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Mortality weighting-based method for aggregate urban air risk assessment*

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Abstract: This paper deals with a mortality-weighted synthetic evaluation (MWSE) method for evaluating urban air risk. Sulphur dioxide (SO_2), nitrogen oxide (NO_x), and particulate matter (PM_{10}) were used as pollution indices. The urban area of Hangzhou, China is divided into 756 grid cells, with a resolution of 1 km×1 km, and is evaluated using the MWSE and the air quality index (AQI), a widely-used method to evaluate ambient air quality and air risk. In an evaluation of one day in April 2004, the surface areas categorized as levels I and III, as defined by the integrated air risk evaluation, were 27.3% and 3.3% lower, respectively, than grades I and III defined by the AQI evaluation. Meanwhile, the areas classified as level II or above level III by the integrated air risk evaluation were 55.1% and 101.1% higher, respectively, than grade II or above grade III when using the AQI evaluation. From this comparison, we find that the MWSE method is more sensitive than the AQI method. The AQI method uses a single index to assess integrated air quality and is therefore unable to evaluate integrated air risks due to multiple pollutants. The MWSE method overcomes this problem, providing improved accuracy in air risk assessment.

Key words: Integrated air risk, Mortality-weighted synthetic evaluation (MWSE), Air quality index (AQI), Air pollution
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1 Introduction

Environmental indices are important tools in environmental assessment, providing a quantitative indication of risk from a synthesis of available information (Environmental Protection Agency (EPA), 2003). Many cities assess ambient air quality using the air quality index (AQI) developed by the EPA. The AQI has been widely used to describe the severity of air pollution (Nagendra *et al.*, 2007). AQI defines air quality based on the maximum concentration among several common air pollutants. The use of a single index to assess air quality ignores the potential aggravating contributions of other pollutants (Kyrkilis *et al.*, 2007; Xu *et al.*, 2008; Wei *et al.*, 2011b). For example, while the maximum air pollutant index may be defined by PM_{10}, the overall health effect of the pollution may depend on the concentrations of other species (Aunan and Pan, 2004).

Other studies have developed synthetic environmental evaluation methods employing fuzziness, grey relationships, or grey clusters (Xu *et al.*, 2006; 2008; Liu and Yu, 2009). However, the indices obtained using these methods are too abstract for the public to grasp the relationship between air pollution and health and to indicate when sensitive groups such as asthmatics should take precautionary measures. It

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is therefore important to establish an evaluation of urban air quality based on the public health burden attributable to an air pollution risk level that is easily understood by the general public.

Some researchers have selected PM_{10} as an index of air risk to avoid overestimation or as part of a revision of the AQI (Zhang *et al.*, 2007a). Nevertheless, air pollutants such as NO_2, SO_2, and PM_{10} usually coexist in ambient air, and different air pollutants have different exposure-response characteristics. Studies have demonstrated that all-cause daily mortality increases by 0.6% (95% CI (confidence interval) 0.4–0.8) for each 10 $\mu g/m^3$ increase in PM_{10}. Mortality due to acute respiratory disease (ARD) and chronic obstructive pulmonary disease (COPD) may increase 4.86% and 0.416% with a 10% increase in ambient NO_x concentration, and ARD and COPD mortality increase 2.35% and 0.156% following a 10% increase in ambient SO_2 (Katsouyanni *et al.*, 2001; Wang *et al.*, 2008). Research on the health burden attributable to PM_{10} in Hangzhou, China has also demonstrated that PM_{10} from traffic contributes 0.2% to total mortality, while only accounting for 0.9% of total PM_{10} emission (Zhang *et al.*, 2008a). In contrast, the annual average concentrations of CO and NO_x attributable to transportation are 79.45% and 40.91%, respectively (Zhang *et al.*, 2008b). To select one air pollutant, such as PM_{10}, as the index for assessing air risk leads to an underestimation of the adverse health impact because none of the individual pollutants are sufficiently representative of the overall risk (Kyle *et al.*, 2002).

