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Potency of the pandemic on air quality: An urban resilience perspective

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HIGHLIGHTS
• Most cities respond within 4 days after the COVID-19 lockdown.
• Divergent spatial-temporal sensitivities of urban resilience.
• Mega cities showed the least urban resilience features.
• Urban resilience offers reference for environmental policy management.

GRAPHICAL ABSTRACT

Abstract
Since the outbreak of COVID-19 pandemic, the lockdown policy across the globe has brought improved air quality while fighting against the coronavirus. After the closure, urban air quality was subject to emission reduction of air pollutants and rebounded to the previous level after the potency period of recession. Different response patterns exhibit divergent sensitivities of urban resilience in regard to air pollution. In this paper, we investigate the post-lockdown AQI values of 314 major cities in China to analyse their differential effects on the influence factors of urban resilience. The major findings of this paper include: 1) Cities exhibit considerable range of resilience with their AQI values which are dropped by 21.1% per day, took 3.97 days on average to reach the significantly decreased trough point, and reduced by 49.3% after the lockdown initiatives. 2) Mega cities and cities that locate as the focal points of transportation for nearby provinces, together with those with high AQI values, were more struggling to maintain a good air quality with high rebounds. 3) Urban resilience shows divergent spatial sensitivities to air pollution controls. Failing to consider multi-dimensional factors besides from geomorphological and economical activities could lead to uneven results of environmental policies. The results unveil key drivers of urban air pollution mitigation, and provide valuable insights for prediction of air quality in response to anthropogenic interference events under different macro-economic contexts. Research findings in this paper can be adopted for prevention and management of public health risks from the perspective of urban resilience and environmental management in face of disruptive outbreak events in future.

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Keywords:
COVID-19
Air quality
Urban resilience

1. Introduction

In December 2019, the outbreak of novel coronavirus (COVID-19) started to spread globally first sight from China. Since March 11, 2020, WHO has declared the COVID-19 pandemic as a global health
emergency, which needs international scientific findings and knowledge on COVID-19 to tackle this crisis. Evidence shows that the coronavirus is environmentally sensitive (Carlson et al., 2020), and exerts propound impacts on the human health and global economies (Chakraborty and Maity, 2020; Saadat et al., 2020). According to the COVID-19 Impact Survey launched by the UN-Habitat Data & Analytics Unit, this has been a global crisis during which 95% of COVID-19 cases have taken place in urban settlements with over 1500 cities affected worldwide (Acuto et al., 2020). In order to suppress the spread of COVID-19 virus via minimized transmission rates, large-scale lockdown policy was implemented worldwide with travel restriction orders and business close-down measures. Effectiveness of the lockdown policy has been widely studied and proved to be evident with reduced air pollution across the globe (Li et al., 2020b). Changes in human mobility and living patterns have given rise to substantial improvement of air quality status globally (Chauhan and Singh, 2020; Kanniah et al., 2020; Muhammad et al., 2020; M. Feng, J. Ren, J. He et al. Science of the Total Environment 805 (2022) 150248).

The efforts to control coronavirus did result in a drop of primary gaseous pollutants during the COVID-19. The dramatic perturbations of environmental quality were primarily calculated within a period during the COVID-19 pandemic (usually a few months) and compared with historical measurements (mostly from year 2019). Since early 2020, studies have been carried out on cities in India (Sharma et al., 2020; Mahato et al., 2020); Kazakhstan (Kerimray et al., 2020); Italy (Collivignarelli et al., 2020; Fattorini and Regoli, 2020; Zoran et al., 2020); Brazil (Dantas et al., 2020; Nakada and Urban, 2020); Spain (Baldasano, 2020; Tobias et al., 2020); Canada (Adams, 2020); and the USA (Bashir et al., 2020; Berman and Ebisu, 2020; Zangari et al., 2020). Evidence of improved air quality was also found in Chinese cities including Wuhan (Lian et al., 2020) and other cities in China (Dutheil et al., 2020; Li et al., 2020a; Liu et al., 2019; Wang et al., 2020; Wang and Su, 2020; Xu et al., 2020; Zheng et al., 2020b).

