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Integrated GIS and AHP-Based Air Quality Zonation in the Kurdistan Region of Iraq

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ABSTRACT

Kurdistan Region of Iraq (KRI) faced significant challenges related to air quality due to the rapid urbanization and industrial activities, which necessitate the air quality assessments. The advanced techniques of remote sensing, Geographic Information Systems (GIS), and the Analytic Hierarchy Process (AHP) were combined in this research to perform air quality zonation for the KRI. The Ozone (O3), Nitrogen Dioxide (NO2), Sulfur Dioxide (SO2), Carbon Monoxide (CO), and UV Aerosol Index, were the selected air pollutants from Sentinel 5P as average of 2024 to use as a critical parameters for air quality assessments. The considered parameters were weighted using pairwise comparison, and thematic maps were created to calculate air quality zonation map for KRI. The results were categorized into five pollution levels: very low, low, medium, high, and very high. The findings showed that 2,815 km² (6.1%) of KRI identified as region with very high air pollution, suggesting the critical need for targeted mitigation strategies. This study aid notably in sustainable environment and offers important information for policymakers to enhance public safety.

1. Introduction

Air quality has notable impact on health and economic activities. The rapid urbanization, industrial development and transportation activities influenced the air quality patterns in the world (Bai, Wang et al. 2018). The life sustainability on earth influenced by the pollutants in the air, as air quality related issues caused annual death of 7 million people (Crippa, Guizzardi et al. 2018) which 250 thousand people die annually due to cancer related to air pollution (Lelieveld, Pozzer et al. 2020) and costing \$4 trillion annually (Maghirang 2019). The particulate matter 2.5 (PM2.5), nitrogen oxides, ozone, sulfur dioxide, and volatile organic compounds are the main pollution sources in the atmosphere, resulting from transportation, power generations, industrial, and household activities (Thakran, Narsimha et al. 2020). Globally, the Air Quality Index (AQI) is utilized to inform the public about pollution levels and associated health risks (Kumari and Jain 2018).

The World Health Organization standards for air quality indicated that Iraq surpassed the air pollutions levels (Abbas and Abbas 2021) as it is ranked as second for poor air quality, specifically in Erbil city when air quality index of 162 was recorded for the PM 2.5 (Ali, Salam et al. 2023). The poor air quality was noticed in various studies in KRI cities, such as Erbil and Sulaymaniyah (Ali, Salam et al. 2023). A study linked the degradation of air quality to the urbanization and inadequate public services in KRI (Hama-Aziz 2022). Moreover, Ali et al. found the notable number of days of unhealthy PM2.5 levels in Erbil city during an investigation for Erbil city between 2018 and 2022 (Ali, Salam et al. 2023). Also, the level of carbon dioxide (CO_2), ozone (O_3), carbon monoxide (CO), methane (CH_4), and hydrogen sulfide (H_2S) near the traffic areas of Zakho city, which found pollutants exceeded the limits with varying levels (Hassan, Yousif et al. 2022). As well an investigation was conducted on heavy metal content in dust storm samples in Erbil city, finding the potential health risks regarding the metals which highlighted the children face higher risk and are more vulnerable to air pollution risks (Hassan, Othman Abdullah et al. 2024). Additionally, a study highlighted the decreased level of selected air pollutants during the COVID 19 lockdown in Erbil city, emphasizing the role of human and industrial activities impact on the air quality in the city (Chomani 2024).

While there are particular investigations in some parts of KRI and provide significant insights for air quality conditions in the region, such as for Erbil (yashooa, Khider Mawlood et al. 2022), however there are lack of detailed map and effective air quality risk zonation for entire KRI. Integrating satellite imagery, geographic information systems (GIS) and Analytic Hierarchy Process (AHP) aid significantly in global monitoring of variations on air quality and environmental assessments (Li, Ji et al. 2021). Sentinel-5P is one of the effective satellite which provide valuable global data on various air pollutants, such as SO_2, CO, NO_2, aerosol and O_3 (Al-Alola, Alkadi et al. 2022).