In this paper, an alternative approach is described to assess the integrated health risk level in terms of the public health burden attributable to air pollution (per 100 000 persons). Hangzhou (a typical city in the Yangtze delta of South China) was selected as our case study city and PM_{10}, SO_2, and NO_x were selected as the indices. The air risk grade was estimated using an exposure-response function and an ambient air quality standard. Because air pollutants have different exposure-response functions, the relative risk of each exposure-response function meta-analysis was adopted for weighting. The authors previously collected basic data for this research, including a 1 km×1 km resolution geographic information system (GIS)-based urban air pollutant concentration distribution simulated with the AMS/EPA regulatory model (AERMOD) (Zhang *et al.*, 2008a; Wei *et al.*, 2011a). Here we attempted to establish an integrated air risk level for three air pollutants based on public health burden.

2 Methodology

2.1 Exposure-response functions

The common air pollutants PM_{10}, SO_2, and NO_x were selected as indicators to assess the air pollution health risk level. Because death represents the most serious health endpoint, acute death was selected as the outcome under investigation. An exposure-response function that expresses the relative increase in adverse health effects for a given increment in air pollution is widely used for estimating mortality attributable to air pollutants (Abbey *et al.*, 1991; Samoli *et al.*, 2005). The number of cases for a given air pollution concentration may be expressed as (Schwartz *et al.*, 2002)

$$E = E_0 \times \exp[\beta(C - C_0)], \tag{1}$$

where E is the frequency of health outcome (per 100 000 persons), E_0 is the threshold of health outcome frequency (per 100 000 persons), β is the coefficient of exposure-response per 10 $\mu g/m^3$ increase in air pollutant level, C is the actual exposure level (mg/m^3), and C_0 is the reference concentration level (mg/m^3).

Meta-analysis was used to determine the exposure-response coefficient β, which is defined as the increase in mortality occurring after a 10 $\mu g/m^3$ increase in pollutant concentration. Epidemiological studies on mortality attributable to PM_{10}, SO_2, and NO_x in China offer a systematic set of results with which to perform meta-analysis (Dockery *et al.*, 1993; Pope *et al.*, 1995). Table 1 lists the all-cause mortality coefficient β from epidemiological studies in China. Table 2 lists the β (upper and lower 95% CI) incurred per 10 $\mu g/m^3$ increment of air pollutants in terms of the mortality exposure-response function, integrated with meta-analyses. In this process, we assume that $C_{PM_{10}} = 0.65 \times C_{TSP}$, where $C_{PM_{10}}$ and C_{TSP} are the concentrations of PM_{10} and total suspended particulates (TSPs), respectively.

Table 1 All-cause mortality β from increases of 10 μg/m^3 in air pollutants (data from epidemiological studies in China)

Air pollutant	Effect estimate relative risk (95% CI)	Reference (particle measure in original study)
PM_{10}	0.051 (0.004–0.098)	Gao *et al.*, 1993 (TSP)
	0.040 (−0.020–0.110)	Xu *et al.*, 1994 (TSP)
	0.039 (0.027–0.051)	Dong *et al.*, 1995 (TSP)
	0.008 (0.002–0.014)	Jin *et al.*, 1999 (TSP)
	0.0017 (0.0012–0.0023)	Xu *et al.*, 2000 (TSP)
	0.0053 (0.0022–0.0085)	Dai *et al.*, 2003 (PM_{10})
	0.003 (0.001–0.005)	Kan and Chen, 2003 (PM_{10})
SO_2	0.097 (0.035–0.157)	Gao *et al.*, 1993
	0.110 (0.050–0.160)	Xu *et al.*, 1994
	0.020 (0.014–0.026)	Dong *et al.*, 1995
	0.0024 (0.0015–0.0033)	Xu *et al.*, 2000
	0.014 (0.008–0.021)	Dai *et al.*, 2003
	0.016 (0.011–0.021)	Kan and Chen, 2003
NO_x	0.015 (0.008–0.022)	Dai *et al.*, 2003
	0.020 (0.012–0.027)	Kan and Chen, 2003

Table 2 All-cause mortality β for a 10 μg/m^3 increment in air pollutant concentration

Air pollutant	Effect estimate relative risk (95% CI)
PM_{10}	0.00189 (0.00102–0.00276)
SO_2	0.01034 (0.00962–0.01106)
NO_x	0.01413 (0.01324–0.01502)

2.2 Reference air pollutant concentration C_0

Many studies set C_0 to be the lowest assessed concentration level (Kan and Chen, 2004) rather than the threshold air pollutant concentration that does not generate health effects. Since there is often no previous research to determine the lowest pollutant concentration causing a health burden, C_0 is generally assigned one of the following four values: the pollutant concentration attributable to natural emission, the lowest assessed concentration level observed in epidemiological studies, the concentration limits established by air pollution standards, or simply zero. Different assumptions of C_0 will produce different results when evaluating the health burden attributable to air pollutants, and consistency in setting the reference concentration is important. Considering that the Ambient Air Quality Standard (NEPB, 1996) does not stipulate a lowest assessed concentration level for all air pollutants, we assumed the lowest assessed concentration levels of PM_{10}, SO_2, and NO_x to be zero.

