management and smart urban planning in energy-constrained cities.

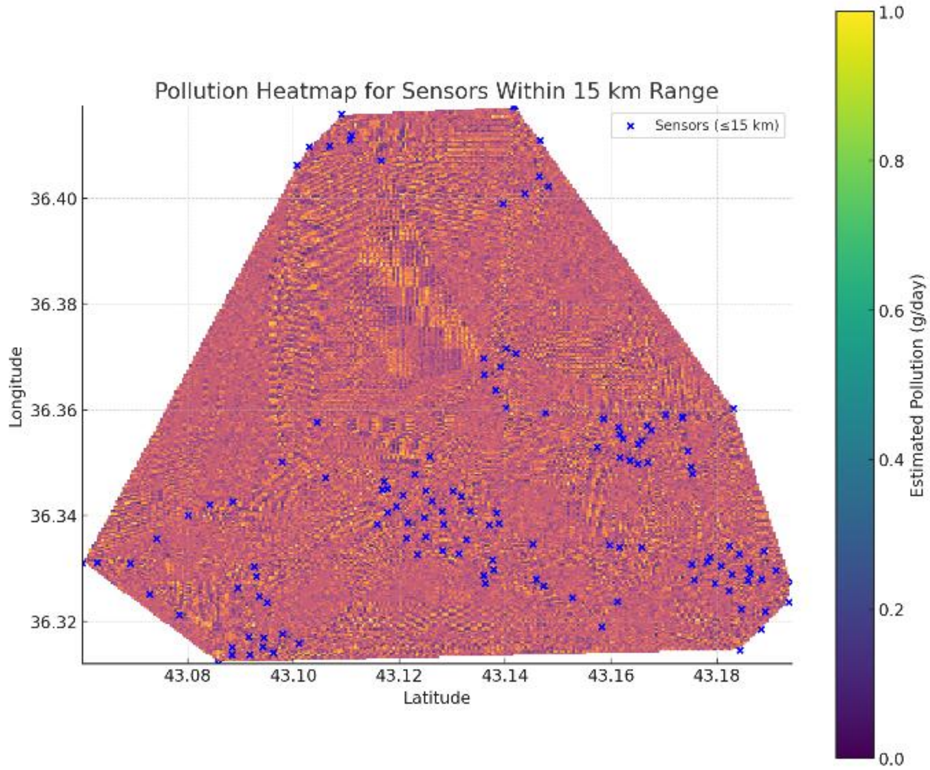

Figure 12. Pollution Distribution Over Mosul City

3.10.1 LOS and Range Filtering

To maintain the integrity and validity of the spatial models and communication analyses, a selective filtering mechanism was employed to eliminate sensor nodes that were outside the effective LoRaWAN transmission range, which was conservatively estimated as 15 kilometres from the nearest deployed gateway. This range limit was based on empirical performance metrics for long-range LoRa communications under urban interference conditions. For enforcement of this limitation, viewshed analysis tools were employed to verify LOS conditions between all sensor nodes and their respective gateways, allowing only the nodes with unobstructed propagation channels and within realistic RF range to be included in final visualization layers. Filtering was necessary to remove communicative or spatially isolated outliers from the dataset to reduce noise and distortion in the interpolated pollution heatmaps. As such, the visual models derived much higher spatial fidelity, and the resultant pollution estimates and network performance measures like packet delivery success rates and signal strength were rendered more representative, credible, and decision ready. This LOS-based filtering process thus formed a pre-requisite prerequisite to the accuracy and operational effectiveness of both the environmental monitoring system and its geospatial representations.

3.10.2 Strategic Outcomes

GIS-based visualization and spatial clustering were core analytical engines driving the best outcome of this study. Through the transformation of raw geolocation and sensor data into smart, multilevel spatial models, the GIS platform delivered precise pollution gradient mapping, ideal LoRaWAN gateway positioning, and data-driven hotspot identification. Through processes like viewshed modelling, interpolated heat maps, and multi-scale clustering algorithms, the system provided not only a diagnostic window to urban CO_2 emission dynamics but also a strategic planning portal to optimize infrastructure and environmental intervention. These GIS-derived results made it possible to translate complex spatial patterns into actionable intelligence, facilitating real-time prioritization of high-emission zones, network design validation, and development of spatially targeted mitigation plans. Ultimately, GIS visualization and clustering did not simply confirm the study's findings—they guided its very impact, enabling a level of precision, scalability, and policy salience that would have been impossible using conventional analytical tools. GIS visualization and clustering were central to the resulting impacts:

- Successful identification of pollution hotspots, immediately linked to generator clusters.
- Optimized network deployment plan, minimizing gateways while maximizing sensor coverage.
- Enabling real-time environmental monitoring, the foundation for adaptive air quality management and public health protection.

By the integration of geospatial analysis in the network planning and data interpretation stage, the project helped in the development of a smart, scalable urban sensing infrastructure suitable for resource-constrained smart city deployments.