The objective of this study was to perform air quality zonation for the Kurdistan region of Iraq using the integration of GIS, remote sensing and AHP techniques. Multiple contributed air pollutants parameters from Sentinel-5P were considered to identify air quality zonation for KRI. The air quality zonation and results of this study offers significant insights for public health, urban planning, and environmental management. This study suggests the air quality mitigation strategies by offering valuable information of air quality patterns and distributions in KRI.

2. Materials and methods:

2.1. Study area

Kurdistan region is located in north of Iraq (Fig. 1) with nearly 6 million people and four major provinces, Erbil, Sulaymaniyah, Duhok and Halabja. KRI recognized the significance of environmental issues, such as air quality, resulting to aim reform in environmental management and public sectors (Kazho and Atan 2022). Additionally, the historical conflicts and economic challenges in the region resulted in degradation of environment, making it essential areas for air quality assessment (H Sherwani and Ahmad 2023).

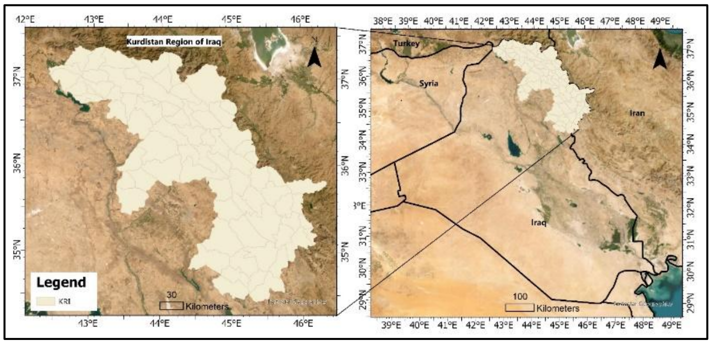

Figure 1: Study area, Kurdistan Region of Iraq (Prepared by the author).

2.2. Datasets

The Sentinel 5P was the primary data for this study to model the air quality zonation in KRI. Six parameters were considered at first, such as O3, NO2, SO2, CO, CH4, Aerosol Index (AI), but due to unavailability of data for entire study area, CH4 excluded in 2024. The google earth engine (GEE) platform (https://earthengine.google.com/) and ArcGIS Pro version 3.0 (https://www.arcgis.com/index.html) software were used to download and prepare the data for each parameters. Detailed information on the used datasets in this research is listed in Table 1. The flowchart of the study illustrated in Fig. 2.

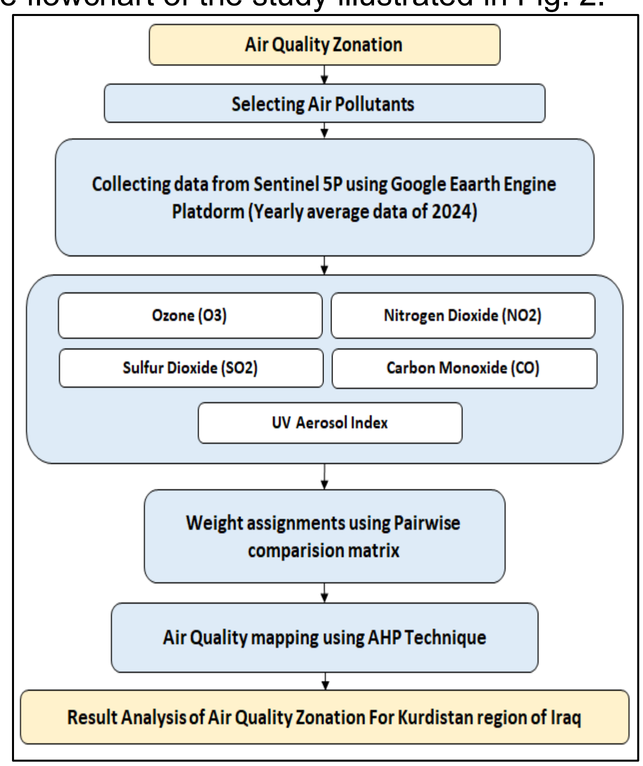

Figure 2: The flowchart of the study fir Air Quality Zonation mapping.

