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Twenty Years of Air Pollutant Index Trend Analysis in Kuching, Sarawak, Malaysia (2000-2019)

(20 Tahun Analisis Trend Indeks Pencemaran Udara di Kuching, Sarawak, Malaysia (2000-2019))

SITI HASYYATI DRAHMAN, HISYAMMUDIN MASERI*, MAQUELINE CYNDI NAP & ZETTY BAIDURI HOSSEN

Faculty of Engineering and Technology, i-CATS University College, 93350 Kuching, Sarawak, Malaysia

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ABSTRACT

Sarawak is expected to face environmental challenges due to air pollution arising from industrial emissions and urbanisation as it strives towards achieving developed and high-income status by 2030. Therefore, it is important to conduct a comprehensive Air Pollutant Index (API) trend analysis. There are currently limited studies on API trend analysis that focus on Kuching, the capital known for its extensive industrial zones and densely populated urban centre. The main focus of this study was to perform a comprehensive analysis of the API trends in the Kuching region over a period of 20 years (2000-2019) using a visual representation in the form of a contour plot. To achieve this purpose, a five-term Fourier model was employed to predict the missing API data using Matlab software. Then, a complete version of a contour plot was developed to clearly illustrate the fluctuations in air quality over time. It was found that a five-term Fourier model used to forecast missing API data provides a strong correlation with the API readings, with most of the R values greater than 0.91. Moreover, the generated contour plot demonstrates a visual congruence between the forecasted data and the original dataset. Elevated API readings, signifying highly detrimental air quality, were primarily identified as a result of haze episodes stemming from uncontrolled fires in neighbouring countries, particularly during El Niño events. The findings of this study contribute to a better understanding of API trends in Kuching by means of the contour plot.

Keywords: Air Pollutant Index; contour plot; five-term Fourier model; Kuching; trend analysis

ABSTRAK

Sarawak dijangka menghadapi cabaran alam sekitar disebabkan oleh pencemaran udara yang berpunca daripada pelepasan industri dan perbandaran, seiring dengan usahanya untuk mencapai status maju dan berpendapatan tinggi menjelang tahun 2030. Oleh itu, adalah penting untuk menjalankan analisis arah aliran Indeks Pencemaran Udara (IPU) yang komprehensif. Kajian mengenai analisis arah aliran IPU yang tertumpu kepada Kuching, ibu negeri yang terkenal dengan zon perindustrian yang luas dan pusat bandar yang padat, masih terhad pada masa kini. Fokus utama kajian ini adalah untuk menjalankan analisis menyeluruh terhadap arah aliran IPU di kawasan Kuching dalam tempoh 20 tahun (2000-2019) dengan menggunakan penggambaran visual dalam bentuk plot kontur. Bagi mencapai tujuan ini, model Fourier lima-terma digunakan untuk meramalkan data IPU yang hilang dengan menggunakan perisian Matlab. Kemudian, plot kontur versi lengkap dibangunkan untuk menggambarkan dengan jelas perubahan dalam kualiti udara sepanjang masa. Didapati bahawa model Fourier lima-terma yang digunakan untuk meramalkan data IPU yang hilang memberikan korelasi yang kuat dengan bacaan IPU, dengan kebanyakan nilai R melebihi 0.91. Selain itu, plot kontur yang dihasilkan menunjukkan keselarasan visual antara data yang diramalkan dan dataset asal. Bacaan IPU yang tinggi menunjukkan kualiti udara yang sangat buruk, terutamanya dikenal pasti sebagai hasil daripada episod jerebu yang berpunca daripada kebakaran tanpa kawalan di negara-negara jiran, terutamanya semasa peristiwa El Niño. Penemuan kajian ini menyumbang kepada pemahaman yang lebih baik mengenai arah aliran IPU di Kuching melalui plot kontur.

Kata kunci: Analisis arah aliran; Indeks Pencemaran Udara; Kuching; model Fourier lima-terma; plot kontur

Introduction

Kuching is the capital of Sarawak located in East Malaysia and the most densely populated urban centre (The Official Portal of the Sarawak Government 2023), which contributes to significant growth and urbanisation. Kuching is a highly significant economic region in Sarawak and Malaysia, known for its substantial development of infrastructure, industrial, and residential zones. Nevertheless, this advancement has resulted in an adverse effect on the air quality, resulting in substantial deterioration. Air pollution arises when there is a release of particulate matter and noxious gases into the atmosphere at sufficient levels to cause detrimental effects on human health (Isiyaka & Azid 2015). This specific type of air pollution is accountable for a substantial proportion of the atmospheric haze that is generated. Haze can be described as a combination of smoke, dust, moisture, and suspended vapour present in the atmosphere, which has the potential to limit visibility (Quah & Varkkey 2013). Therefore, the assessment of air quality concerns in Sarawak possesses crucial significance (Abdullah, Abu Samah & Jun 2012).

