



Assessment and comparison of three different air quality indices in China

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ABSTRACT

Air pollution index (API) is used in Mainland China and includes only SO₂, NO₂ and PM₁₀. In 2016, air quality index (AQI) replaced API. AQI contains three more air pollutants (CO, O₃ and PM_{2.5}). Both the indices emphasize on the effect of a single pollutant, whereas the contributions of all other pollutants are ignored. Therefore, in the present work, a novel air quality index (NAQI), which emphasizes on all air pollutants, has been introduced for the first time. The results showed that there were 19 d (5.2%) in API, 28 d (7.7%) in AQI and 183 d (50.1%) in NAQI when the indices were more than 100. In API, PM₁₀ and SO₂ were regarded as the primary pollutants, whereas all five air pollutants in AQI were regarded as primary. Furthermore, four air pollutants (other than the CO) in NAQI were regarded as primary pollutants. PM₁₀, as being the primary pollutant, contributed greatly in these air quality indices, and accounted for 51.2% (API), 37.0% (AQI) and 52.6% (NAQI). The results also showed that particulate matter pollution was significantly high in Luzhou, where stricter pollution control measures should be implemented.

Keywords: Air pollution index, Air quality index, Luzhou, Particulate matter

1. Introduction

Air is one of those fundamental necessities, without which life cannot exist in its current form. Nevertheless, urban ambient air quality is decreasing due to industrialization and urbanization in China [1-2]. Periods of haze and dust have made Chinese people feel anxious for the quality of ambient air. In order to keep the citizens informed of the urban air quality, many cities assess air quality through air quality monitoring networks, which continuously record the mass concentrations of different air pollutants [3]. The concentrations of several criteria pollutants can be included in the air pollution index (API), which is easy to be understood by the public. API and air quality index (AQI) have been used to obtain and convey information regarding the urban air quality in a number of countries and zones worldwide [4].

Bodnar *et al.* [5] used the index methodology proposed by Bruno and Cocchi (BC Indices) to compare the air quality in Italy, Germany and Poland, and proposed to have a unique, unanimous index in Europe. Based upon the relationship between the health risk and the concentrations of different air pollutants, Cairncross *et al.* [6] developed a novel air pollution index. Cheng *et al.* [7] revised

the air quality index for PM_{2.5} according to entropy principle, and compared it with Pollutant Standard Index (PSI) and AQI. The revised air quality index (RAQI) not only demonstrated higher accuracy, but also distinguished different pollution episodes. In order to represent the global ambient air quality, Cooper *et al.* [8] developed a satellite-based multi-pollutant index for the concentrations of PM_{2.5} and NO₂. In short, there are numerous reports in the literature, which detail the comparison and assessment of ambient air quality using different kinds of air pollution or air quality indices [9-15].

API and AQI usually include several air pollutants, such as SO₂, NO₂, TSP, PM₁₀, PM_{2.5}, CO, O₃, Pb and VOCs. In Mainland China, only three criteria air pollutants, namely the SO₂, NO₂ and PM₁₀, are used to calculate API, which is based on National Ambient Air Quality Standard (NAAQS, GB3095-1996) that was issued in 1996 [16]. Due to the drastic increase in the number of vehicles, air pollution has become a serious concern due to their exhaust emissions. In the US, Korea, Hong Kong and other countries, CO and O₃ have already been included in the API and AQI since past few years [12]. Due to this reason, the Chinese government issued AQI guideline on January 1, 2016, which was strict, objective



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and accurate for the evaluation of results. Both API and AQI consider only the maximum values of sub-indices, and discard the values of other sub-indices and synergistic effects of other air pollutants [17]. Therefore, an attempt has been made to build a novel air quality index (NAQI), which is based on combined effects and weights of different air pollutants. In this paper, based on the data for the concentrations of five air pollutants collected in 2009 (365 d) in Luzhou, both the comparison and assessment of three different air-quality indices (API, AQI and NAQI) are presented and discussed.

