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Assessing Urban Air Quality in Iraq: Examining Karbala City Through Air Quality Index Analysis

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Abstract

The escalating global climate crisis, exacerbated by anthropogenic pollutant emissions and insufficient mitigation efforts, necessitates urgent investigation into air pollution cases and viable solutions. This study assessed spatial variations in ambient air quality across four monitoring stations in Karbala, Iraq, using the Air Quality Index (AQI). Results revealed AQI values ranging from "Moderate" to "Very Unhealthy" (50-300), with ground-level ozone (O3) identified as the primary pollutant, followed by sulfur dioxide (SO2) and fine particulate matter (PM2.5). The poor air quality, attributed to meteorological conditions and human activities, poses significant health risks, underscoring the critical need for effective air quality management strategies in the region.

***Keywords**:* Air Quality Index, Karbala, Pollution, Environment, Health risk, Correlation coefficient.

تقييم جودة الهواء الحضري في العراق: دراسة مدينة كربلاء من خلال تحليل مؤشر جودة الهواء

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الملخص

تستلزم أزمة المناخ العالمية المتصاعدة، التي فاقمتها انبعاثات الملوثات البشرية المنشأ وعدم كفاية جهود التخفيف الكافية التحقيق العاجل في حالات تلوث الهواء والحلول القابلة للحياة. قيمت هذه الدراسة الاختلافات

المكانية في جودة الهواء المحيط عبر أربع محطات مراقبة في كربلاء، العراق، باستخدام مؤشر جودة الهواء (AQI). كشفت النتائج عن قيم AQI التي تتراوح من "معتدلة" إلى "غير صحية للغاية" (50-300)، مع الأوزون على مستوى الأرض (O_3) تم تحديده على أنه الملوث الأساسي، يليه ثاني أكسيد الكبريت (SO_2) وجسيمات دقيقة ($PM_{2.5}$). إن جودة الهواء الرديئة، التي تعزى إلى ظروف الأرصاد الجوية والأنشطة البشرية، تشكل مخاطر صحية كبيرة، مما يؤكد الحاجة الحاسمة لاستراتيجيات فعالة لإدارة جودة الهواء في المنطقة.

الكلمات المفتاحية: مؤشر جودة الهواء، كربلاء، التلوث، البيئة، المخاطر الصحية، معامل الارتباط.