Kuching has been affected by haze since 1997 due to Indonesia's transboundary haze pollution (Chooi & Yong 2016; Department of Environment Malaysia 2021; Islam, Pei & Mangharam 2016). The most severe haze was documented with an Air Pollution Index (API) reading of 850 (Chooi & Yong 2016). Therefore, Kuching conducts continuous and manual surveillance of air quality to detect any alterations in the condition of the surrounding air that may pose a threat to human health and the environment. It is carried out using the New Ambient Air Quality Standard established by the Department of Environment (DOE 2000) Malaysia, which has replaced the Malaysian Ambient Air Quality Guidelines that have been in place since 1989. The new Malaysian Ambient Air Quality Standard encompasses six distinct categories for air pollutants such as particles measuring 10 μm or less (PM_{10}), sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3) and suspended particles with a size of 2.5 μm or less ($PM_{2.5}$). The inclusion of the new standard measure, $PM_{2.5}$, was utilised due to its heightened significance in relation to environmental impacts (Department of Environment Malaysia 2022c; Shi et al. 2012; Thangavel, Park & Lee 2022). Throughout the past twenty years, the aforementioned data was utilised for this research. However, the presence of certain missing data posed challenges in conducting a comprehensive analysis.

All of the aforementioned characteristics are utilised in the assessment of ambient air quality. The API was designed with seven distinct value ranges (good, moderate, unhealthy, very unhealthy, hazardous, and emergency) to communicate air quality, instead of utilising precise measurements of air contaminants. This index also signifies its effect on human health, ranging from good to emergency. The API is widely recognized as an important indicator for assessing air quality and for quantifying the relationship between air pollution and its impact on human health (Abd Rahman et al. 2016). The API system closely adheres to the Pollutant Standard Index (PSI) established by the United States Environmental Protection Agency (US-EPA) (Department of Environment Malaysia 2022a). As indicated in Table 1, all categories are crucial in the context of air quality management and their essential role in the decision-making process for data interpretation. The benefit of utilising API for policies and regulatory actions is that it can accurately indicate the air quality status and the impact on human health. Consequently, prompt measures can be implemented once the most severe air quality condition is identified.

TABLE 1. API status indicator (Department of Environment Malaysia 2000)

API	Status	Level of pollution
0 – 50	Good	Low pollution without adverse impact on health
51 – 100	Moderate	Mild pollution without any adverse impact on health
101 – 200	Unhealthy	Deterioration in the health of high-risk individuals, specifically those with heart and lung issues
201 – 300	Very unhealthy	Deterioration in the health status and decrease the physical exercise capacity of individuals with heart and lung issues. Impact on public health
> 300	Hazardous	Harmful for people who are at high risk and for public health
> 500	Emergency	Harmful for people who are at high risk and for public health

Numerous studies on API trend analysis have been conducted for various districts of Malaysia, i.e., Abd Rani et al. (2018), Koo et al. (2020), Rahman et al. (2015), Suris et al. (2022), and Zakaria et al. (2018), to name a few. Unfortunately, there is a dearth of research on the study of API trends specifically pertaining to Kuching, Sarawak. Previous studies include the analysis of API trends and forecasts from different air monitoring stations in Malaysia over a period of time, with API datasets offered in the form of a time series plot. A time series plot is inadequate for analysing data over a longer period of time. Hence, an API calendar-based graphic was developed by Abd Rahman and Lee (2020) to facilitate the visualisation of trend profiling and analysis. Consequently, this graphical approach may be quite tedious when analysing data over a longer time period. Moreover, the visual representation of the data in a calendar-based form renders it unsuitable for continuous time analysis. A contour plot is a graphic analysis that exhibits similarities with the API calendar. As a results, adopting the contour plot technique is a more acceptable option for this study as it consistently generates graphical visuals over a longer period and easily recognisable visual images.

The aim of this study was to investigate the historical trend for Kuching of ambient air pollution over 20 years (2000 to 2019). A five-term Fourier model series, applied to predicting unavailable API data, exhibits a robust association with the API measurements. Nevertheless, it is imperative to ensure that all data that is presently missing is promptly filled in to expedite the analysis procedure. The analysis focuses on the fluctuations in air quality observed during the designated time frame by means of a contour plot. The novelty in this study is in the development of a comprehensive contour map utilising a mathematical formulation from the curve fitting toolbox in Matlab software. This plot is specifically used to anticipate the missing API data.