It is worth to mention that cities with decreased air pollutant concentrations show noticeable differences associated with urban communities, economic structures and innate regional discrepancies such as climate region settings. The Air Quality Index (AQI) is defined as the maximum value of individual air quality index calculated per 24 h based on the level of six atmospheric pollutants of PM2.5, PM10, SO2, NO2, CO, and O3 (Hu et al., 2015). Wang et al. (2020) discovered that reduction of Air Quality Index (AQI) values in provinces of China was related to the number of motor vehicles in use and the percentages of secondary industries. Bouffanais and Lim (2020) found that transmission rates were particularly high in large cities. Apart from the reduction of anthropogenic emissions (Zheng et al., 2021), meteorological effects could be superimposed to enhance the air pollutant changes (Salma et al., 2020). Zheng et al. (2020a, 2021) found that industry sector was the main driver in both the decline and rebound of CO2 emissions in China during the pandemic. The increased CO2 emissions during the lockdown from January to March in 2020 from Guangxi province was induced by the drought event compared with the status in 2019. Xu et al. (2020) also suggested an enhanced impact of COVID-19 on the AQI with low relative humidity and high temperature conditions.

While admitting the fact that pandemic has largely affected the air pollutant reduction, it is also worth while looking at the AQI reduction behaviours from the point view of responsive time. Berman and Ebisu (2020) indicated that there was particular clear reduction of PM2.5 in urban counties with early lockdown measures. These response patterns show divergent sensitivities to mitigate the lockdown-induced air pollution. Cities are complex and multi-faceted. Defining and measuring the urban resilience as post-stress phenomenon is challenging with continuously changing environment. To further refer this to the ability of urban system to restore or rapidly recover from disturbances, urban resilience (Meerow et al, 2016) offers a new paradigm for tackling the issue here after the radical measures for the COVID-19 pandemic.

The COVID-19 lockdown is a forced experiment that urban environment is faced with sustainable challenges to optimise capability of resilience to withstand and refrain from unexpected circumstances (Acuto et al., 2020). Although devastating to human societies, the pandemic has set up a unique chance to examine the adaptive natural urban resilience while the human activities were minimized during the lockdown periods (Cariolet et al., 2018; Cheshmehzangi, 2020; Duh et al., 2008). To examine the potency and efficacy of the lockdown policy on the ‘bounce-back ability’ of urban air quality status, we regard the lockdown policy here as an attempt by the governmental authorities to influence the level of transmission by controlling human activities in various fields and consequently the changes in environment. In history, there are a number of cases where governmental authorities issued policies in restricting human activities to reduce air pollutants during special events, e.g. Beijing Olympic in 2008 (Wang et al., 2010) and Hangzhou G20 (Li et al., 2019) in 2016. The lockdown scale and duration in the past are not comparable to the one in place during the pandemic. During the 2016 G20 period, meteorological conditions including temperature, relative humidity, atmospheric pressures, and wind speed were not atypical among the three years so that comparisons of air pollutant concentrations were consistent (Li et al., 2019). Wang et al. (2010) found out that good air qualities during the Beijing Olympics Games in 2008 were partly explained by the persistent rainfall, the associated lowered temperatures, and more frequent regional transportation induced by wind during that period.

Strategic city-wide pollution reduction actions have occurred in China, most notably during the Beijing 2008 Summer Olympics (Rich et al., 2012) and 2010 Shanghai World Expo (Huang et al., 2012) that temporarily shut down all construction activities in the city, reduced traffic by approximately half and increased the frequency of road cleanings by wet methods (Wang et al., 2020). Many past human intervention events have shown effective impacts on environmental pollutants such as the G20 Summit held in Hangzhou in 2016, which resulted in reductions of the PM2.5/PM10 in Hangzhou (Chen et al., 2021; Li et al., 2019; Yu et al., 2018). To advance the policy management with similar practices in every host city for world level events, these costly practices can be challenging with differed effects and multiple causalities.