1. Introduction

Air pollution is a major problem that the world is suffering from at the present time, due to its catastrophic effects on various ecosystems. It is considered one of the most dangerous types of environmental pollution and is directly related to human life, because it cannot live without air for more than a few minutes [1], it also affects the global climate, changing its composition on a large scale [2]. Urban areas suffer from air pollution due to human activities especially consuming fuel in transportation and industrialization, as well as particulate matter transported by wind. pollutants are emitted away from the source to the atmosphere and can exist in it from hours to several days according to meteorological parameters, which is governed them [3]. The most famous elements related to air pollution are O_3, NO_2, SO_2, CO, $PM_{2.5}$, PM_{10} [4, 5]. Many physical and psychological ailments may be induced by weather pollutants, such as respiratory issues. Some studies have linked asthma to air pollutants (PM, NO_2, CO, and O_3) [6] and deterioration in lung function [7], nose and throat irritation, hypertension, atherosclerosis development, acute coronary syndrome, ischemic stroke, cardiac arrhythmias [8]. Air pollution may cause cognitive decline and dementia, according to current studies. In one research, those who resided in locations with significant air pollution, notably $PM_{2.5}$, had a greater dementia risk [9]. Air pollution increases the risk of lung and other cancers [10]. Urban areas around the world are developing rapidly. This development has been accompanied by a rapid increase in population and growth in vehicle levels, which has increasingly led to problems associated with air pollution especially in developing countries including Iraq [11]. The city of Karbala is among these cities with rapid development due to its geographical location as well as its religious and tourism importance. The Air Quality Index is used by governments and other organizations to report air quality to the public and identify areas with severe pollution. Many relevant agencies and organizations have developed mathematical models of health indicators for air quality to provide citizens with information about the impact of air quality on their general health. These indicators depend on conducting continuous monitoring, that is, measurements of pollutants in the ambient air, and then incorporating these measurements into the air quality index models [12]. Many studies have studied air pollution and its effects on ambient air quality in Iraq. Mohammed et al (2015) measured the concentrations of O_3, NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} in the city of Kirkuk during the year 2014, and then the air quality index for this city was calculated using the pollutants mentioned and they concluded that the (AQI = 101-200) [13]. Shihab (2021) studied the air quality in the city of Mosul, Iraq, for 6 locations. He calculated the daily AQI for each site and classified it according to AQI categories according to the USEPA approach. The categories that were deduced were between moderate to unhealthy for the sensitive group. He demonstrated that AQI is subject to seasonal changes, and his results showed that the PM_{10} contaminant is the main contributor. In determining AQI in the city of Mosul [14]. Asmaa at el (2023) studied the air quality in the AL-Nahrawan area of Baghdad using geographic information systems and remote sensing tools. They concluded that the northeastern and western parts of AL-Nahrawan are the most polluted, as all pollutants emitted are at their maximum concentration during most months in 2021. The source of these pollutants is the Brick factories are close to the area, and therefore there is poor ambient air quality in this area [15]. Zana et al (2023) studied a variety of pollutants in the city of Erbil, Iraq. The study revealed a significant increase in the levels of various pollutants during the study period. The results also revealed that areas with high sea levels showed the lowest levels of pollution, and vice versa for areas with low sea levels [16]. The aim of this research is to evaluate the air quality index of period (April 2015-April 2016) for four stations in the city of Karbala using the US Environmental Protection Agency's air quality index and determine which of the measured pollutants contribute to determining the air quality index.

2. Materials and methods

2.1 Study area

Karbala Governorate is situated at a distance of roughly 100 km southwest of the capital city, Baghdad in the Middle Euphrates area. The region encompasses around 52 km^2, with an altitude of 32 m relative to sea level. The region in question is characterized by a semi-arid climate, with desert terrain to the west and agricultural fields to the east, so it can be considered an example of subtropical regions. Furthermore, it is situated in close proximity to the Euphrates River and the Hussein River. Karbala is renowned as a prominent religious and tourist destination in Iraq, mostly because of its abundance of Islamic mosques and sacred monuments. The population is estimated to be over 1.35 million people [17, 18].

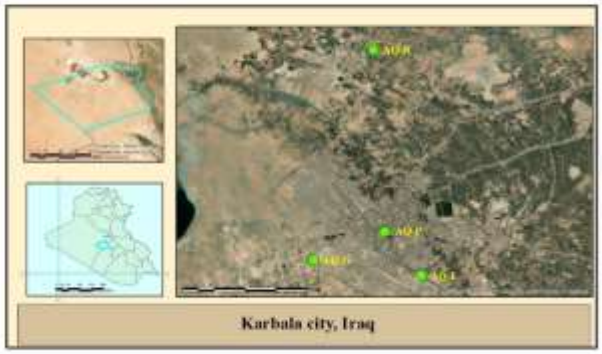


Fig. 1. Study Area

2.2 Ground Base Measurement

AQM 60 is a device is specifically designed to measure ambient air quality index. It measures various common air pollutants as well as a range of meteorological parameters. This device is affiliated with the Iraqi Ministry of Environment. The data from these devices has been utilized for several reasons: the measurement period for pollutants and meteorological elements occurs every two minutes, the margin of error is minimal, it provides real-time accurate pollutant concentrations, and there is a scarcity of such devices for real-time pollution monitoring in Iraq in general. The measured data includes O_3, NO_2, SO_2, CO, $PM_{2.5}$, and PM_{10} for the period from April 2015 to April 2016.