Materials and Methods

The Department of Environment (DOE) has been engaged in continuous monitoring of ambient air quality by means of their monitoring station network, comprising a total of 68 stations strategically positioned throughout Malaysia. This study exclusively examines the air pollutant index (API) for the monitoring station located at Medical Store Kuching, Sarawak, with coordinates 01°33.734’N and 110°23.329’E. This station is located in Kuching’s industrial areas, indicating the probability of high API readings.

In this study, the daily API dataset from 2000 to 2019 were utilised for the trend analysis. This API dataset was acquired from DOE Malaysia. The hourly data obtained from the air monitoring station was calculated based on the average concentration of each pollutant over a specified time period. The pollutant parameters include sulphur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), and carbon monoxide (CO). Using a specific mathematical formula (Table 2), the calculated data were then normalised to produce dimensionless values referred to as the sub-index. From the sub-index of each pollutant, the maximum sub-index will be considered as API reading. The API value was usually determined by particulate matter since it was the dominating concentration most of the time, particularly during haze in Malaysia (Department of Environment Malaysia 2022b). Prior to April 2017, the primary parameter influencing the API values was PM_{10}, whereas from July 2017 onwards, $PM_{2.5}$ became the predominant contributor.

The API trend was analysed using Matlab software (ver. 2023a). The analysis consists of a 20 years dataset from 2000 to 2019 with a total of 7,212 API readings. From April 2017 to July 2017, a total of 82 API readings were invalid due to the exchange of concessions and the utilisation of new equipment. There was also a total of 6 unavailable API readings in December 2017, January 2018, and February 2018. These API readings will be referred to as missing API data throughout this study. Among the formulas available in the curve fitting toolbox in Matlab software, a five-term Fourier model, as expressed in Equation (1), was proposed in this study to simulate the missing API readings over the years on a daily basis.

$$\begin{aligned}\mathrm{API} = {} & a_0 + a_1\cos(t\cdot w) + b_1\sin(t\cdot w) + a_2\cos(2t\cdot w) \\ & + b_2\sin(2t\cdot w) + a_3\cos(3t\cdot w) + b_3\sin(3t\cdot w) \\ & + a_4\cos(4t\cdot w) + b_4\sin(4t\cdot w) + a_5\cos(5t\cdot w) \\ & + b_5\sin(5t\cdot w)\end{aligned} \quad (1)$$

where a and b with subscripts 1 to 5 and w are the auto-generated constants obtained from the Matlab software, and t is the number of days.

TABLE 2. API equations for each pollutant (Abd Rani et al. 2018; Department of Environment Malaysia 2000)

Pollutant	Breakpoint of concentration	Equation for API
Carbon Monoxide, CO (8-hour average, unit ppm)	$0 < \rho \leq 9$	API = $\rho \times 11.11111$
	$9 < \rho \leq 15$	API = $100 + [(\rho - 9) \times 16.66667]$
	$15 < \rho \leq 30$	API = $200 + [(\rho - 15) \times 6.66667]$
	$\rho > 30$	API = $300 + [(\rho - 30) \times 10]$
Ozone, O_3 (1-hour average, unit ppm)	$0 < \rho \leq 0.2$	API = $\rho \times 1000$
	$0.2 < \rho \leq 0.4$	API = $200 + [(\rho - 0.2) \times 500]$
	$\rho > 0.4$	API = $300 + [(\rho - 0.4) \times 1000]$
Nitrogen Dioxide, NO_2 (1-hour average, unit ppm)	$0 < \rho \leq 0.17$	API = $\rho \times 588.23529$
	$0.17 < \rho \leq 0.6$	API = $100 + [(\rho - 0.17) \times 232.56]$
	$0.6 < \rho \leq 1.2$	API = $200 + [(\rho - 0.6) \times 166.667]$
	$\rho > 1.2$	API = $300 + [(\rho - 1.2) \times 250]$
Sulfur dioxide, SO_2 (24-hour average, unit ppm)	$0 < \rho \leq 0.04$	API = $\rho \times 2500$
	$0.04 < \rho \leq 0.3$	API = $100 + [(\rho - 0.04) \times 384.61]$
	$0.3 < \rho \leq 0.6$	API = $200 + [(\rho - 0.3) \times 333.333]$
	$\rho > 0.6$	API = $300 + [(\rho - 0.6) \times 500]$
Particulate matter 10 μm or less in diameter, PM_{10} (24-hour average, unit $\mu g/m^3$)	$0 < \rho \leq 50$	API = ρ
	$50 < \rho \leq 150$	API = $50 + [(\rho - 50) \times 0.5]$
	$150 < \rho \leq 350$	API = $100 + [(\rho - 150) \times 0.5]$
	$350 < \rho \leq 420$	API = $200 + [(\rho - 350) \times 1.4286]$
	$420 < \rho \leq 500$	API = $300 + [(\rho - 420) \times 1.25]$
	$\rho > 500$	API = $400 + (\rho - 500)$
Particulate matter 2.5 μm or less in diameter, $PM_{2.5}$ (24-hour average, unit $\mu g/m^3$)	$0 < \rho \leq 12.0$	API = $\rho \times 4.16667$
	$12.1 \leq \rho \leq 50.4$	API = $51 + [(\rho - 12.0) \times 1.24682]$
	$50.5 \leq \rho \leq 55.4$	API = $101 + [(\rho - 50.5) \times 10]$
	$55.5 \leq \rho \leq 150.4$	API = $151 + [(\rho - 55.5) \times 0.51633]$
	$150.5 \leq \rho \leq 250.4$	API = $201 + [(\rho - 150.5) \times 0.99099]$
	$250.5 \leq \rho \leq 350.4$	API = $301 + [(\rho - 250.5) \times 0.99099]$
	$\rho \geq 350.5$	API = $401 + [(\rho - 350.5) \times 0.66044]$