2. Methodology

2.1. Sample Location and Data Collection

There are 5,543 valuable air quality monitoring data points in Luzhou, China. As per 2009, these data points consisted of four monitoring sites (Jiushi Mountain (JS), Xiaoshi Duck (XS), Zhongshan Monitoring Station (ZS), Lantian Bridge (LT)), which extended from north to south across the central part of the city (Fig. 1). Since the JS site is regarded as a background site, the data from this monitoring station was not considered in this work. Average daily mass concentrations of SO₂, NO₂, PM₁₀, CO and O₃ were recorded using ambient air successive auto monitoring. The monitoring methods used were the ones recommended by the Environmental Protection Ministry of China.

2.2. API Calculations

The data were used to calculate the API, whereas the reference scale values are reported in Table 1. The calculation of API was carried out accordingly to Eq. (1) and Eq. (2).

$$API = \max(API_1, API_2, \dots, API_n) \quad (1)$$

$$API_i = \frac{API_h - API_l}{c_h - c_l} (c_i - c_l) + API_l \quad (2)$$

where API_i is the sub-index of pollutant i , c_i is the mean concentration of the pollutant i , c_l is the break point $\leq c_i$, c_h is the break point $> c_i$, API_h and API_l are the API values when the concentration values are c_l and c_h (respectively), and n is the number of pollutants. When the API value was less than or equal to 50, the air quality was considered to be good, and nothing was regarded as the primary

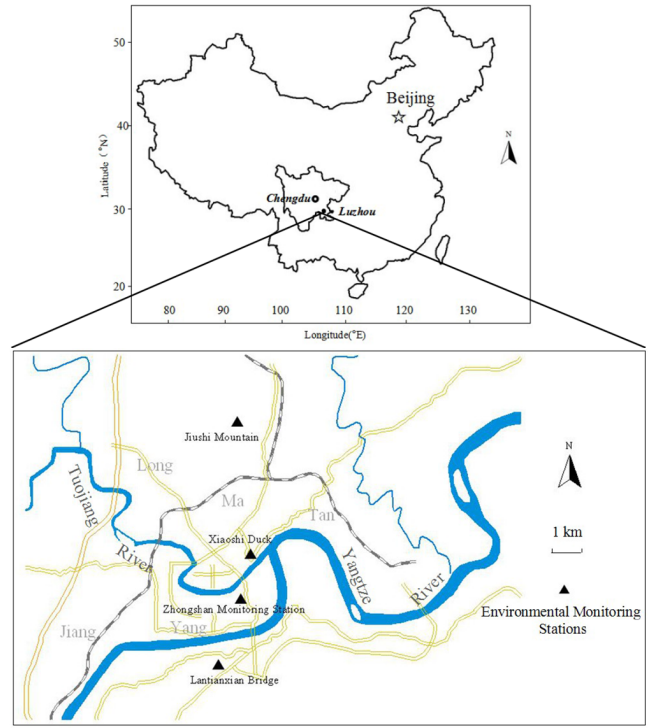


Fig. 1. Location of the environmental monitoring sites in Luzhou City.

pollutant. However, when the API value was higher than 50, the pollutant which had the maximum API_i was regarded as the primary pollutant. If the API_i values of air pollutants were the same, the pollutant which was in turn of SO₂, NO₂, PM₁₀, CO, O₃ and PM_{2.5} was regarded as the primary pollutant.

2.3. AQI Calculations

The method to calculate AQI is the same as API except that the mass concentration limits of these air pollutants were different. The AQI values, their description and corresponding concentrations are listed in Table 1. There are six air pollutants, namely the SO₂, NO₂, PM₁₀, CO, O₃ and PM_{2.5}. The concentration data of PM_{2.5} was not included as PM_{2.5} sub-index was not considered for calculating AQI, and thus was not monitored. This shortcoming was rectified as the mass concentration of PM_{2.5} was started to be monitored from October 2013 onwards.