Table 1. Coordinates of study areas

Code	Station Name	Location	Description
AQ-G	Gypsum and Lime Plants Station	N:32^{O}34 46.3^{O} E:43^{O} 58 38.6^{O}	Residential area
AQ-I	Industrial area Station	N:32^{O}34 03.3^{O} E:44^{O} 03 13.7^{O}	Industrial area
AQ-R	Al-Rafii Station	N:32^{O}43 54.7^{O} E:44^{O} 00 50.4^{O}	Rural area
AQ-P	City centre (Park) Station	N:32^{O}35 56.7^{O} E:44^{O} 01 39.2^{O}	Residential area

2.3 Correlation coefficient (R)

The linear correlation coefficient, denoted as R, is a metric that quantifies the magnitude and direction of a linear association between two variables. The linear correlation coefficient is often known as the Pearson product moment correlation coefficient, named after its creator, Karl Pearson. The mathematical equation used to calculate the value of R is [19]:

$$R = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \ldots\ldots\ldots 1$$

2.4 Air Quality Index (AQI)

The main objective of an Air Quality Index (AQI) is to transform the measured levels of different air contaminants into a unified numerical value using a suitable aggregation method. Each indicator should ideally precisely reflect both the quantifiable and publicly perceived level of air quality for the particular time period it covers. Air quality indices seek to standardize and unify air pollution data, enabling straightforward comparisons and fulfilling the public's need for dependable and clearly comprehensible information[20]. Table 2 contains the Categories of air quality index U.S EPA.

Table 2. Categories of air quality

AQI	Descriptor	Colour
0 to 50	Good	Green
51 to 100	Moderate	Yellow
101 to 150	Unhealthy for Sensitive Groups	Orange
151 to 200	Unhealthy	Red
201 to 300	Very Unhealthy	Purple
301 to 500	Hazardous	Maroon

Sub-indices are computed using the equation below:

$$I_P = \frac{I_{Hi} - I_{Lo}}{BP_{Hi} - BP_{Lo}}(CP - BP_{Lo}) + I_{Lo} \ldots\ldots 2$$

Where (IP) is index for pollutant *p*, (CP) is truncated concentration of pollutant p, (BPHI) is concentration breakpoint greater than or equal to CP, (BPLo) is concentration breakpoint less than or equal to CP, (IHi) is AQI value corresponding to BPHI, (ILo) is AQI value corresponding to BPLo.

The value of the highest sub-indices AQI is considered the AQI of the site (eq. 3) [14].

$$\text{AQI} = Max(I_a, I_b, I_c, \dots, I_n \dots\dots\dots 3$$

3. Results and Dissections

3.1 Multi-Station AQI Evaluation

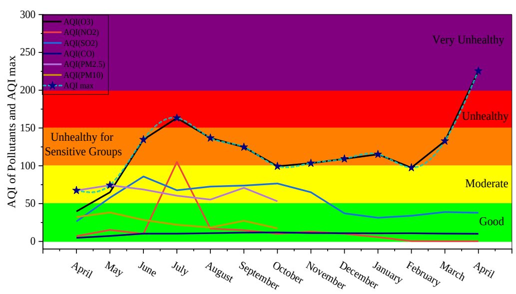
AQI values were analyzed across four stations (AQ-G, AQ-I, AQ-R, and AQ-P) for various pollutants. At AQ-G, AQI(O_3) showed the most fluctuation, ranging from Good to Very Unhealthy, Figure.2 with a strong positive correlation (R = 0.988) to AQImax. AQI(NO_2) mostly remained "Good" with one "Moderate" instance (AQI=105) in July 2015. AQI(CO) consistently stayed "Good," while AQI(SO_2) oscillated between "Good" and "Moderate." AQI($PM_{2.5}$) was consistently "Moderate," and AQI(PM_{10}) was "Good." At AQ-I, O_3 was the primary concern, mostly "Unhealthy for Sensitive Groups," with a strong correlation to AQImax (R=0.97). SO_2 was secondary, generally "Moderate" with R=0.52 correlation to AQImax. $PM_{2.5}$ was "Moderate" from April to October 2015, with a weak negative correlation (R=-0.39). NO_2, CO, and PM_{10} were predominantly "Good." At AQ-R, AQI(O_3) fluctuated between "Good" and "Unhealthy," strongly correlating with AQImax (R=0.96). AQI($PM_{2.5}$) was consistently "Moderate," while NO_2, CO, SO_2, and PM_{10} were mostly "Good." At AQ-P, AQI(SO_2) was consistently "Unhealthy for Sensitive Groups" with a strong correlation to AQImax (R=0.93). AQI(O_3) varied between "Good" and "Unhealthy for Sensitive Groups" (R=0.44 with AQImax). AQI($PM_{2.5}$) ranged from "Good" to "Moderate," while PM_{10}, CO, and NO_2 remained "Good" throughout the study period. Table 3. Correlation coefficient between AQI pollutants and AQImax in all stations.