Note: ρ is the pollutant concentration

Results and Discussion

API TRENDS: 2000 – 2019

Figure 1 shows the API trends for Kuching, Sarawak, from 2000 to 2019. The data shows a trend of fluctuations in API values over a span of two decades, with API readings beyond 100 were observed periodically within five-year intervals. The elevated API readings can be attributed to the advancements in development as one of the contributing factors. The significant haze episodes that occurred in Sarawak during the period spanning from 2000 to 2019 have been reported in the years 2006, 2015, and 2019 (Department of Environment Malaysia 2021; Khan et al. 2020). A notable increase in API readings in Kuching exceeding 200 was observed in both 2015 and 2019, indicating a state of very unhealthy air quality. In 2006, it was reported that the air quality was unhealthy, with API readings exceeding 150 and almost hitting 200. The haze phenomenon during those years was caused by the transboundary pollution that originated from the uncontrolled fire outbreaks in Indonesia for the purpose of land clearance, resulting in catastrophic environmental, social, health, and economic consequences (Koplitz et al. 2016; Sofiyuddin et al. 2021). Meanwhile, the API readings reported in 2002, 2009, 2011, 2014, and 2018 were within the range of 101 to 150 (unhealthy category), which poses a potential risk to individuals belonging to sensitive groups (U.S. Environmental Protection Agency 2022).

CONTOUR PLOT VISUALIZATION

In order to provide a clear visual representation of the API trend from 2000 to 2019, a contour plot was constructed for the dataset, as illustrated in Figure 2. As can be seen from the figure, there were several blank regions due to the missing data as aforementioned. The API readings exhibit a notable degree of consistency over the years for each individual month. A five-term Fourier model, as given in Equation (1), can demonstrate a strong correlation with the API readings and was therefore employed to simulate the missing API readings over the years on a daily basis. All the constants in Equation (1) were automatically computed via the Matlab software. For instance, the auto-generated constants with the respective correlation coefficients for the missing API readings in April 2017 are presented in Table 3.

The forecasted API values offered in Table 3 were determined by substituting the auto-generated constants obtained from the Matlab software into Equation (1). It can be seen that the forecasted API values in April 2017 fall within the good (0 – 50) and moderate (51 – 100) categories. The relationship between API and number of days employing the five-term Fourier model was measured using the coefficient of correlation, *R*, as provided in Table 3. It is observed that most of the *R* values fall within the interval of 0.91 and 1.00, indicating a very strong correlation between API values and number of days. Meanwhile, certain *R* values are found to be