Table 1: The study dataset sources.

Satellite	Parameter	Reference
Sentinel-5P TROPOMI: TROPOspheric Monitoring Instrument	Ozone (O3) total column	https://developers.google.com/earth-engine/datasets/catalog/sentinel-5p
	Nitrogen Dioxide (NO2), total and tropospheric columns	
	Sulfur Dioxide (SO2) total column	
	Carbon Monoxide (CO) total column	
	UV Aerosol Index	

2.3. Air Quality Zonation Thematic Maps

2.3.1. Aerosol Index

The UV Aerosol Index (UVAI) in Sentinel-5P shows the aerosol concentrations in the atmosphere, which is an important factor that should be considered for air quality zonation mapping. Using UVAI as a factor enhances the accuracy of air quality assessments (Tampubolon, Yanti et al. 2023). The Sentinel-5P contributed essentially in decision making processes as it helped researchers to understand the impacts of the air pollution more effectively (Mazlan, Zaki et al. 2023, Zhang, Liu et al. 2024) and pollutions source identifications, making it important for targeted implementations of air quality improvements (Campanelli, Siani et al. 2019, Ahn, Torres et al. 2021). The average data in 2024 for study area were calculated and the thematic map for aerosol index was generated for KRI (Fig. 3, a). After generating the AI thematic map, negative values were masked out from the result, which can occur due to sensor noise or retrieval errors (Morillas, Alvarez et al. 2024). After cleaning the dataset from negative values, it was subsequently utilized in the AHP for air quality assessment. The generated map was classified and ranked from 1 to 5, 1 for least air pollution and 5 for high air pollution. The thematic map then was utilized in air quality zonation.
3.

2.3.2 Nitrogen dioxide (NO2)

The vehicular emissions and industrial activities are primary source of Nitrogen dioxide (NO2) concentrations, which should be considered as a parameter for air quality assessments (Benchrif, Wheida et al. 2021). The high level of NO2 in dense urban regions is dangerous for vulnerable residents such as children and old citizens (Zheng, Haseeb et al. 2024). For more comprehensive evaluations of air quality, the integration of NO2 with GIS techniques aid significantly to visualize and identity air quality patterns, playing critical role in better decision making process (Broqueza, Cruz et al. 2024). The average data for the study area were download and thematic map was generated and ranked to use it as a critical parameter in AHP and air quality zonation mapping (Fig. 3, b).

2.3.3 Carbon monoxide (CO)

CO is colorless gas which produces primarily from incomplete combustion of fossil fuels. It's a notable parameter which should be considered for urban air quality assessments, as it has significant effect on environment and public health (Munfarida and Arida 2023, Shamsudin, Kamaludin et al. 2023). Studies highlighted the increased level of CO contribution with vehicle emissions (Zakaria and Mahyuddin 2022). Using CO with other parameters, such as NO2, provide more comprehensive assessment for air quality monitoring (Szyszkowicz and de Angelis 2021). CO not only provide insights about the air quality, but also offer significant insights about the influence of temperature, humidity and wind patterns on environmental conditions (Jadoon, Nawazish et al. 2022, Srbinovska, Andova et al. 2023). The CO data were download form GEE and thematic map was generated to use it as one of the essential parameters for air quality zonation for KRI (Fig. 3, c).

2.3.4 Sulfur dioxide (SO2)

The Sulfur dioxide (SO_2) also used in this research as a parameter for air quality assessments, as it shows the information about anthropogenic pollution which is caused from the combustion of fossil fuels in industrial processes, power generation, and vehicular emissions (Braghiroli, Bouafif et al. 2019). Utilizing SO2 with air pollutants from Sentinel-5P satellite data have impact on enhancing the air quality monitoring (Vinh, Tuan et al. 2022). The SO2 map for the KRI region was created and categorized into 5 categories, and each category ranked based on their contribution to air pollution (Fig. 3, d).