In this paper, through analysing the improvement of air quality status, the delayed effects of the lockdown policy are analysed as well as the urban resilience such as the responsive rates of cities. We focus on the post-epidemic performance of AQI of 314 major cities in China. We analysed their differential effects of AQI at both temporal and spatial scales in order to identify the influence factors for urban resilience. The results can unveil the major fault lines and fragilities in current urban systems, as well as provide valuable insights for the development of resilient cities under different macro-economic contexts (Leach et al., 2021).

### 2. Methodology

In previous studies, the underlying relationship between the lockdown policy and air pollution is simply assumed as a cause-effect situation that the air quality is improved due to complicated factors induced by the lockdown initiative. Although it is possible to determine the overall relationship and differences before and after the lockdown, improvement of air quality varies in each city, and the performance gain is largely affected by the feature of ‘inherent urban resilience’ in each city. We analyse the ‘revival’ of air quality after the implementation of lockdown measures through the lens of urban resilience, and evaluate it from the perspective of how much and how fast the urban air quality recovers. These responsive features were also analysed with consideration of meteorological effects under different climatic conditions in each city.

#### 2.1. Dataset

The official lockdown date for each province and city was collected from government announcements (http://www.nhc.gov.cn/), and
summarized in Table 1. As the mean residence time of particle pollutants and submicron particles is up to 100 to 1000 h in the absence of precipitation (Bolin et al., 1974; Esmen and Corn, 1971), we use 30 days as the post-lockdown period to analyse the urban air quality changes in this study. Extensive air quality measurements in 314 prefecture cities in China were analysed covering 31 provincial-level administrative regions (See Fig. 1 for the locations of the cities).

Daily average AQI values were collected from January 1, 2020 to May 31, 2020 using the open source API from Envicloud platform (www.envicloud.cn). Meteorological monitoring data including wind speed, air temperature, and rainfall were collected at daily scale for 148 out of the 314 cities during the same period. Detailed information of the datasets can be found in supplementary material Table S1.

2.2. Evaluating the urban resilience

Being inspired by the classical definition of environmental resilience (Holling, 1973), the concept of urban resilience has been applied to the risk management of urban systems such as flood, earthquake, sea water, air pollutions and so on. It refers to the ability of urban systems to maintain or rapidly restore the required functions in the event of disturbances, the ability to adapt to change, and the ability to change systems rapidly that limits current or future adaptability (Chelleri, 2012; Meerow and Newell, 2019). As a highly adaptive complex system, the urban resilience through disturbance-rebuild perspective is critical but not limited to disasters or destructions. The ability of an urban system in face of disturbance is reflected on both adaptation and development. It is hard to compare the reduction of air pollution only, as it is associated with multiple factors such as historical pollutant levels, energy consumption, population, GDP and meteorological conditions. In this case, the effectiveness of lockdown policy on improved air quality is an excellent chance of experiment that reveals the feature of urban resilience with regards to the recovery after external human activities are minimized. To delve into the systematic behavior of an urban system responses, it is worthwhile looking at both sides of the characteristics. A quantitative approach is applied for measuring and mapping the urban resilience related to air pollution.

2.2.1. Drop

To analyse the changes of air quality in each city after the lockdown initiative, we start from identifying the trend and abrupt change points of the time series data on air quality in each city. Firstly, the modified non-parametric trend test proposed by Hamed and Rao (1998) is employed to detect the monotonic trends in daily AQI time series. To remove the impact of noise in the time series, the modified MK test with trend-free pre-whitening method (Yue and Wang, 2002) is used to remove the trend component and pre-whiten the time series before applying the MK trend test. The calculations were performed by using the pyMannKendall package (Hussain and Mahmud, 2019) in python 2.7.