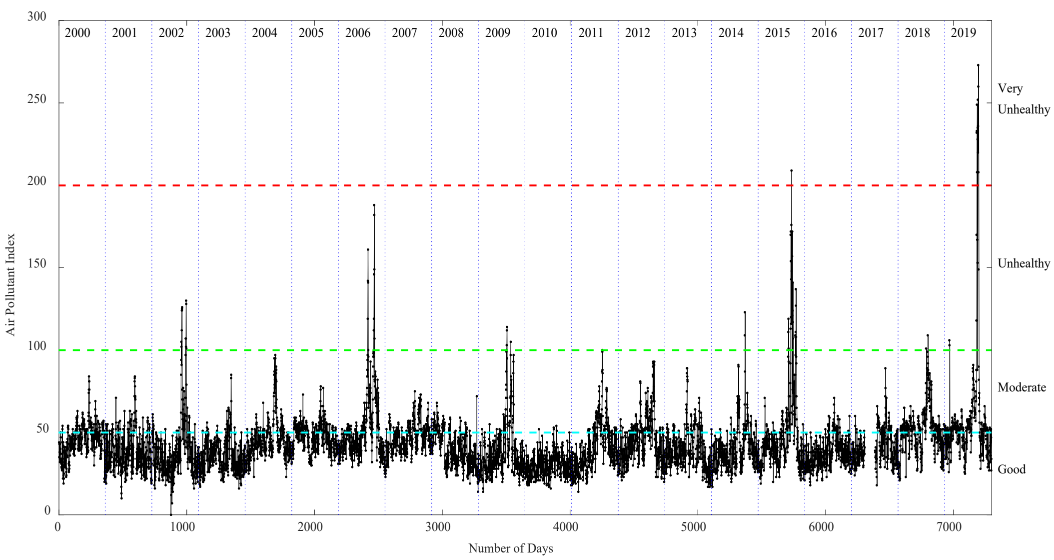

FIGURE 1. API trends for Kuching, Sarawak, from 2000 to 2019

between 0.71 and 0.90, signifying a strong correlation between both parameters (Piaw 2013). For the remaining missing API readings, the measured values of *R* exceeded a threshold of 0.71. Therefore, it can be inferred that the utilisation of the five-term Fourier model is justifiable in its ability to forecast the missing API readings.

To produce a complete contour plot of Figure 2, all the missing API readings were simulated using the five-term Fourier model and then integrated with the original dataset, as illustrated in Figure 3. The entire process was coded using Matlab software, which was computationally time efficient, from data entry to the generation of the complete contour plot. It can be seen that the forecasted data visually matches the original dataset. The predominant presence of blue colour in the contour plot depicted in Figure 3 during the months of January to June and November to December indicates favourable air quality conditions during those months. However, there was a noticeable increase in API values from July to October, with September exhibiting the most prominent increase, particularly in 2006, 2015, and 2019. This upward trend can be attributed to the occurrence of El Niño condition during those time periods, which further intensified the agricultural and land clearing fires in Indonesia, as reported by Koplitz et al. (2016). This can be exacerbated by anthropogenic activities that have a strong influence on air quality (Isiyaka & Azid 2015). Consequently, a dense haze has emerged, imposing adverse public health impacts on populations, over the majority of Equatorial Asia, including Malaysia. Therefore, it is important for the government to implement stringent legal measures, especially during the occurrence of El Niño events that occur about every three to seven years (Goddard & Gershunov 2020), in order to mitigate the formation of haze.

ANNUAL FREQUENCIES OF API CATEGORIES

Figure 4 shows the annual frequencies of each indicator, i.e., good, moderate, unhealthy, and very unhealthy, from 2000 to 2019. The annual frequencies in this context represent the number of days in a year. It can be observed that the annual frequency varies over the years. The year 2019 exhibited the most unfavourable air quality conditions, with 12 days of very unhealthy air quality, followed by 7 days of unhealthy air quality, 205 days of moderate air quality, and 141 days of good air quality. The worst air quality ever recorded in these 20 years occurred on September 19, 2019 with an API of 273. The predominant parameter during this period was particulate matter, with significantly higher concentrations observed