2.3 Threshold of health endpoint E_0

E_0 is the expected outcome frequency for a given exposure level C_0 (Kan and Chen, 2004) and is usually assigned a constant value. We calculated E_0 with Eq. (1) based on mortality and annual daily average ambient concentrations of air pollutants in Hangzhou in 2003. The mortality of Hangzhou excluding accidents (E) is about 557 per 100 000 persons in 2003 (Jin *et al.*, 2005). According to environmental quality report of Hangzhou in 2003, the annual daily average concentrations of SO_2, NO_2, and PM_{10} are 0.049, 0.056, and 0.119 mg/m^3, respectively. In this process, we assume that $C_{NO_2}=0.65\times C_{NO_x}$, where C_{NO_2} and C_{NO_x} are the concentrations of NO_2 and NO_x, respectively. The E_0 values for PM_{10}, SO_2, and NO_x are listed in Table 3.

Table 3 Mortality frequency E_0 (mortality per 100 000 persons)

Air pollutant	Health outcomes frequency E_0 (95% CI)
PM_{10}	561 (555–567)
SO_2	546 (544–548)
NO_x	523 (520–526)

2.4 Integrative model with mortality weighting

The aim of this study is to formulate an integrated air risk level that indicates the health burden attributable to air pollution. We calculated each integrated risk level using the equation:

$$E_i=\sum_{j=1}^{n}\left(\frac{\beta_j}{\sum_{i=1}^{n}\beta_i}\times E_{i,j}\right), \qquad (2)$$

where j=1, 2, 3 indicate the individual pollutants, and E_i is the aggregate number of mortality per 100 000 individuals under grade i of the Ambient Air Quality Standard. Because each country has a different ambient air quality standard, we selected the Ambient Air Quality Standard of China (AAQSC) to evaluate the air risk in the case study city. Table 4 lists different air pollutant daily average concentration limits of AAQSC.

Table 4 Air pollutant concentration limits of AAQSC (24 h) (μg/m^3)

Air pollutant	Concentration limit		
	Grade I	Grade II	Grade III
PM_{10}	50	150	250
SO_2	50	150	250
NO_x	100	100	150

3 Study area

The city of Hangzhou was selected as our case study city to evaluate the health risks due to PM_{10}, SO_2, and NO_x pollutions. Hangzhou is located within the Yangtze delta in South China and is typical of cities in that area. The population of the urban area of Hangzhou is 3.93 million in 2004.