For an urban system, the original status was subject to changes starting from the critical point of change since the lockdown. As

| Lockdown date | Province                      |
|---------------|-------------------------------|
| 23rd Jan      | Guangdong, Hubei, Hunan, Zhejiang |
| 24th Jan      | Anhui, Beijing, Chongqing, Fujian, Guangxi, Guizhou, Hebei, Jiangsu, Jiangxi, Shandong, Shanghai, Sichuan, Tianjin, Yunnan |
| 25th Jan      | Gansu, Hainan, Heilongjiang, Hensan, Neimenggu, Jilin, Liaoning, Ningxia, Qinghai, Shanxi, Xinjiang |
| 26th Jan      | Shan-xi                       |
| 29th Jan      | Tibet Autonomous Region       |
indicated in Fig. 2: this initial point of the timeline is indicated as $t_1$. It is expected that after the lockdown, the air quality could be improved and hence the AQI value will drop. Along with the changes afterwards, a trough point $t_2$, which represents a low point in a regular series of high and low points, is identified by an automated searching algorithm developed in Matlab® R2020b (Mathworks, Inc., Natick, MA, USA). Starting from the lockdown date, the first valley is detected where the AQIs drop to the bottom point. It is considered to reach the best air quality after the lockdown and recognized as the first change point, ‘trough point’.

The drop of AQI values represents the rate of change starting from its lockdown time ($t_1$) to the trough point ($t_2$) (Eq. 1). It measures the recovery speed of a city’s good air condition to the interference of lockdown policy. A larger drop means that the current status of a city’s air quality status has stronger ability of recovery.

$$\text{drop} = \frac{\text{AQI}_{t_2} - \text{AQI}_{t_1}}{\text{AQI}_{t_1}} \cdot \frac{1}{t_2 - t_1}. \quad (1)$$

2.2.2. Rebound

The other index is the rebound of air pollution levels after the recession period when the AQIs reach the bottom. In the automated searching function, we continue the search until the AQI values come back to a ridge point about the same level as on the lockdown date. Then this change point is recognized as the ‘ridge point’ $t_3$. The rebound measures the speed of ‘recovery’ when air pollution is resumed to another continuously increasing ridge point after the recession (Eq. 2). It reflects the impulse response of air pollution after the recession. A smaller rebound indicates greater ability of an urban system to resist to the ‘resumption’ of air pollutions and vice versa.

$$\text{rebound} = \left( \frac{\text{AQI}_{t_3} - \text{AQI}_{t_1}}{\text{AQI}_{t_1}} \right) \cdot \frac{1}{t_3 - t_2}. \quad (2)$$

2.2.3. Resilience index

The urban resilience is characterized by the duration of the time span and the improvement of air quality. An urban system with better resilience by nature implies that a larger drop in ‘absorption’ to the changes, and smaller rebound to an unlikeable ‘recovery’ of the pollution level. Adapted from the one-number measurement approach developed by Han and Goetz (2015), the Resilience Index (RI) is thus interpreted as the ratio of drop and rebound, as defined in Eq. (3) and (4). The larger the RI value, the better resilience capability is shown for a city in face of air pollution controls.

$$\text{ratio} = \ln \left( \frac{\text{drop} - \min(\text{rebound}) + s}{\text{rebound} - \min(\text{rebound}) + s} \right). \quad (3)$$

$$\text{RI} = \frac{\text{ratio} - \text{mean(ratio)}}{\text{std(ratio)}}. \quad (4)$$

where mean( ) is the mean and std( ) is the standard deviation. To ensure that the ratio is a positive number, which allows to use the logarithm function, $\min( )$ that returns the smallest value among all cities and a small constant $s=0.0001$ to avoid the possible zero denominator in Eq. (3) are introduced.