Table 3. Correlation coefficient between AQI pollutants and AQImax

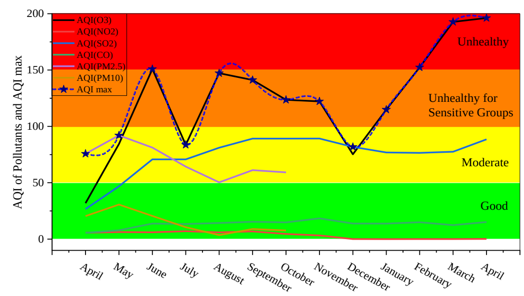
	AQI Pollutants	AQI(O_3)	AQI(NO_2)	AQI(SO_2)	AQI(CO)	AQI($PM_{2.5}$)	AQI(PM_{10})	AQI max
AQ -G	AQI(O_3)	1						
	AQI(NO_2)	0.22407	1					
	AQI(SO_2)	0.15109	0.33236	1				
	AQI(CO)	0.51569	0.04495	0.4119	1			
	AQI($PM_{2.5}$	-	-0.2074	-0.26471	-0.49138	1		

	)	0.37036						
	AQI(PM_{10})	-0.62083	-0.25924	-0.49755	-0.73683	0.92795	1	
	AQI max	0.98855	0.2294	0.09413	0.39054	-0.35532	-0.59702	1
		AQI(O_3)	AQI(NO_2)	AQI(SO_2)	AQI(CO)	AQI($PM_{2.5}$)	AQI(PM_{10})	AQI max
AQ-I	AQI(O_3)	1						
	AQI(NO_2)	-0.37922	1					
	AQI(SO_2)	0.66023	-0.33539	1				
	AQI(CO)	0.57885	-0.27314	0.94179	1			
	AQI($PM_{2.5}$)	-0.40913	0.10145	-0.67659	-0.66479	1		
	AQI(PM_{10})	-0.47434	0.07745	-0.74173	-0.74451	0.99071	1	
	AQI max	0.97485	-0.38573	0.52495	0.44364	-0.39703	-0.44835	1
		AQI(O_3)	AQI(NO_2)	AQI(SO_2)	AQI(CO)	AQI($PM_{2.5}$)	AQI(PM_{10})	AQI max
AQ-R	AQI(O_3)	1						
	AQI(NO_2)	0.55345	1					
	AQI(SO_2)	-0.64976	-0.42175	1				
	AQI(CO)	-0.86317	-0.47443	0.59937	1			
	AQI($PM_{2.5}$)	0.01689	-0.23235	-0.32889	-0.07401	1		
	AQI(PM_{10})	0.05588	-0.22771	-0.31948	-0.13918	0.9911	1	
	AQI max	0.9677	0.4977	-0.72335	-0.74987	0.05568	0.07583	1
		AQI(O_3)	AQI(NO_2)	AQI(SO_2)	AQI(CO)	AQI($PM_{2.5}$)	AQI(PM_{10})	AQI max
AQ-P	AQI(O_3)	1						
	AQI(NO_2)	0.23564	1					