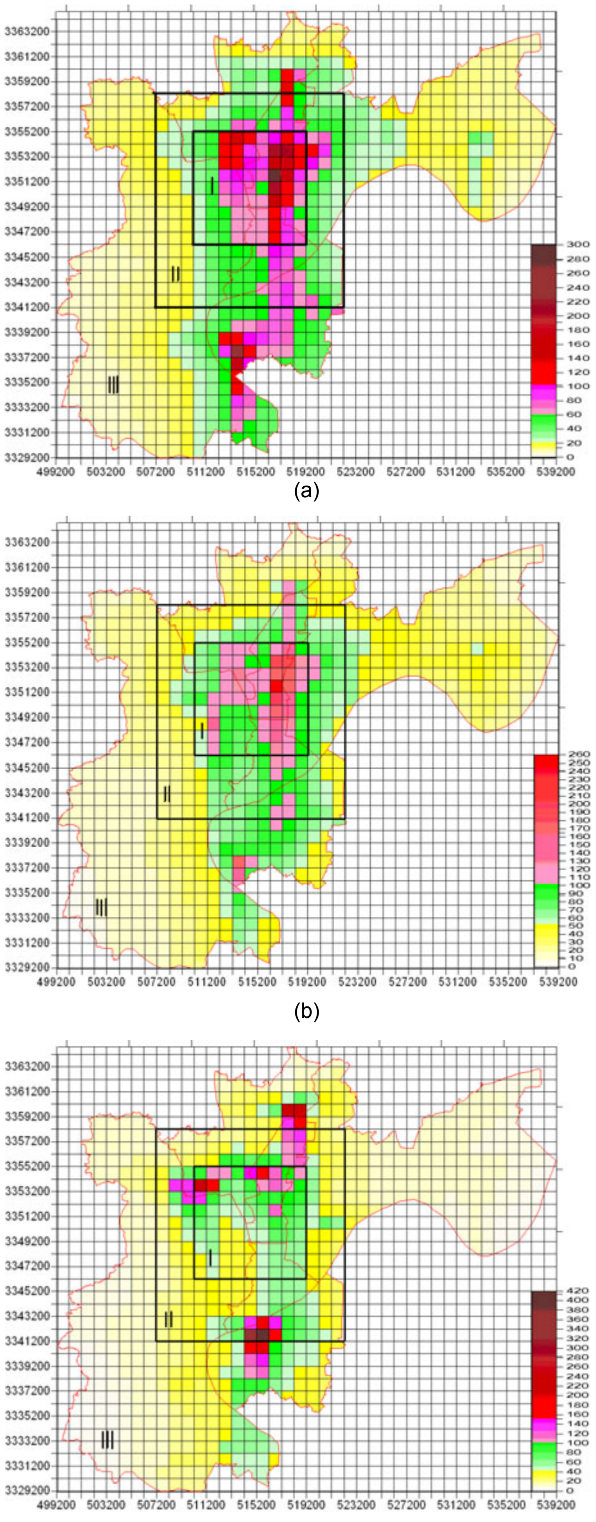
The largest source of energy is coal, and there were approximately 0.68 million vehicles in the area in 2004. The total annual emissions of SO_2, NO_x, and PM_{10} were 41385.9, 54780.4, and 24239.2 t in 2004, respectively (Zhang *et al.*, 2008a). For our study the city was divided into 756 grid cells with a resolution of 1 km×1 km. The population distribution and concentrations of PM_{10}, SO_2, and NO_x from all sources were measured in each grid location. The PM_{10}, SO_2, and NO_x concentration distributions in each grid were simulated using the AERMOD (Zhang *et al.*, 2008a). The total PM_{10}, SO_2, and NO_x concentration distributions are illustrated in Figs. 1a–1c.

The city was divided into three parts (Fig. 1c) according to population density and urban function (Zhang *et al.*, 2008a). Part I contains the central urban area with the highest traffic and population density and has an area of 81 km^2. The traffic and population density of part II are lower than those of part I; this region covers approximately 170 km^2 and includes the West Lake in the southwest corner. Part III covers 505 km^2 and represents areas with a high density of industrial activity.

4 Results and discussion

4.1 Air risk level limits

Table 5 is a summary of the integrated air risk levels for PM_{10}, SO_2, and NO_x. The air risk level I of PM_{10}, SO_2, and NO_x is calculated with Eq. (1) under



(a)

(b)

(c)

Fig. 1 SO_2 (a), NO_x (b) and PM_{10} (c) spatial concentration distributions of Hangzhou in 2004 (Zhang *et al.*, 2008a)
Grids with yellow, green and red mean air pollutants concentrations (μg/m^3) in grades I, II and III, respectively

the concentration of grade I (Table 4), and so on. The integrated air risk levels are estimated with Eq. (2). When the mortality is less than or equal to 55 per 100 000 persons, the integrated air risk is defined as level I. When the mortality is between 55 and 80 per 100 000 persons, the integrated air risk is termed level II. When the mortality is between 80 and 132 per 100 000 persons, the integrated air risk is defined as level III. Mortality rates over 132 per 100 000 are referred to as being over level III.

The results presented in Table 5 indicate that NO_x and SO_2 risk levels are dominant for levels I and III, respectively, while NO_x and SO_2 together dominate the integrated air risk level of level II.