Table 1. AQI and API Value, Description and Their Corresponding Mass concentration (μg/m³)

Value	Grade	Description	AQI					API		
			SO ₂	NO ₂	PM ₁₀	CO	O ₃	SO ₂	NO ₂	PM ₁₀
0-50	I	Good	50	40	50	2,000	100	50	80	50
51-100	II	Moderate	150	80	150	4,000	160	150	120	150
101-150	III	Unhealthy for sensitive people	475	180	250	14,000	215	475	180	250
151-200	IV	Unhealthy	800	280	350	24,000	265	800	280	350
201-300	V	Very unhealthy	1,600	565	420	36,000	800	1,600	565	420
301-500	VI	Hazardous	2,620	940	600	60,000	—	2,620	940	600

2.4. NAQI Calculations

Both API and AQI are based on the concentration limits of air pollutants. However, AQI is easier to be understood. Furthermore, more countries and regions of the world use AQI to get information on the ambient urban air quality. The complexity of the calculating method and disregarding other air pollutants besides the ones having highest API or AQI values are the main shortcomings of API and AQI indices [18]. The process of calculating AQI is shown in Fig. 2. In fact, the mass concentration limits of air pollutants are very important. When AQI or API value was less than 100, the limit value was equal to Grade-II mass concentration value in the National Ambient Air Quality Standard (NAAQS, GB3095-2012), as listed in Table 2. With improvement of environmental quality and the enhancement of environmental consciousness, the NAAQS has become stricter and more scientific. In this way, the AQI values became higher, and more significant changes in air quality were observed. The modified NAAQS is divided into six grades, which makes the calculation of AQI a little difficult. On the other hand,

the final AQI value of some city or site might be the highest among all the AQI_i values. In such a circumstance, the effect of air pollutant having the maximum AQI_i value on human health also covers the effects of all other air pollutants [19]. For example, when AQI_{SO_2} , AQI_{NO_2} , and $AQI_{PM_{10}}$ had values of 119, 110, 120, respectively, the AQI value was considered to be 120. The calculating method of AQI is the same as that of the API. Therefore, the PM_{10} is the primary pollutant among three air pollutants, whereas the SO_2 , and NO_2 are ignored. However, it is widely accepted that both the SO_2 and NO_2 can have deteriorating impact on the health of humans.

In order to remove these shortcomings in the AQI, a NAQI was introduced in the current study [20]. Eq. (3) - Eq. (5) were used to calculate NAQI.

$$NAQI = 100 \times \sum_{i=1}^n W_i P_i \quad (3)$$

$$W_i = \frac{\frac{c_i}{s_i}}{\sum_{i=1}^n \frac{c_i}{s_i}} \quad (4)$$

$$P_i = \frac{c_i}{s_i} \quad (5)$$

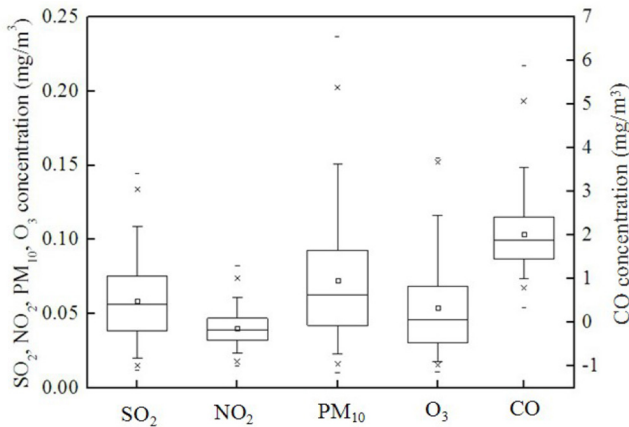


Fig. 2. Mass concentrations of five air pollutants in Luzhou City.