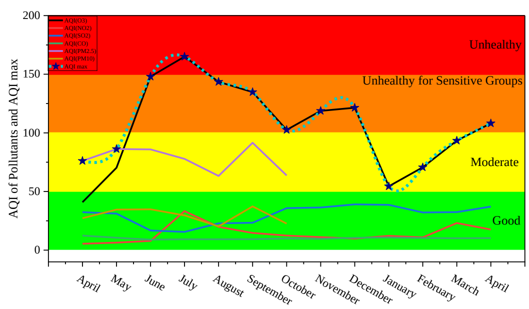
	AQI(SO_2)	0.30458	0.21751	1				
	AQI(CO)	0.05929	-0.42558	0.23746	1			
	AQI($PM_{2.5}$)	-0.65227	0.68964	-0.08614	-0.86099	1		
	AQI(PM_{10})	-0.59744	0.65459	-0.10861	-0.90373	0.96559	1	
	AQI max	0.44485	0.17468	0.93594	0.26544	-0.08614	-0.10861	1



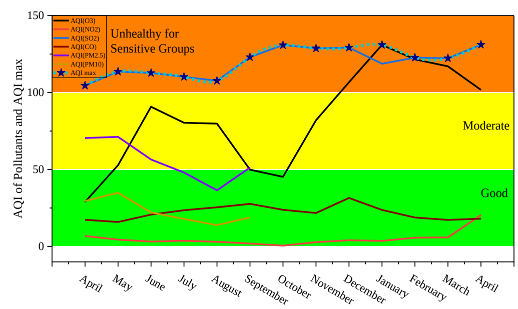
AQ-G station



AQ-I station



AQ-R station



AQ-P station

Fig. 2. Time series of AQI stations, Karbala, Iraq.

3.2 Analyze and study the causes of pollutant formation.

Tropospheric ozone is the primary contributor to elevated Air Quality Index (AQI) values and poor air quality in numerous locations. As a secondary pollutant, it forms through atmospheric chemical reactions in the presence of solar radiation, particularly ultraviolet radiation, high temperatures, and other erosive factors [21]. Iraq, including Karbala, experiences significant solar radiation, especially during summer months [22, 23]. The region is characterized by minimal cloud cover, primarily limited to winter and spring seasons [24], and high temperatures [25]. These factors collectively contribute to elevated ground-level ozone concentrations in Karbala. Temperature plays a crucial role in increasing air pollutant levels, as demonstrated by Hussein Aboudi et al. in their study on the relationship between solar radiation and temperature [26]. The positive correlation between temperature and pollutant concentrations has been observed in studies conducted in Erbil, Iraq [27], and its effect on AQI has been noted in both Mashhad [28] and Taipei [29]. Sulfur dioxide ranks as the second most significant atmospheric pollutant at sites AQ-I and AQ-G, and the primary contributor at the AQ-P site. Its main sources are anthropogenic activities, particularly the combustion of sulfur-containing fossil fuels [30]. The AQ-P station is situated in one of Karbala's busiest areas, specifically in the city center's largest park. This location is surrounded by commercial zones and densely populated residential areas, bordered by four main streets. The area experiences high traffic density and congestion, especially during official working hours (07:00-15:00). Small and large private electric generators further contribute to local pollution levels. Since 2003, the number of vehicles in Iraq has increased to approximately 4.5 million, with a consistent growth rate of about 17.5%. This increase, combined with the presence of equipment, heavy machinery, and diesel generators, has led to significant pollutant emissions [31]. Iraqi diesel fuel contains exceptionally high sulfur levels, exceeding 10,000 ppm, which is considered among the worst globally [32, 33]. Iraqi gasoline also contains high sulfur content at 500 ppm [34]. The elevated SO_2 levels in this area can be attributed to vehicular emissions, generators, and other unaccounted sources such as power plants and fires. Regarding particulate matter, $PM_{2.5}$ ranks third in its effect on increasing AQI and deteriorating air quality across most locations. Results indicate that the AQI for $PM_{2.5}$ falls within the moderate category, while PM_{10} does not significantly affect AQI increases. It should be noted that atmospheric particle data was limited to April-October 2015, with the remainder of the study period lacking this information. Available data was analyzed for the aforementioned period, corresponding to the hot and dry season, particularly August. Despite vehicular and human activities contributing to particulate matter emissions, the good to moderate AQI rates for particles can be attributed to meteorological factors. Iraq's summer season spans June to August, during which temperatures peak [25], correlating with a decrease in monthly average particulate matter concentrations. A similar study found a strong negative relationship between monthly average PM levels and temperature [35]. Several mechanisms account for this negative correlation. Temperature influences the chemical composition of particulate matter, leading to the formation of secondary atmospheric particles, which results in decreased local $PM_{2.5}$ and PM_{10}