Table 5 Air risk level of Hangzhou E_i (mortality per 100 000 persons)

Air pollutant	Air risk level limit		
	Level I	Level II	Level III
SO_2	28.9	91.6	161.1
NO_x	80.7	80.7	125.6
PM_{10}	5.3	16.1	27.1
Integrated	55.0	80.0	132.0

4.2 Evaluation of ambient air risk level

Fig. 2 illustrates the integrated air risk level of Hangzhou evaluated using the aggregate air risk index for data collected on Apr. 15, 2004. The urban area contains 344 km^2 at risk level I, 107 km^2 at level II, 116 km^2 at level III, and 189 km^2 above level III. A total of 74 km^2 (91.4%) of Part I was over level III, while the remaining 7 km^2 (8.6%) was level III. In Part II, there were 18 km^2 at risk level I, 42 km^2 at level II, 62 km^2 at level III, and 52 km^2 above level III, accounting for 10.3%, 24.2%, 35.6%, and 29.9% of the total area of Part II, respectively. In Part III, there were 326 km^2 at a risk level I, 65 km^2 at level II, 47 km^2 at level III, and 63 km^2 over level III, accounting for 65.1%, 13.0%, 9.3% and 12.6% of total area of Part III, respectively. The average integrated air risk level was the highest in Part I and the lowest in Part III, paralleling the population density in the various regions. To protect public health, areas with higher risk levels should ideally have lower population densities, the opposite of the situation in Hangzhou.

4.3 Comparison with air quality evaluation

To compare the air risk evaluation obtained using MWSE with the AQI, we also calculated the AQI for the same day. Fig. 3 illustrates the ambient air quality grade obtained using the AQI. The area in grade I was 473 km^2, in grade II 69 km^2, in grade III 120 km^2, and over grade III 94 km^2. The areas of grade I and grade II based on AQI were larger than those of level I and level II defined using MWSE by 129 and 4 km^2, while the areas for the other two grades were lower than other two levels. In general, the reported air risk level is higher with MWSE than with the AQI. The areas of air risk levels I and III were 27.3% and 3.3% lower than those of AQI grades I and III, while the areas of risk level II and over level III were 55.1% and 101.1% higher than AQI grade II and over grade III areas, respectively.

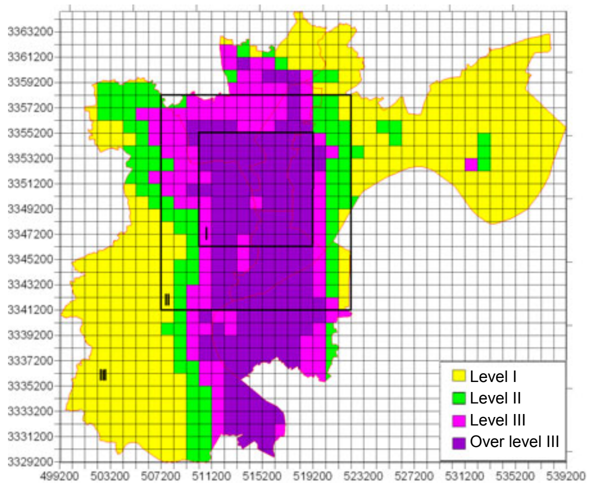


Fig. 2 Integrated air risk evaluation spatial distribution for Hangzhou on Apr. 15, 2004

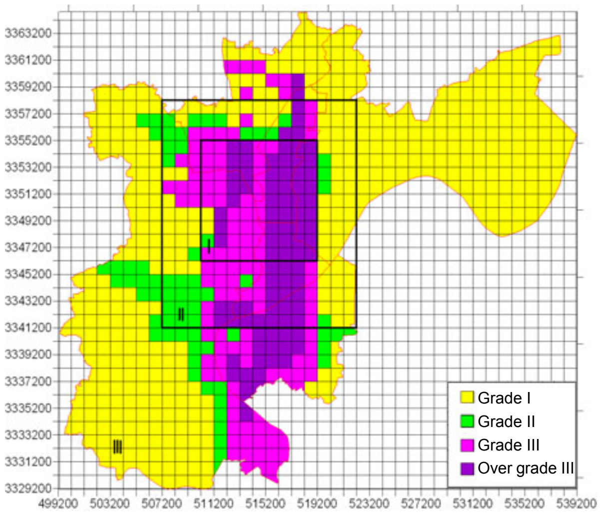


Fig. 3 Air quality grade evaluation with AQI spatial distribution for Hangzhou on Apr. 15, 2004

According to the AQI algorithm, the concentrations of SO_2 and PM_{10} do not have any effect on ambient air quality grade in the 118 grids where the NO_x concentration is at the highest grade. In contrast, the air risk levels evaluated using the MWSE method is defined using all air pollutants. In these 118 grids, there are 27 grids in level III and 91 grids over level III due to the effect of different SO_2 and PM_{10} concentrations on the level evaluation (Table 6).