where $NAQI$ is the AQI of a city or a site, W_i is the weight of the pollutant i , P_i is the index of the pollutant i , c_i is the mean concentration of the pollutant i , and s_i is the mass concentration value of the pollutant i for Grade-I in NAAQS, respectively. When the API or AQI value was higher than 50, the pollutant which had the maximum API_i or AQI_i value was regarded as the primary pollutant. If the API_i or AQI_i values of air pollutants were the same, the pollutant that was in turn of SO_2 , NO_2 , PM_{10} , CO , O_3 and

Table 2. National Ambient Air Quality Standard in China

Air pollutants	Average time	Concentration limit($\mu\text{g}/\text{m}^3$) (GB3095-2012)		Concentration limit($\mu\text{g}/\text{m}^3$) (GB3095-1996)		
		Grade I	Grade II	Grade I	Grade II	Grade III
Sulfur dioxide (SO_2)	Annual	20	60	20	60	100
	24 h	50	150	50	150	250
	1 h	150	500	250	500	700
Nitrogen dioxide (NO_2)	Annual	40	40	40	40	80
	24 h	80	80	80	80	120
	1 h	200	200	120	120	240
Particulate matter (PM_{10})	Annual	40	70	40	100	150
	24 h	50	150	50	150	250
Carbon monoxide (CO)	24 h	4,000	4,000	4,000	4,000	6,000
	1 h	10,000	10,000	10,000	10,000	20,000
Particulate matter ($PM_{2.5}$)	Annual	15	35	—	—	—
	24 h	35	15	—	—	—

PM_{2.5} was regarded as the primary pollutant. As long as the P_i of a pollutant was more than 1.0, the pollutant was regarded as the primary pollutant in NAQI. Eq. (5) was used to calculate P_i . Similarly, all those pollutants, which had a P_i value of more than 1.0, were considered as the primary pollutants.

3. Results and Discussion

3.1. Variation in Ambient Air Quality

Fig. 2 shows the annual mean mass concentrations of five air pollutants. The mean concentrations of SO₂, NO₂, PM₁₀, CO and O₃ were 59 ± 27 , 40 ± 12 , 72 ± 40 , $2,017 \pm 801$ and 54 ± 31 µg/m³, respectively. The concentrations of SO₂ and NO₂ were very close to Grade-II annual mean concentrations of 60 µg/m³ and 40 µg/m³, respectively. The concentrations of other three pollutants were much lower than their corresponding annual mean concentration limit values. The concentrations of SO₂, CO and O₃ were substantially higher than those reported for big cities, such as Beijing, Shanghai, Guangzhou, Chengdu, and Seoul (Table 3). This could be due to the burning of coal in industry, which has high sulfur ratio. On the contrary, the mass concentrations of NO₂ were lower than those in Beijing, Shanghai, Guangzhou, Chengdu, and Seoul. It was demonstrated that the air pollution from the exhausts of vehicles was not the main source of pollution in these cities.

In general, the trends for monthly mean concentrations of SO₂, NO₂, PM₁₀ and CO were similar to those for the annual concentrations, as shown in Fig. 3. The mass concentrations of these pollutants were higher in winter and spring than those in summer and autumn, as observed by Wan *et al.* [21]. However, the variation in O₃ concentration showed a different trend, in which, the concentrations were lower in colder months than in the hotter ones. Lu *et al.* [12] obtained similar results for monthly variations in pollutants' concentrations in Hong Kong. The seasonal variations can be explained by the combined influence of high temperature, rainy weather, and unstable atmospheric conditions in summer, whereas these were caused by low temperature, dry weather and more stable atmospheric conditions during winter.

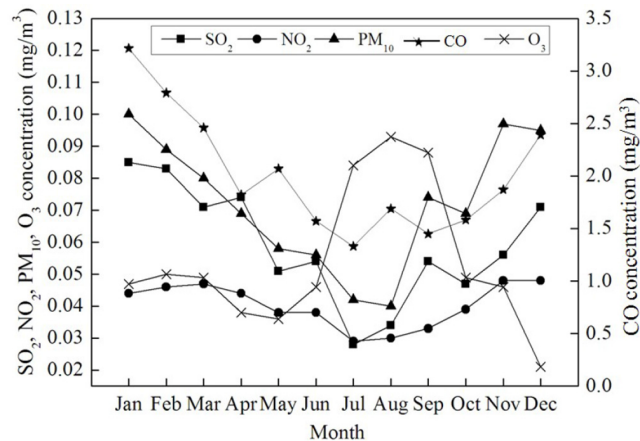


Fig. 3. Monthly mean mass concentrations of five air pollutants in Luzhou City.