concentrations[36-39]. Additionally, temperature affects the height of the atmospheric boundary layer, inducing convective movements that efficiently transport PM upward, leading to faster dispersion [40-43]. Gravitational effects must also be considered, particularly for particles 10 micrometers or larger in diameter. Coarse particles are rapidly removed from the air by sedimentation, with residence times ranging from minutes to hours. This factor, combined with the aforementioned reasons, may explain why monthly average AQI values for PM_{10} remain within the safe category for the population [44]. AQI(NO_2) values at all sites fall within the safe category, except for the AQ-G site in July, where a significant increase in NO2 concentration elevated the AQI(NO2) to levels unhealthy for sensitive groups. The AQ-G station is located west of Karbala, with residential areas to the east and open desert to the west. The pollutant monitoring device is situated in a green space adjacent to a main road entering the city. Monthly average AQI(NO_2) values were in the good category throughout the study period, except for July. The significant increase is likely attributable to anthropogenic activities, possibly including arson or uncontrolled fires near the AQ-G station or burning of nearby vegetation. NO_2 is a component of the nitrogen oxides (NOx) family (NOx= NO+NO_2). Primary sources of NOx emissions are combustion processes [45, 46], while specific NO2 sources include fossil fuel combustion, biomass burning, soil emissions, and lightning [47]. During the study period (April 2015 to April 2016), AQI(NO_2) indicators remained within the good category. This may be attributed to NO2's role in atmospheric interactions, particularly in tropospheric ozone formation through photochemical reactions with volatile organic compounds (VOCs) in the presence of sunlight and elevated temperatures [21, 48, 49]. Nitrogen oxides are also precursors to nitrate aerosol formation [50]. and can react with OH radicals or atmospheric moisture to form nitric acid (HNO_3) rain, which adversely affects vegetation, buildings, and other anthropogenic structures [51]. AQI(CO) calculations indicate that carbon monoxide levels fall within the safe category and do not pose a significant pollution risk at any of the selected sites. This low concern for CO concentrations can be attributed to several factors. Firstly, CO is present in trace amounts in the atmosphere [52, 53] and has a short atmospheric lifetime ranging from 4 to several weeks [54, 55]. Secondly, CO participates in photochemical reactions, interacting with hydroxide radicals, methane (CH_4), formaldehyde (HCHO), and CO2 [53]. It is also an important precursor to ground-level ozone formation [21, 56]. Lastly, certain bacteria oxidize CO, facilitating its removal from the atmosphere [52]. When in contact with soil, CO can be oxidized to carbon dioxide and can also be converted to methane by anaerobic methanogenic microorganisms (Methanosarcina bakterii and Methanobacterium formicum)[57].