2.3. Regional disparities analysis

To further analyse the spatial difference of air quality improvements in response to the lockdown policy, we analysed the correlation of AQI values with meteorological factors including air temperature, precipitation and wind speed to evaluate the influence of meteorological effects on air pollution variations. Furthermore, we focus on the inherent features of an urban system and analysed the underlying regional disparities of these lagged effects while including geomorphic characteristics of elevation and GPS coordinates of each city. For the 314 cities, the resilience indexes are analysed using the spectral clustering method (Yu and Shi, 2003). We take the GPS coordinates, the lockdown time, the trough time and the rebound time point with their corresponding AQI values as the input feature vectors $f_i$, $i=1,2...N$, where $N=314$ denotes the number of cities used in this study. We apply the spectral clustering to find the regional disparities of the resilience patterns for all cities. More specifically, we first build the neighbourhood matrix $W \in \mathbb{R}^{N \times N}$ using these N feature vectors, where its element $w_{ij}$ is defined as:

$$w_{ij} = \exp \left\{ - \frac{\| f_i - f_j \|^2_2}{2\sigma^2} \right\}. \quad (5)$$

The Laplacian matrix $L$ is defined as $L = D - W$, where $D$ is the degree matrix, a diagonal matrix with the diagonal value as $d_{ii} = \sum_j w_{ij}$. A normalized Laplacian matrix is then obtained as $L = D^{-0.5}L D^{-0.5}$. We then find the $k$ eigenvectors corresponding to the smallest eigenvalues of $L$ and project the features $f_i$ into the subspace formed by these $k$ eigenvectors. Finally, a $k$-means clustering algorithm could be used on the projected features to derive the $k$ clusters. $k$ is a predefined parameter depending on the empirical knowledge of the data. According to (Webb, 2003), the $k$ value is set to the double number of aimed classes for classification. In this paper, we set $k=24$ as the climatic regions in China are set to 12 categories according to Zheng et al. (2013). For more information on the spectral clustering algorithm, readers are referred to Yu and Shi (2003) and Webb (2003).

In this way, we could map the clusters of the lockdown initiative’s potency and efficacy to identify the hotspot of resilient cities. Results are analysed with Matlab® R2020b (Mathworks, Inc., Natick, MA, USA) and visualised in the Geographic Information System (ArcGIS 10.3.2).

3. Results and discussions

3.1. Air pollution changes

Noticeable variations of air pollution index have been observed during the lockdown period of the COVID-19. While the starting lockdown date of each city throughout China varies from Jan 23, 2020 to Jan 29, 2020, most cities reacted within less than a week. Starting from the lockdown date, results of trend and change point analysis showed that
only 3 out of 314 cities did not show decreasing trend with reduced AQIs. These three cities are Yichun, Jingdezhen and Huangshan. However, the AQIs of these cities are very low at the beginning of the lockdown date and there is limited room for further significant improvements. The overall reduction of AQI values after lockdown was limited due to the originally low pollution levels under very few impacts from human activities. Among the rest 311 cities, 21% of them (64 cities) respond within 24 h, while 67% (208 cities) reach the trough point in three days. Two cities have long-term decreasing trend beyond two months, which are Guilin in Guangxi province, and Dali in Yunnan province. It took 3.97 days on average to show response in air pollution after the lockdown. It demonstrates the resilience of these cities in dealing with the reduction of air pollution caused by lockdown. After lockdown, the average reduction of AQIs in all cities was 63 (Std = 72.1), while the maximum reduced AQI was 434. Results indicate that cities locked down on January 25 demonstrated more noticeable effects followed by the 24th and 23rd city groups as showed in Fig. 3. In general, the daily average AQI values were significantly decreased after lockdown. The greatest reduction across all provinces is found in Shanxi, Shan-xi, Liaoning and Neimenggu provinces, which belong to the northern part of China with heavy industries (Fig. 5). This echoes with the findings proposed by Wang et al. (2020) that the largest AQI reduction occurred in Ningxia, Shandong and Henan, those provinces who have a large number of vehicles and many secondary industries in operation. It also reveals the varying performance of AQI reduction at different climate regions across China (Shi et al., 2014).
the northern and northeastern China, regions where air temperatures are very low in January, the air pollution levels are negatively correlated with high AQI values. Reduced AQIs in the southern and southeastern China are limited with good air quality in the first place and low air temperature during this period of study.