Table 3. Comparison of the Air Pollutant Concentrations in Luzhou in 2009 with Other Cities (µg/m³)

City	SO ₂	NO ₂	PM ₁₀	CO	O ₃
Beijing ^a	34	53	121	1,600	
Shanghai ^b	35	53	81		
Guangzhou ^c	39	56	70		
Chengdu ^d	38	55	111		
Luzhou ^e	59	40	72	2,017	54
Tokyo ^f	6	43	23	500	4
Seoul ^g	14	72	54	750	26
Europe ^h	40	24	0.025	400	47

^a Beijing Environmental Protection Bureau

^b Shanghai Environmental Protection Bureau

^c Guangzhou Environmental Protection Bureau

^d Chengdu Environmental Protection Bureau

^e This study

^f Tokyo Bureau of Environment

^g Seoul Air Quality Management District

^h European Environmental Agency

3.2. Comparison of Different Air Quality Indices

API includes only SO₂, NO₂ and PM₁₀, whereas AQI includes two more criteria pollutants (CO and O₃) on top of the ones present in API. The corresponding mass concentration of NO₂ was different between the API and AQI indices. The NO₂ concentration was 40 µg/m³ and 80 µg/m³ for Grade-I and Grade-II in AQI, respectively, whereas the values for NO₂ mass concentration in API were 80 µg/m³ and 120 µg/m³ for Grade-I and Grade-II, respectively. NAQI also consists of five air pollutants, namely the SO₂, NO₂, PM₁₀, CO, and O₃. However, the corresponding mass concentrations of these five air pollutants were only based on the daily average concentrations in Grade-I of NAAQS. The contributions of these five air pollutants to air quality were considered in NAQI and emphasized on the importance of NAAQS.

According to 2009 air quality monitoring data in Luzhou, three different air-quality indices were calculated on daily basis. According to the API values, the number of days monitored were 99, 247 and 19 for Grades I, II and III, respectively. The number of days for which the air quality was good and/or moderate was 346 (94.8%). This means that, the number of days when API > 100 accounted for only 5.2% of the total number of days, as shown in Fig. 4. According to AQI values, the number of days were 63, 274 and 28 for Grades I, II and III, respectively. Compared to API, the number of days for good air quality decreased to 36, whereas the number of days for Grades II and III increased to 27 and 9, respectively. The number of days when AQI > 100 was 28 and accounted for 7.7% of the total number of days.

According to NAQI values, the number of days were 23, 159, 116, 44, 22 and 1 for Grades I, II, III, IV, V and VI, respectively. Six grades of air quality were obtained using the NAQI method. According to NAQI values, there were 183 days when NAQI > 100, and these accounted for 50.1% of the total number of days in 2009. The maximum NAQI value was 330, which was observed on November 11, 2009. The mass concentration of PM₁₀ was 4.7 times higher than that of the Grade I concentration of NAAQS.

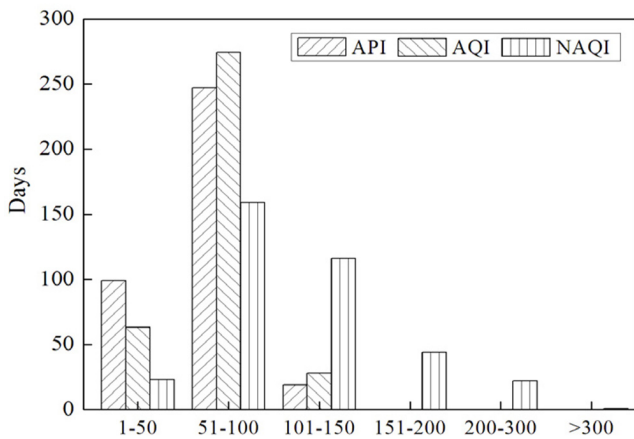


Fig. 4. Comparison of air quality index values.