3.3 Spatial Variations in AQI and Associated Health Risks.

Air Quality Index (AQI) values across all monitoring stations in Karbala, Iraq, exhibit significant monthly variations. The study sites consistently record AQI values ranging from moderate to very unhealthy (AQI=50-300), with the "unhealthy for sensitive groups" category (AQI=100-150) predominating at most locations. Ground-level ozone is the primary driver of these elevated AQI levels at stations AQ-G, AQ-I, and AQ-R, while it ranks second at the AQ-P station. At AQ-P. Sulfur dioxide (SO_2) is the primary contributor to AQI levels between 50 and 200, and it ranks second at both AQ-G and AQ-I. Fine particulate matter ($PM_{2.5}$) consistently ranks third at AQ-G, AQ-I, and AQ-P, but second at AQ-R. Although only four sites were studied, their distribution across the northern, western, central, and southern areas of Karbala suggests that air pollution is a pervasive issue throughout the city, albeit with varying intensity. This widespread pollution is of significant concern, given the well-documented impacts of air pollution on human health and the environment [58]. O_3 exposure is associated with a range of health effects, including respiratory diseases, impaired lung function, asthma exacerbation, increased mortality (both from short- and long-term exposure), cardiovascular disease, irregular heartbeats, and neurological impacts such as increased risk of autism in children. As a strong oxidant, O_3 can cause oxidative damage to airway cells and fluids [59, 60]. SO_2 considered a significant air pollutant, especially in developing countries, causing health problems [61]. SO_2 has adverse health effects on the human respiratory, cardiovascular, and nervous systems and causes type 2 diabetes and non-accidental deaths [62]. Particulate matter (PM) exposure from ambient air has been implicated in various diseases [63], Fine particles with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) are considered more harmful than PM_{10} [64, 65]. This is because while PM_{10} occupies the upper respiratory system, $PM_{2.5}$ goes further to reach the alveolar part of the lower respiratory system[66]. PM exposure has been associated with lung cancer, chronic obstructive pulmonary disease, cardiovascular disease, autoimmune disorders, neoplastic diseases, and the exacerbation of various other conditions [64, 67]. While the AQI values for CO and nNO_2) at all study sites do not currently pose a significant threat to public health, exceeding permissible limits could lead to major health issues. CO inhalation results in the formation of carboxyhemoglobin (COHb), which has a reduced oxygen-carrying capacity. COHb concentrations above 1% can cause respiratory problems, impaired visual perception, headaches, and nausea [68]. Prolonged CO exposure may exacerbate asthma, chronic bronchitis, and increase susceptibility to respiratory infections [69]. NO_2 shares some health effects with CO and is additionally associated with cancer, premature birth, and diabetes [70].

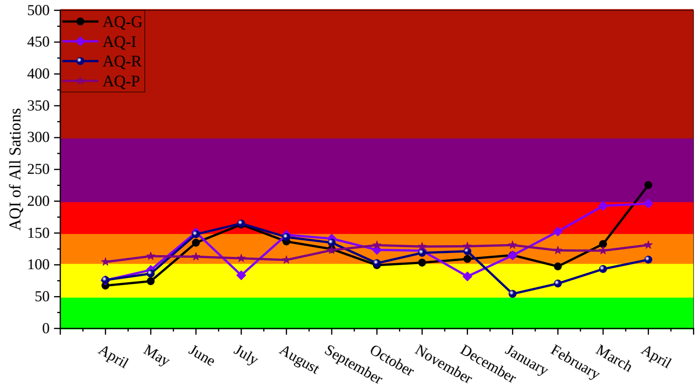


Fig. 3. Time series of AQI station, Karbala, Iraq

4. conclusions

Air quality in Karbala, Iraq exhibits notable spatiotemporal variability (AQI=50-300). O_3 predominates at most stations, correlating strongly with peak AQI. SO_2 ranks second or first, attributed to high-sulfur fuel combustion. $PM_{2.5}$ typically ranks third, with limited data. NO_2, CO, and PM_{10} generally maintain "Good" levels. Meteorological and anthropogenic factors exacerbate poor air quality, posing significant health risks. This study underscores the need for comprehensive air quality management and further research, particularly regarding particulate matter, to elucidate seasonal variations and long-term trends.

Conflict of Interests: The authors declare that there is no conflict of interest related to this article.

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