2.3.5 Ozone (O3)

The ozone (O3) considered as an important factors from Tropospheric Monitoring Instrument (TROPOMI) in literature for investigation related to air quality (Pope, Graham et al. 2019). The satellite data from TROPOMI aid essentially to better understand the patterns of the O3 over large areas (Kazemi Garajeh, Laneve et al. 2023). Multiple studies validated the TROPOMI with ground data, making it a reliable resource for air quality monitoring (Hubert, Heue et al. 2020). Additionally, combining geospatial analysis with GEE made the large data processing and interpretation more easy (Tabunschik, Gorbunov et al. 2023). The thematic map of O3 for KRI was created using downloaded data from GEE and presented in Fig.

2.4 Air Quality Zonation mapping using AHP

There is no one specific parameters which have primary role in air pollutions, but multiple factors contribute in air quality degradation (Marinello, Butturi et al. 2021). Therefore, it's significant to use an approach which considers multiple and complex parameters to identify regions with diverse air quality. One of the most commonly used and popular approach for considering multiple parameters is MCDM, specifically AHP (Sarkar, Kumar et al. 2022, Chomani 2023, Gururani, Kumar et al. 2023, Abdo, Vishwakarma et al. 2024, Younus Mustafa, Mohammed Dler et al. 2025). The AHP considers the parameters based on their importance and influence on air quality, each parameters weighted accordingly. The integration of AHP, GIS and remote sensing techniques aid significantly in more effective air quality assessments and environmental monitoring (Ahmadi, Sahak et al. 2023). Additionally, each class in each parameters also ranked based on their contribution in air pollution. The pairwise comparison (PC) matrix were used to give the weights for each parameters considering the expert opinions (Ifediegwu 2022), which is a structured methodology used for quantitative comparison of decision criteria

(Kader, Islam et al. 2024).

The ranking of air pollutants were based on considering both environmental and health impacts in the region. The increased industrial activity and vehicular emissions elevated ozone levels, which is a potent oxidant leads to asthma exacerbations and reduced lung function. Studies from similar climate conditions, such as Iran, found the increased hospital admissions due to the ozone exposure, making it one of the significant source of pollutions (Ghozikali, Mosaferi et al. 2015). Similarly, the NO2 is primarily emitted from vehicular and industrial operations, which showed notable increase in Erbil city based on a study between 2018 and 2022 due to the rapid urban expansion and increased fuel consumption. The World Health Organization (WHO) highlighted the detrimental health effects of NO_2, making it a second most significant pollutant in this study (Zana, Dedar et al. 2023). Another significant pollutant is SO2 which linked to industrial facilities and power plants in the Kurdistan region of Iraq. Studies highlighted the increased level of SO2 concentrations near oil production sites, which have notable health impacts such as respiratory and heart diseases (Assaf and Abdulla 2023). The SO2 levels are concerning but generally they are lower than NO2 and Ozone, leading to giving a moderate weight in the process of AHP model. However, regarding other pollutants, studies highlighted the lower levels of CO and AI, emphasizing less impact on health and environment compared to the other pollutants (Hama-Aziz 2022). Therefore lower weights were assigned for CO and AI in the air quality assessment. The weighting and ranking assignments of this study were based on the expert judgment and literature review considering the study area. While the AHP is widely adopted technique, its dependence on expert judgments is one of its limitations, specifically in environmental applications, as its subjective which can lead to biases. Moreover, in complex environments the judgments may not cover the issue correctly. While AHP is useful tool but these limitations also should be considered and implemented cautiously (Soltanifar and Kamyabi 2024).

The results of the matrix should be checked by using consistency ratio, which shows the reliability of the generated matrix. The consistency ratio should be less than 10% to be acceptable (Yang, Kang et al. 2022). The assessments were showed that the CR value of the matrix was 5.6%. The parameters were ranked and weighted using the integration of GIS and AHP to generate the air quality zonation mapping (AQZM) using the ArcGIS Pro version 3.0 tools (Eq. 1). Moreover, the statistical analysis were performed for the generated AQZM using zonal statistics to create air quality zonation map for Kurdistan region of Iraq.

$$AQZM = (W_1 \times F_1 + W_2 \times F_2 + \ldots + W_n \times F_n) \quad (1)$$

Where weight of the factors represented by W and the used parameters is the F.