4. RESULTS AND DISCUSSIONS

The deployment of a LoRaWAN-enabled real-time air quality monitoring system in the city of Mosul is an innovation in the way cities sense, manage, and respond to environmental pollution. Unlike conventional monitoring methods founded upon discrete manual sampling and fixed-station points, this study introduces a fully dynamic, spatially enabled, and continuously streaming infrastructure that revolutionizes the tempo and resolution of environmental data acquisition. At the heart of this revolution is the integration of long-range, low-power wireless sensor networks, carefully designed through LOS-confirmed gateway positioning to provide uninterrupted communication and minimized signal loss, even across winding terrain and dense cityscapes. This precision-engineered connectivity framework has enabled the realization of a real-time urban air intelligence network—one capable of automatically sensing, measuring, and reporting CO_2 concentration levels with unprecedented accuracy and spatial resolution. The resulting data fidelity facilitates proactive decision-making, wherein city governments can transition from reactive mitigation to predictive environmental management. Through the incorporation of advanced geospatial analysis and real-time telemetry, this system transforms the management of air quality from a passive monitoring function to a strategic urban function with the potential to inform policy, protect public health, and accelerate the creation of smart, sustainable cities. The following outcomes highlight how this system not only scales effectively but also produce insight-rich outputs that can potentially revolutionize city planning and environmental policy in regions grappling with energy and pollution challenges.

4.1 Advantages of LoRaWAN in a Smart City Framework

- Real-Time Data Acquisition: Unlike static models, the deployed sensors provide continuous updates on air quality, allowing city planners and policymakers to make informed decisions.
- Scalability and Cost-Efficiency: The LoRaWAN network's long-range and low-power capabilities reduce infrastructure and operational costs, making it a viable option for large-scale smart city deployments.
- Accurate Pollution Source Identification: The clustering and hotspot analysis enabled precise mapping of high-emission areas, guiding targeted policy interventions and emission reduction strategies within the city.
- Early Warning System: The system allows city officials to monitor trends and detect anomalies, potentially predicting hazardous air quality conditions before they escalate.

4.2 Challenges and Future Considerations

Despite its benefits, the LoRaWAN-based approach within a smart city context faces several challenges:

- Network Congestion: As sensor density increases, gateway saturation and data collisions could impact transmission reliability, requiring adaptive network management strategies.
- Environmental Interference: Atmospheric conditions such as humidity and temperature variations may influence sensor accuracy, necessitating regular calibration.

- Energy Constraints: While LoRaWAN sensors consume low power, prolonged operation in extreme urban environments could affect battery lifespan, highlighting the need for renewable-powered solutions.
- Integration with Smart City Systems: To maximize its impact, the system should be incorporated into existing smart city infrastructure, ensuring compatibility with traffic control, public health, and environmental policies.

4.3 Future Enhancements

Drawing upon the successful history of the current LoRaWAN-based system, several strategic enhancements are seen to increase even further the system's intelligence, precision, and societal value in future deployments. Foremost among these is integrating machine learning and artificial intelligence (AI) to design predictive models for forecasting pollution. By analysing actual-time trends and historical patterns in data, AI-powered algorithms are capable of forecasting increases in emissions and environmental anomalies and enabling proactive countermeasures as well as nudging the system from reactive sensing to anticipatory city governance. Concurrently, the use of multi-sensor fusion platforms such as CO_2, NOx, and PM2.5 sensors with weather parameters such as wind speed, humidity, and temperature will greatly enhance the degree of detail and contextual accuracy of pollution assessments. This multimodal data fusion can potentially offer more detailed environmental models, showing how pollutants blend and settle under varying conditions of the atmosphere, and offering a more complete picture of urban air quality phenomena. Similarly revolutionary is the proposed transition to citizen-oriented open data platforms. By opening access to real-time air pollution data through mobile dashboards and web platforms, the system can provide openness, community action, and social change. With communities empowered with environmental intelligence not only increase awareness but also mobilize collective action towards sustainability, positioning the citizen squarely as an active co-creator towards healthier cities. Together, these future innovations will enable the system to maintain its position as a scalable, smart, and participatory platform for next-generation smart cities.

5. CONCLUSION

This methodology enables:

- Optimized placement of LoRaWAN gateways for 100% sensor coverage in a smart city environment.
- Identification of pollution hot spots for urban air quality monitoring in real time and implementing combating mechanisms.
- Pollution modelling based on data and scalability, whereby such models can be pulled back to fit into smart city environments based on diesel generators.
- The results show that LoRaWAN-based air quality monitoring has the potential to transform smart cities by offering an affordable, scalable, and real-time solution to stop urban air quality challenges.

Anyway, several limitations provided in this study allow for further research. Firstly, although CO_2 was the chief targeted pollutant, future studies should incorporate multi-pollutants like NO_2, SO_2, and PM2.5 in aid of broader urban air quality and public health hazard analysis. Secondly, sensor drift corrections and calibration must be upgraded to strengthen the reliability of long-term data under variable temperature and humidity conditions. Thirdly, to mitigate RF interference and packet loss in urban areas, exploration needs to be made into redundant routing protocols, signalling optimizations, or hybrid LPWAN designs. Besides, while deployment in this design is static, prospective deployment could feature mobile sensor nodes attached to buses or drones to increase coverage of hard-to-reach or high-risk zones. Lastly, the safeguarding of data transmission through.

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Awfa Aladwani: Project Administration, Writing – Review & Editing;
Ali abduljabbar: Project Administration, Supervision, Writing – Review & Editing.

CONFLICT OF INTERESTS

No conflict of interests was disclosed.

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Our publication ethics follow The Committee of Publication Ethics (COPE) guideline. https://publicationethics.org/

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