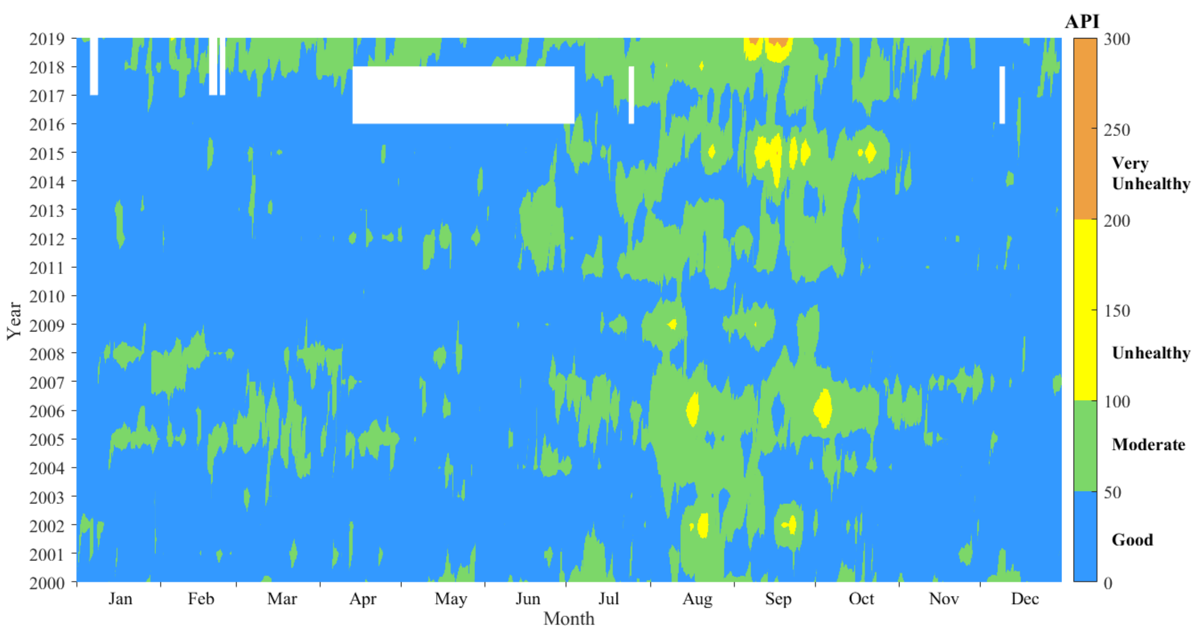

FIGURE 2. Contour plot for daily API from 2000 to 2019: Original dataset

TABLE 3. Auto-generated constants of the five-term Fourier model in forecasting the missing API readings in April 2017

Date	Constant values												API[a]	R[b]
	a_0	a_1	b_1	a_2	b_2	a_3	b_3	a_4	b_4	a_5	b_5	w		
14/4	40.034	-2.424	5.204	8.065	1.684	1.715	-2.625	-1.475	-1.873	5.307	4.086	0.485	49.252	0.926
15/4	36.215	-1.329	2.731	-0.515	-1.125	4.505	3.919	-1.022	5.250	-2.762	6.546	0.337	23.764	0.885
16/4	37.157	1.016	1.106	-5.571	-4.619	0.403	5.797	-0.765	4.591	-4.749	5.393	0.341	21.544	0.857
17/4	39.363	-0.025	0.913	5.420	-1.501	-1.346	5.625	-0.654	2.733	5.119	-5.891	0.446	23.840	0.931
18/4	40.237	0.107	-1.060	-2.871	-2.070	7.205	5.754	0.041	1.414	-2.752	3.206	0.334	35.168	0.922
19/4	39.019	-5.033	2.480	9.262	3.597	2.220	3.779	-0.279	0.252	-0.849	4.048	0.501	54.119	0.953
20/4	40.101	-5.666	1.359	6.460	1.770	0.712	3.159	0.708	2.084	-2.192	1.731	0.505	51.728	0.947
21/4	39.180	-4.923	0.524	5.117	-0.224	-2.123	4.835	3.780	2.005	4.194	3.484	0.490	50.307	0.921
22/4	38.126	-7.404	-0.457	7.452	-1.620	-3.474	3.043	-0.264	4.728	2.421	2.830	0.497	52.951	0.978
23/4	$-4.775(10^4)$	$9.253(10^3)$	$8.264(10^4)$	$5.280(10^4)$	$-1.195(10^4)$	$-8.254(10^3)$	$-2.390(10^4)$	$-6.959(10^3)$	$3.275(10^3)$	$5.989(10^2)$	$9.920(10^2)$	0.137	30.398	0.927
24/4	39.508	-0.702	4.230	5.303	-1.547	1.317	4.134	-1.793	-5.413	-5.575	-5.592	0.444	31.016	0.892
25/4	38.120	-1.676	-5.647	4.091	2.295	4.044	6.088	-3.493	-3.535	-0.921	2.474	0.664	37.950	0.779
26/4	35.912	10.612	-1.990	2.009	4.387	6.216	-1.930	3.114	-1.176	0.418	-2.247	0.974	32.585	0.941
27/4	37.068	-6.501	5.947	10.472	-0.044	1.086	5.047	2.852	0.367	5.061	4.424	0.490	57.634	0.949
28/4	38.640	-3.692	1.649	8.321	-4.009	-0.762	4.978	-0.258	3.040	3.025	6.933	0.490	56.072	0.951
29/4	$5.087(10^8)$	$-7.442(10^8)$	$-4.166(10^8)$	$2.593(10^8)$	$4.227(10^8)$	$-7.791(10^6)$	$-1.913(10^8)$	$-2.000(10^7)$	$3.955(10^7)$	$3.872(10^6)$	$-2.619(10^6)$	0.049	54.093	0.935
30/4	46.293	7.687	-10.289	1.029	-3.665	2.327	-8.898	4.972	-3.659	0.042	-5.146	0.243	51.385	0.867

[a]Forecasted Air Pollutant Index (API) values by using five-term Fourier model via Matlab software

[b]Coefficient of correlation, R, is used to measure the strength of five-term Fourier series relationship between API and number of days