3. Results and discussions:

The integration of GIS, remote sensing and AHP for air quality zonation mapping for KRI indicated a concerning distribution pattern. Five different air pollutants such as NO2, CO, AI, O3, and SO2 were considered in this research (Fig. 3). Based on the literature and expert opinions the weight of each parameter was assigned using the PC matrix (Table 2). Additionally, each the thematic map was generated for each parameters and classified into 5 different classes based on their influence on the air quality (Table 3).

Table 2. The pairwise comparison matrix for assigning the weights.

Parameters	O3	NO2	SO2	CO	AI	Weight %
O3	1	2	3	3	4.00	34
NO2	0.50	1.00	2.00	3.00	4.00	27
SO2	0.33	0.50	1.00	2.00	4.00	20
CO	0.33	0.33	0.50	1.00	3.00	13
Aerosol Index (AI)	0.25	0.25	0.25	0.33	1.00	5

Table 3. The weights of each air quality zonation factors (W) and ranking of each category (R).

Parameters	Classes	R	W %
NO_2	0.0000594 to 0.0000738	1	27
	0.0000378 to 0.0000789	2	
	0.0000789 to 0.0000934	3	
	0.0000934 to 0.000134	4	
	0.000134 to 0.000248	5	
CO	0.02055 to 0.0258	1	13
	0.0258 to 0.0288	2	

	0.0288 to 0.0305	3	
	0.0305 to 0.0314	4	
	0.0314 to 0.033	5	
AI	0 to 0.05	1	5
	0.05 to 0.126	2	
	0.126 to 0.224	3	
	0.224 to 0.4	4	
	0.4 to 0.72	5	
O_3	0.135 to 0.136	1	34
	0.136 to 0.137	2	
	0.137 to 0.138	3	
	0.138 to 0.139	4	
	0.139 to 0.141	5	
SO_2	0.000047 to 0.00017	1	20
	0.00017 to 0.0002	2	
	0.0002 to 0.0004	3	
	0.0004 to 0.0006	4	
	0.0006 to 0.0009	5	

The findings showed medium air pollution zones dominate the central region of KRI, covering 16,116 km² (34.8%) of the total area (Table 4). High air pollution zones is second by covering area of 12,206 km² (27.3%), while low quality regions account for 11,267km² (24.4%) of the KRI. Notably, very high air pollution regions in KRI are relatively limited, which they cover 2,815 km² (6.1%) of the territory. Additionally, zones with very low pollution levels are minimal, spanning only 4,030 km² (8.7%) of the region (Fig. 4). This results of air quality distributions suggests that 33.4% of KRI is experiencing significant air quality concerns considering both high and very high pollution zones, while only 33.1% of KRI have better quality of air considering low and very low pollution zones (Fig. 5). The identified zones as high and very high indicate a critical need for targeted air quality management strategies in the KRI.

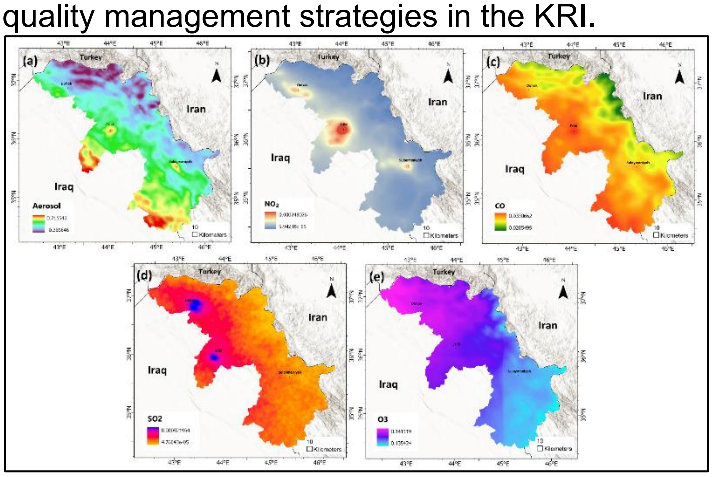

Figure 3: The air quality parameters: (a) Aerosol, (b) NO2, (c) CO, (d) SO2, and (e) O3.