To delve into the meteorological effects on air pollution variations, the correlation analysis between AQI values and wind speed, air temperature and precipitation is carried out respectively, as shown in Fig. 4. Fig. 4 shows that precipitation is not closely correlated with the air pollution levels as most correlation coefficients are close to 0. For cities with high pollution levels, AQI is mostly negatively correlated with air temperature, which indicates that AQI will decrease with an increased air temperature. For cities with very low air pollution levels (i.e. AQI below 50), the increasing air temperature will lead to an increased AQI values. Similar trends are also found in the correlation study between AQI and wind speed, as shown in Fig. 4(c). Detailed information on the statistics of meteorological changes along with AQI reductions can be found in the supplementary data. To help understand the varying situations from different climate regions in China, we plot the AQI reductions of all 314 cities across different regions in China (Fig. 5). Results showed that precipitation is weekly correlated with the air pollution levels with the correlation coefficients mostly locate between −0.1 and 0.1. For wind speed and air temperature, negative correlations are more evident throughout different regions. With the decreasing air temperature in winter, air pollution levels are increasing accordingly.

3.2. Varying urban resilience

Results of the resilience index have shown significant difference among 314 cities across China. Different response patterns in each city indicate divergent sensitivities to mitigation of traffic-related human impacts, as well as the capabilities for recovery. For each city, we evaluate its urban resilience feature as the ratio of drop and rebound to delve into the integrated characteristics of recovery and resistance.

As shown in Fig. 6(a), distribution of drops showed a distinct range from a minimum value of 0 up to 1. The top two largest drops are Lishui and Taizhou both from Zhejiang province. Cities with the smallest drops of zero indicating no decrement were identified in Yichun and Jingdezhen both from Jiangxi province, and Huangshan in Anhui province. Generally these cities were with very good air quality where their daily average AQI values were below 15, so that there was limited room for AQI reduction when the lockdown measures were in place. The histogram of drops showed a skewed normal distribution with the average is 0.21, which means that the AQI values were decreased by 21% per day during the recession period after the lockdown.

As noted, rebound reflects the impulse response of air pollution after the recession. A smaller rebound indicates greater ability of resistance to

![Fig. 5. Spatial variation of (a) AQI reductions, and correlation between AQI values with (b) precipitation, (c) air temperature, and (d) wind speed. Results are interpolated for different regions across China.](image-url)
the ‘resumption’ of air pollution level. On average, the rebounds across all cities were 0.57 and the median was 0.43. The distribution of rebounds exhibited a power-law decay relationship with the AQI values as shown in Fig. 6(b). A few cities take longer time to resume back to previous air pollution levels after the recession, while most of them were resumed fairly quickly. In other words, cities with high rebounds might subject to other major sources of pollutants other than traffic-induced air pollution, so that the air pollution levels were quickly resumed although the traffic-induced emissions were limited during the lockdown. The largest rebound scores were as follows: 3.65 in Dongying, Shandong province, 3.26 in Laibin, Guangxi province, and 3.07 from Weifang in Shandong province as well. These cities are known focal points for nearby provinces in terms of transportation and economic activities.

In combination with the characteristics of both drops and rebounds, the integrated resilience index showed more comprehensive results of the urban resilience characteristics. A city with good resilience is expected to have large drop and limited rebound. It reflects the ability of an urban system to recover quickly with restriction of external influences such as human activities, but also the resistant feature to be
changed again after the potency of the lockdown policy. The larger the RI value indicates better resilience capabilities for a city in face of air pollution controls.