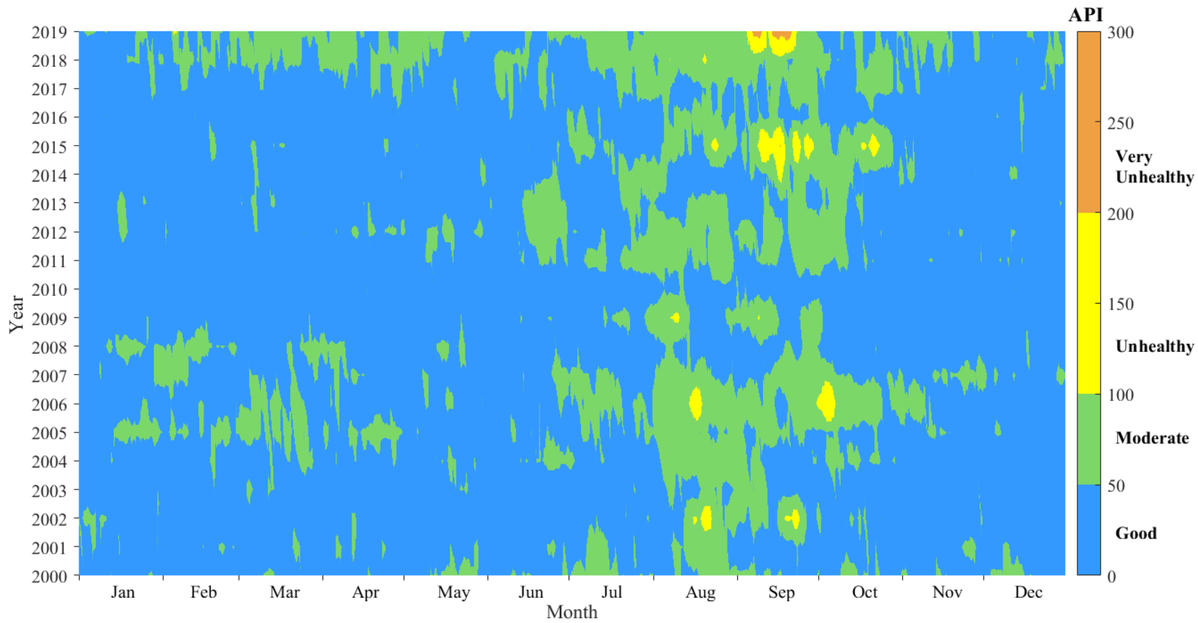

FIGURE 3. Contour plot for daily API from 2000 to 2019: Combination of forecasted API for 2017 and 2018 with the original dataset

during periods of haze compared to non-haze periods, as investigated by Chooi and Yong (2016). The sources of particulate matter were derived from three primary contributors, namely biomass burning, secondary inorganic aerosol, and traffic emissions (Sulong et al. 2017). On September 17, 2015, the highest recorded value of API readings was 209, indicating a state of very unhealthy air quality and marking the peak of the year 2015. It was reported that the occurrence of good, moderate, unhealthy, and very unhealthy air qualities were 264, 75, 25, and 1 days, respectively. Prior to the haze phenomenon in 2015, a high API of 188 was reported on October 4, 2006. The data indicates that there were 225 days with good air quality, 129 days with moderate air quality, and 11 days with unhealthy air quality. The haze phenomenon that occurred during those years resulted in the Kuching region being enveloped by a thick layer of smoke, leading to a significant reduction in visibility throughout the area.

There was a slight haze in the years 2002, 2009, 2014, and 2018, with the highest recorded API readings of 130, 114, 123, and 109, respectively. These values range from 101 to 150, implying unhealthy air quality. While the impact of this range on the general population may be minimal, it could have harmful effects on individuals belonging to sensitive groups, particularly those who suffer from heart and lung complications. The year 2010 was the healthiest in terms of air quality, as evidenced by the fact that there were 360 days with good air quality, and the remaining days falling within the range of moderate air quality. This is followed by the years 2003, 2016, 2001, 2013, 2008, 2004, 2017, 2011, 2000, 2012, 2007, and 2005, with respective frequencies of 335, 326, 301, 293, 290, 276, 274, 273, 258, 242, 241, and 221 days recorded as good air quality within the range of 0-50. Local emissions, specifically traffic, were the primary source of particulate matter during these periods. Fortunately, during those years, the air quality remained predominantly good and moderate, without any discernible negative impacts on social, health, or economic aspects.