Meanwhile the maximum value for both API and AQI was 144 on the same day in 2009, and were caused by PM_{10} pollution. This was due to the reason that particulate matter was produced from burning wood in cold days (for heating purposes), due to which, the air diffused weakly. In short, the urban ambient air quality was the best for API, better for AQI and bad for NAQI as per the results obtained in the current work. Similar conclusions were made and reported by Kyrkilis *et al.* [22]. Therefore, to a certain extent, the fact whether the air quality is good or bad depends on the assessment method used.

3.3. Comparison of the Primary Pollutants

The pollutant of maximum index value was regarded as the primary pollutant when either API or AQI value was more than 50. Meanwhile, SO_2 , NO_2 , PM_{10} , CO and O_3 were in turn termed as the primary pollutants when their values were the same. The difference is that, all the pollutants with P_i values of more than 1.0, were regarded as the primary pollutants.

According to the API values of Luzhou in 2009, both SO_2 and PM_{10} were the primary pollutants, whereas NO_2 did not appear as the primary pollutant during the time considered in the study, as shown in Fig. 5. There were 79 d and 187 d when they were regarded as the primary pollutants, and accounted for 21.6% and 51.2% of the total days, respectively.

According to the AQI values, all five air pollutants, which were regarded as the primary pollutants, appeared in the results. The days when SO_2 , NO_2 , PM_{10} , CO, O_3 were regarded as primary pollutants were 52, 26, 135, 57, and 29, respectively. In addition, PM_{10} accounted for 37.0% of the total days. This value was more than one third of the days for the primary pollutants. It is important to note that NO_2 and CO, which were mainly emitted by automobiles, showed up in the results, and accounted for 7.1% and 15.6% of the total days, respectively. In the secondary air pollutants, O_3 accounted for 7.9% of the total days, which were 29 d as per the AQI values. The days for which the air quality was "less than good" (API, AQI or NAQI > 50) were more in AQI than in API. There were 302 d in AQI and 266 d in API. This meant that, according to AQI, the ambient air quality became worse and more air pollutants caused air pollution in Luzhou, China. However, the main difference was that more air pollutants were regarded

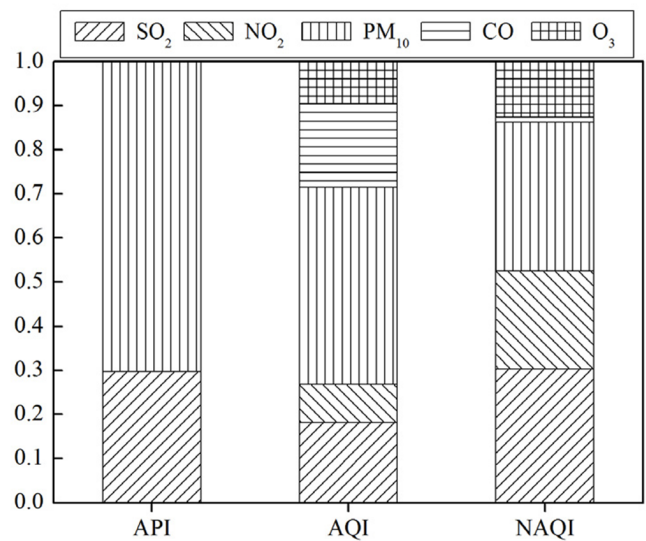


Fig. 5. Comparison of primary pollutants.

as primary pollutants in AQI. NO_2 did not appear in the API as primary pollutant; however, it remained primary pollutant for 26 d in AQI. The reason of the difference was stricter air quality standard set in AQI. The Grade II levels for NO_2 were $80 \mu\text{g}/\text{m}^3$ in AQI and $120 \mu\text{g}/\text{m}^3$ in API. Therefore, it can be seen that, for API or AQI, the level of air quality standard and the kinds of air pollutants were very important. An *et al.* [23] suggested that major efforts need to be made on the standard-setting process to achieve the lowest concentrations for public health priorities. In this regard, the World Health Organization's (WHO) air quality guidelines are worth referencing.