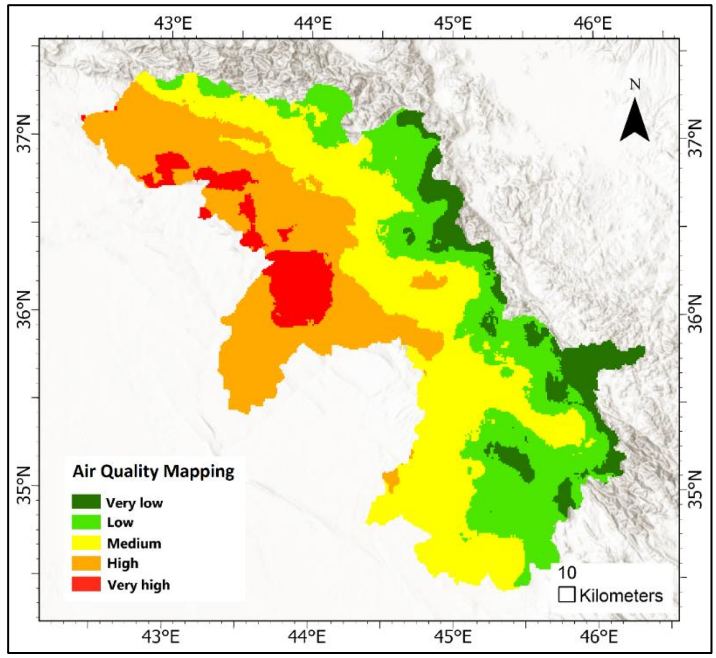

Figure 4: Air quality mapping for Kurdistan region of Iraq.

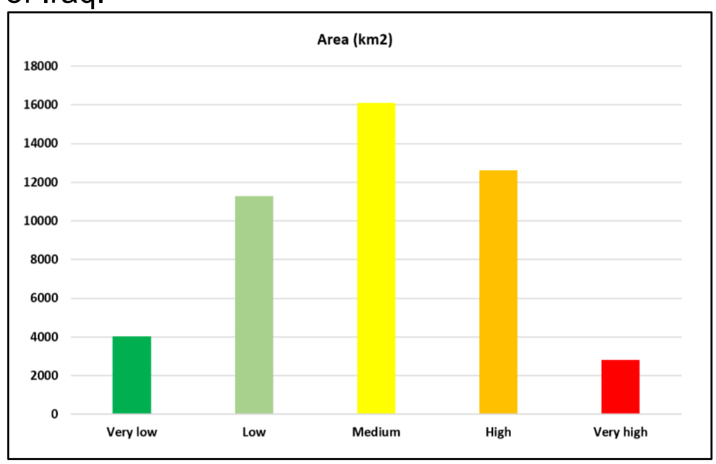

Figure 5: The covered areas of each air quality classes by km2.

Table 4. The results of air quality zonation.

Air pollution classes	Area (km2)	%	Number of zones	%
Very low	4030	8.7	8	10.4
Low	11267	24.4	16	20.8
Medium	16116	34.8	27	35.1
High	12605	27.3	22	28.6
Very high	2815	6.1	4	5.2

Moreover, the results highlighted a notable patterns in air quality zonation distributions, as the highest identified zones were in areas of medium and high pollution with 27 (35.1%) and 22 (28.6%) zones, respectively. While low pollution category contained 16 zones (20.8%), the very high and very low pollution zones were the lowest with 4 (5.2%) and 8 (10.4%) zones, respectively (Fig. 6). While the results showed that severe pollution levels were identified in smaller number of zones, however the findings indicate a critical environmental challenge in south and west in KRI, specifically in Fayde, Duhok, Erbil, and Qasruk zones.