The results indicate that cities with low resilience index values are presented in a significantly clustering trend. Resilience showed obvious spatial disparities of the hotspots that were mainly aggregated across different regions in China. Results indicated that the top three resilient cities were Siping, Jincheng and Linxia which showed the highest resilience scores among all the cities in China (Fig. 7). Interestingly, the lowest resilience cities occur in the Southeastern and Southwestern China especially in the Circum-Bohai Sea Region near Beijing-Tianjin and the lower reaches of Yangtze River. These low-resilience cities share the same characteristics that air pollution levels were usually high but also highly affected by air temperature changes. For mega cities such as Beijing (RI = −0.42) and Shanghai (RI = −0.89), where represent the most complex urban systems, their resilience status is poor. Whereas, there are multi-faceted reasons other than the usage of vehicles or climatic influence as stated before. It is more reasonable to explain the situation as a systematic behavior instead of single-variate or multi-variate based studies.

The identified hotspots have the highest potential for air-quality controls, with 19.43% of the cities contributing to the most AQI drops and limited rebounds. Geographical factors including the meteorological factors in different climate regions influence the urban air pollution along with social and economic factors. The nationwide reduction of air quality index has demonstrated that cities with high pollution levels are proved to have high drop and limited rebound. As discussed, the hotspots (for the traffic-related air pollution) identified in this study may shed lights on urban community resilience through more welcomed and multi-benefited practices (i.e. via Sponge City Program) (Chan et al., 2018; Griffiths et al., 2020).

4. Conclusion

This paper is developed based upon the state-of-art that the COVID-19 induced pandemic has largely influenced air quality with reduced air pollution as induced in the background. Extensive studies have been carried out with consideration of multiple coupling effects from anthropogenic emissions to climatic and meteorological effects. In this paper, the study is based on fact of improved air qualities and focuses on the post-epidemic performance of air pollution improvement from the lens of urban resilience. It analyses the delayed effects of the lockdown policy by looking at the responsive rate from temporal perspectives beyond the actual values of reduced air pollutants. This provides a benefit as the threshold of lockdown time is aligned and the post lockdown air pollution is measured for its potency behaviours at the same temporal scale. The developed resilience index is unit-less but represents the urban system behaviours. The method we have developed and demonstrated here will support efforts to evaluate and cope with changes in air pollution levels in near real time, while it usually takes a much longer time for climatic and meteorological effects. This approach is potentially applicable to other global cities where anthropogenic emissions are dominant and were evident declines during the lockdown measure.

An exploration of the urban resilience features in regard to traffic-related air pollution controls has become a new paradigm for air quality management. Results of the urban resilience features should be referenceable in determining the goals of future traffic-related emission reduction policies. Comprehensive urban resilience framework, which addresses the multiplicity of city management requirements, can be explored in the further studies. Extending from the COVID-19 stress to other similar cases, lessons can also be referenceal for the future urban management policies through the resilience perspectives. Under the challenge of achieving Sustainable Development Goals in the present and post-COVID19 era, this study provides good arguments to address the urban resilience on air pollution, which may exert influence to our stakeholders and decision makers to create a long-term strategic in the urban context (i.e. via Urban Master Plans). It is interesting to reflect on how to deliver sustainable environmental management strategies for different cities and achieve better urban resilience especially in megacities. Results also showed the spatial hotspots of the most evident cities that received the most beneficiary from the lockdown policy. These findings are vitally pushing forward on improving future urban resilience dealing with the urban air pollution in Chinese cities especially on the response and recovery processes by our findings.

CRediT authorship contribution statement

Meili Feng: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft. Jianfeng Ren: Methodology, Software, Formal analysis, Writing - original draft. Faith Chan: Writing - review & editing. Jun He: Writing - review & editing. Chaofan Wu: Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors would like to thank the anonymous reviewers for their valuable suggestions for this paper. We would also like to send our gratitude for the support by the National Natural Science Foundation of China (No. 51909126); the Natural Science Foundation of Zhejiang Province (No. LQ19D010007); and the Interdisciplinary Flexible Research Fund (No. E01200500006) supported by the University of Nottingham. Gratitude are also offered to Xinyu Guo, Shengyi Zhou, Youtian Peng and Yizhou Chen who helped with the data collection and organisation for this project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.150248.

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