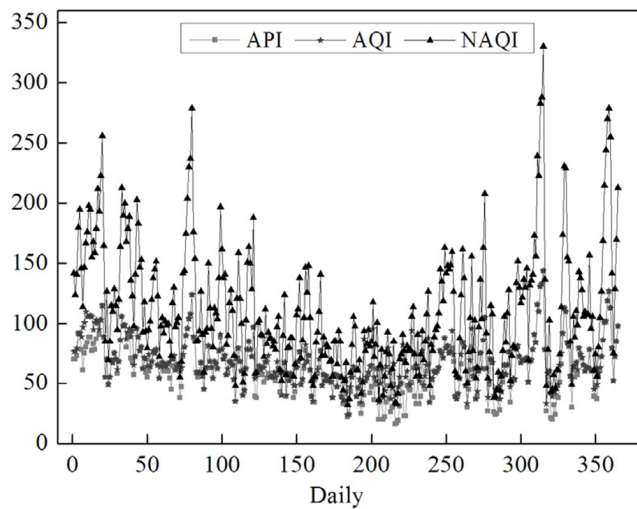
Since the concentration levels and kinds of air pollutants play a key role in API or AQI indices. Therefore, the effects of air quality standards and all kinds of air pollutants should be emphasized. NAQI takes into account the air quality standards and five air pollutants. The last index value was the maximum for AQI or API, whereas the effects of other air pollutants having smaller values were ignored. In NAQI, the last index value was equal to the sum of sub-NAQI values. There were 342 d when NAQI > 50 in NAQI, which consisted of 192 (52.6%) d for PM_{10} , 98 (26.8%) d for SO_2 , 27 (7.4%) d for O_3 and 25 (6.8%) d for NO_2 . In addition, CO did not appear as the primary pollutant in NAQI during the time period considered in the current work, although it appeared in AQI. This could be due to the reason that the concentration limits ($4,000 \mu\text{g}/\text{m}^3$) for Grades I and II were the same in NAAQS. The mass concentration levels of all other air pollutants were higher than the limit level of Grade-I, while the concentration levels of CO were lower than the limit level of Grade-I. Generally, the primary pollutants were obviously different due to three AQIs.

3.4. Assessment of Three Air Quality Indices

The air quality standard levels in AQI were stricter than those in API. In addition, AQI contained additional air pollutants which could be considered as primary pollutants. Comparing the two indices, NAQI synthesized five air pollutants, such as SO_2 , NO_2 , PM_{10} , CO and O_3 and were calculated based on the ratio of each

Table 4. Correlation Analysis between Three Air Quality Indexes and the Air Pollutant Concentrations

Index	Pollutant	Regression equation	R ²	Standard deviation	Significant coefficient
API	SO ₂	y = 0.0010x-0.0039	0.6504	0.0161	0.806**
	NO ₂	y = 0.0004x+0.0164	0.4948	0.0084	0.703**
	PM ₁₀	y = 0.0018x-0.0368	0.9063	0.0123	0.952**
AQI	SO ₂	y = 0.0010x-0.0095	0.5452	0.0184	0.738**
	NO ₂	y = 0.0004x+0.0135	0.4377	0.0089	0.662**
	PM ₁₀	y = 0.0018x-0.0506	0.8114	0.0174	0.901**
	CO	y = 0.0259x+0.2720	0.4087	0.6179	0.639**
	O ₃	y = 0.0001x+0.0460	0.0058	0.0311	0.076
NAQI	SO ₂	y = 0.0004x+0.0106	0.6626	0.0158	0.814**
	NO ₂	y = 0.0002x+0.0218	0.5087	0.0083	0.713**
	PM ₁₀	y = 0.0008x-0.0121	0.9335	0.0103	0.966**
	CO	y = 0.0086x+1.0588	0.3015	0.6715	0.549**
	O ₃	y = -9.5×10 ⁻⁶ x+0.0551	0.0002	0.0312	-0.016