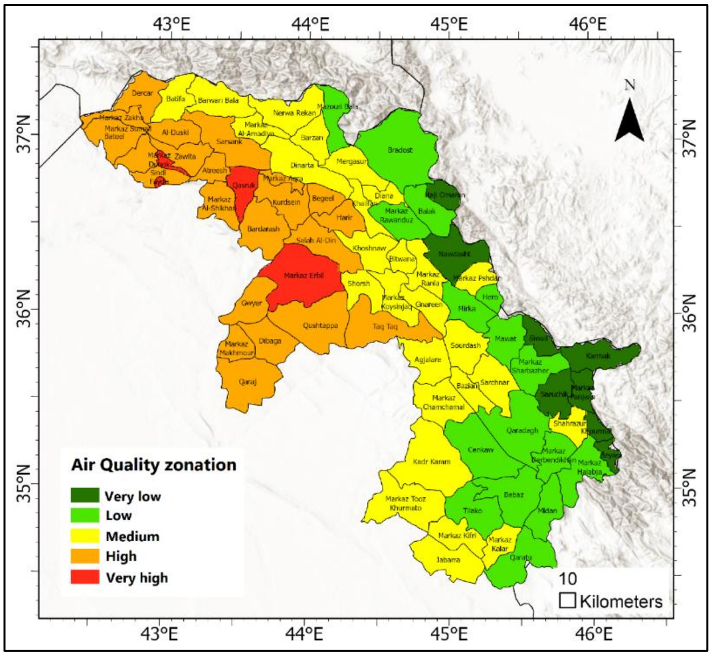

Figure 6: Air quality zonation mapping for Kurdistan region of Iraq.

These findings have critical implications for urban planners, environmental researchers, and policy makers in Kurdistan region of Iraq for better understanding the pollution distributions and robust frameworks of air quality management. And effective and proactive methodologies should be considered in regions which identified as high and very high zones for mitigation strategies. For examples populated cities such as Erbil and Duhok, which identified as very high air pollution zones need more strict codes for air quality mitigation plans to reduce the impact of air pollutants. In contrast, regions in the east of KRI, such as Halabja Penjwen and Biyara cities may not need immediate responses but should be continuously monitored for air pollutants. AHP, GIS and Remote sensing techniques aid significantly in enhancing the accuracy of air quality analysis and playing critical role in giving insights for urban planners and policy makers for informed decision makings (Ahmadi, Sahak et al. 2023). This study not only provide significant insights for better air pollution assessments, but also plays effective role in developing public safety campaigns and community preparedness initiatives and the resilience of the Kurdistan region of Iraq against air pollution threats.

The results of this study showed similar insights with existing literature, as multiple investigations have been done for different parts of KRI for air quality assessments, such as Erbil and Duhok cities. Various researchers highlighted the increased level of particular pollutants and low environmental quality in Duhok city which exceeded the World Health Organization (WHO) standard limits (Muhammed, Karimi et al. 2020, Khaled, Dereen et al. 2023, Muhyadeen and Ramadhan 2023). However, limited investigations Erbil city have been conducted to investigate the air quality. These researches documented a considerable concentrations of NO_2, SO_2, methane (CH_4), CO, O_3, and ultraviolet radiation (UV) pollutants, resulting from transportation, industrial activities, and urban expansion (Sharif and Anjel 2021, Ali, Salam et al. 2023).

Several measures could be implemented for mitigating air pollution in KRI, such as using sustainable energy sources, public transportation expansion and transitioning to alternative fuels, reducing industrial emissions by using cleaner energy and the installation of emission control technologies, and increasing green spaces (Ali, Salam et al. 2023, Venter, Hassani et al. 2024).

Conclusions

The results showed that different regions identified as low air quality, and notable regions were categorized as high air pollution zones. These findings highlight the necessity for considering air quality management more seriously, specifically in densely populated cities such as Erbil and Duhok cities. Additionally, the techniques implemented in this study can be utilized effectively for similar regions that have air pollution issues.

The results of this investigation offer notable information for urban planners and decision makers in KRI to understand the air pollution patterns and implement mitigation strategies to enhance the air quality and public safety in the region. Finally, this study highlights the importance of using geospatial techniques with integration of multi-criteria decision-making techniques in air quality assessments, which help effectively in better decision making processes and sustainable air quality managements.

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