Table 6 Comparison of air risk evaluation and AQI evaluation (Apr. 15, 2004)

AQI grade	Each pollutant grade	Grids	Grids of air risk level				
			I	II	III	Over III	Total
I	P1, S1, N1	473	327	99	47	0	473
II	P1, S2, N1	38	0	0	34	4	38
	P2, S1, N1	27	17	8	2	0	27
	P2, S2, N1	4	0	0	4	0	4
III	P1, S1, N3	11	0	0	8	3	11
	P1, S2, N3	62	0	0	12	50	62
	P2, S2, N3	30	0	0	7	23	30
	P3, S2, N1	2	0	0	2	0	2
	P3, S2, N3	15	0	0	0	15	15
Over III	P1, S1, N4	4	0	0	0	4	4
	P1, S2, N4	28	0	0	0	28	28
	P1, S3, N4	8	0	0	0	8	8
	P2, S2, N4	26	0	0	0	26	26
	P2, S3, N4	6	0	0	0	6	6
	P2, S4, N4	2	0	0	0	2	2
	P3, S2, N4	2	0	0	0	2	2
	P3, S3, N4	2	0	0	0	2	2
	P3, S4, N4	1	0	0	0	1	1
	P4, S2, N3	12	0	0	0	12	12
	P4, S2, N4	3	0	0	0	3	3
Total grids		756	344	107	116	189	756

P, S and N mean PM_{10}, SO_2 and NO_x, respectively, and the subscripts 1, 2, 3 and 4 are AQI of pollutant in grades I, II, III, and over III, respectively

4.4 Sensitivity and uncertainty analysis

We randomly selected 11 grids to analyze the sensitivity of integrated air risk level evaluation using the MWSE method and air quality grade evaluation using the AQI method (Table 7). The ambient air quality grades of grids 1, 5, and 10 are in grade II due to the PM_{10} concentration, while the synthetic air risk levels of grids 1, 5, and 10 are in levels II, III, and over grade III because each air pollutant will create an individual burden for public health. Air risk level evaluation using the MWSE method is therefore more sensitive than air quality grade assessment using AQI.

The uncertainty of air risk level evaluation using mortality weighting mainly stems from the weighting function, and the major source of error is the exposure-response coefficient. At least three mechanisms can contribute to uncertainty in these factors: the statistical determination of mortality attributable to air pollutants, regression analysis of the exposure-response coefficient, and meta-analysis of the coefficient. The CIs of the mortality statistics and regression analysis are 95%. The tolerance of the exposure-response coefficient meta-analysis is less than 10% because error transfers from the mortality data and regression analysis.

Table 7 Sensitivity analysis of air risk evaluation and AQI evaluation (Apr. 15, 2004)

Grid	Concentration (mg/m^3)			Mortality per 100 000 persons	Air risk level	AQI grade
	SO_2	PM_{10}	NO_x	Integrated		
1	66.14	27.21	43.23	56	II	II
2	116.79	28.35	42.66	62	II	II
3	54.95	34.92	55.95	70	II	II
4	133.89	33.44	54.47	76	II	II
5	15.54	50.55	67.89	100	III	II
6	14.56	52.38	68.66	100	III	II
7	18.29	69.22	92.99	117	III	II
8	17.64	70.64	96.45	121	III	II
9	14.52	50.99	81.99	96	III	II
10	13.04	81.14	116.89	145	Over III	II
11	14.58	84.44	121.43	151	Over III	II

5 Conclusions

The integrated air risk calculated using the mortality weighting technique developed in this paper establishes a relationship between ambient air pollutant concentration and public health. This method considers the health burden attributable to various atmospheric air pollutants, resulting in a higher sensitivity than that provided by air quality assessment performed using the AQI method.

The MWSE method can be applied to estimate air risk attributable to ambient air pollutants from different sources. With this method, it is very easy to analyze the exposure intensity of citizens. This is important in city planning and in assessing the effectiveness of pollution control measures.

The MWSE method can also assess whether ambient air quality limits for air pollutants are reasonable. Considering that mortality attributable to air pollutants represents the greatest cost in terms of environmental damage (Zhang *et al.*, 2007b), mortality should be the chief factor in determining ambient air quality limits.

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