Fig. 6. Trends of the three air quality indexes in 2009.

air pollutant's concentration and corresponding first level in NAAQS. According to the calculated results of three AQIs, the trends of daily index values were not different, as shown in Fig. 6. The major difference was that the NAQI values were the greatest in all three AQIs, whereas API values were the minimum. Therefore, the NAQI values can accurately reflect the air quality. The correlation analysis between three AQIs and the concentrations of five criteria air pollutants are listed in Table 4. The air pollutants can be ranked according to decreasing correlation coefficients as PM₁₀, SO₂ and NO₂. This is mainly due to the reason that the source of pollution is industrial coal combustion and the exhausts from automobiles. However, the correlation coefficients for PM₁₀, SO₂ and NO₂ concentration are higher in NAQI than those in AQI, and API. These results illustrated that NAQI can accurately reflect the urban ambient air quality due to PM₁₀, SO₂ and NO₂. According to the correlation coefficients between NAQI, AQI and CO concentrations, AQI can reflect the urban air quality much better than

NAQI. This is due to the reason that CO is regarded as a primary pollutant in AQI, and not in NAQI. On the contrary, both NAQI and AQI cannot reflect the O₃ concentrations due to secondary pollution. The AQI, which can represent air quality due to second air pollution, should be studied in more details.

4. Conclusions

In China, API consists of SO₂, NO₂ and PM₁₀ and has been used to inform citizens of the urban ambient air quality since 2000. AQI has additional pollutants of CO, O₃ and PM_{2.5} since 2016. The two kinds of AQIs only consider the maximum index value of an air pollutant, whereas the contributions and combined effects of other air pollutants were ignored. Due to these reasons, NAQI included the combined effects of all air pollutants, and has the advantage to be calculated in a simple way according to NAAQS.

The data of air pollutant concentrations, including SO₂, NO₂, PM₁₀, CO and O₃, were collected daily in 2009 at four environmental monitoring sites in Luzhou, which is a southern city of Sichuan basin in China. The statistical results showed that the annual mass concentrations of SO₂, CO, and O₃ in Luzhou were higher than those in other big cities (Beijing, Shanghai, Guangzhou, Chengdu, and Seoul). On the contrary, the concentrations of NO₂ and PM₁₀ were lower than the values in these big cities. In addition, all air pollutants except O₃ had monthly variations, which showed that the concentrations of these pollutants were found to be higher in winter and spring than those in summer and autumn.

According to these air pollutants' concentration data, three different AQIs of API, AQI and NAQI were compared. The results showed that there were 19 d (5.2% of the total days) in API, 28 d (7.7% of the total days) in AQI and 183 d (50.1% of the total days) in NAQI when these indices were higher than 100. Overall, depending on the NAQI values, the urban air quality became worse. Both PM₁₀ and SO₂ in API, all five air pollutants in AQI, and four air pollutants except for the CO in NAQI were regarded as the primary

pollutants. PM₁₀ was the main primary pollutant in three AQIs, which accounted for 51.2% (of total days), 37.0% (of total days) and 52.6% (of total days), respectively. Therefore, the particulate matter's pollution was very significant in Luzhou and stricter pollution control measures should be implemented to control it.

The variation trends of three AQIs were not different, though the daily variation of NAQI in 2009 was always higher than those for the AQI and API. The correlation between NAQI and air pollutants' concentration was more obvious than the other two indices. Based upon the results, it can safely be said that NAQI can satisfactorily and systematically reflect the urban ambient air quality situation.

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