Conclusion

This study highlights the significance of addressing Air Pollutant Index (API) trend analysis for Kuching, Sarawak, as the region progresses towards becoming a developed and high-income state by 2030. The centerpiece of this study is the innovative development of contour plots. By effectively mapping API data from 2000 to 2019,

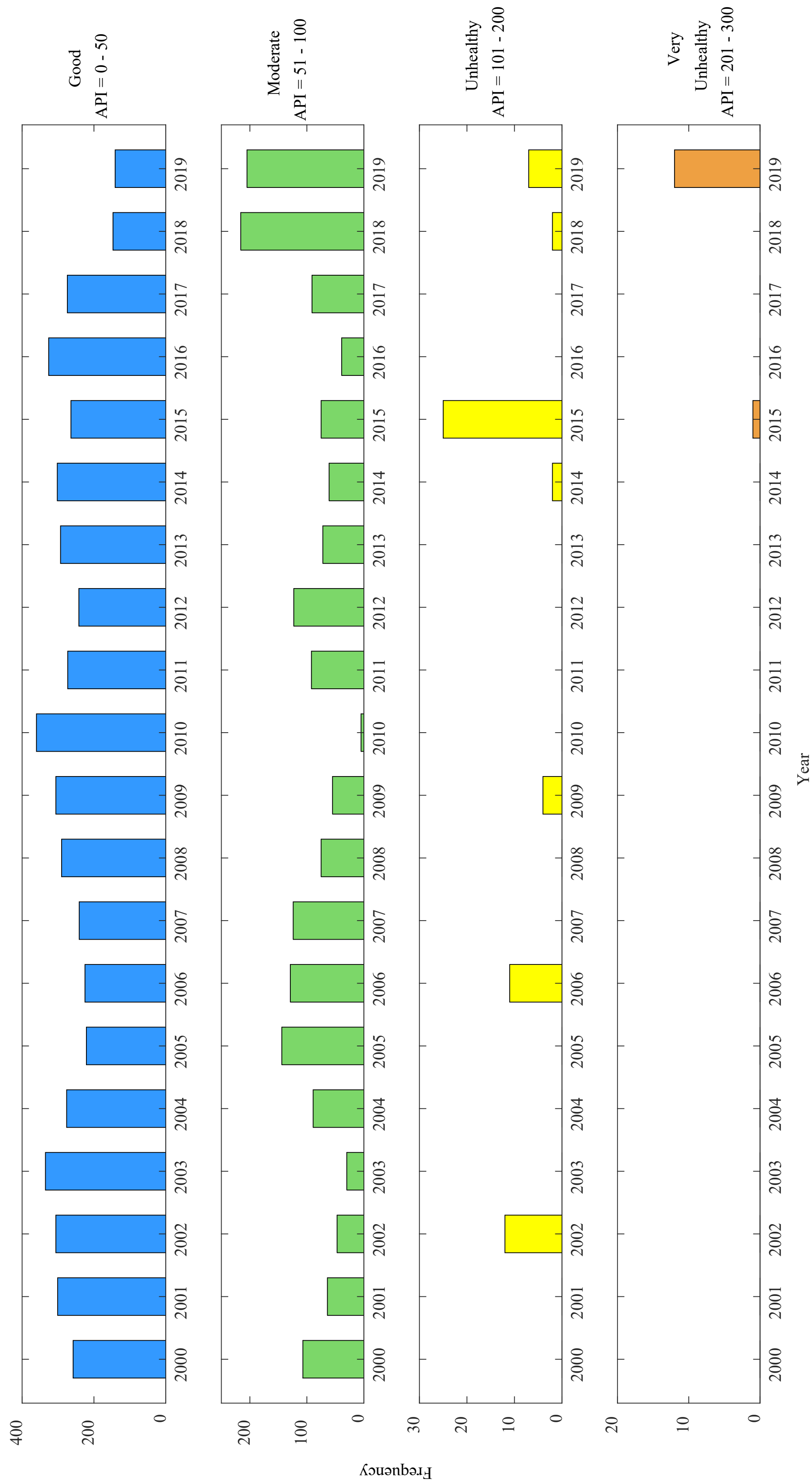

FIGURE 4. Annual frequencies of API indicators from 2000 to 2019

the contour plot has offered a clear view of air pollution patterns in the region. By leveraging the five-term Fourier model, the gaps in API data were effectively bridged, offering a more complete and informative contour plot. The findings indicate a strong correlation between the five-term Fourier model and the API readings, with most *R* values exceeding 0.91. The developed contour plot also exhibits notable visual consistency between the predicted data and the actual dataset. An intense API dataset was observed from July to October, as clearly depicted in the contour plot. The API trend analysis showed fluctuations in air quality over the years, with significant increases in API readings during haze events, especially amid El Niño periods. The findings emphasize the importance of effective regulatory measures to mitigate air pollution and protect public health. It is crucial for the government to monitor air quality continuously, enforce stringent policies during haze episodes, and address the sources of industrial pollutants to sustain air quality improvements in the region. Such measures are essential for achieving sustainable development goals and safeguarding the health and well-being of the population in Kuching, Sarawak.

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*Corresponding author; email: hisyammudinmaseri@icats.edu.my