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Assessment of population exposure to particulate matter pollution in Chongqing, China

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Using an indirect microenvironment model, the population weighted exposure (PWE) to PM_{10} in Chongqing was estimated to be 211 μg/m^3 with significant contribution from indoor pollution.

Abstract

To determine the population exposure to PM_{10} in Chongqing, China, we developed an indirect model by combining information on the time activity patterns of various demographic subgroups with estimates of the PM_{10} concentrations in different microenvironments (MEs). The spatial and temporal variations of the exposure to PM_{10} were illustrated in a geographical information system (GIS). The population weighted exposure (PWE) for the entire population was 229, 155 and 211 μg/m^3, respectively, in winter, summer and as the annual average. Indoor PM_{10} level at home was the largest contributor to the PWE, especially for the rural areas where high pollution levels were found due to solid fuels burning. Elder people had higher PM_{10} exposure than adults and youth, due to more time spent in indoor MEs. The highest health risk due to particulate was found in the city zone and northeast regions, suggesting that pollution abatement should be prioritized in these areas.
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Keywords: PM_{10}; Population exposure; Indoor air pollution; Time activity patterns; Health risk zones

1. Introduction

Particulate matter (PM) pollution has been recognized as one of the most serious environmental problems with enormous impacts on human health. Exposure information to PM is essential for policymakers to identify the potential risk group and to develop appropriate risk reduction measures. Epidemiological studies of PM routinely use concentrations measured with stationary outdoor monitors as surrogates for population exposure, and the epidemiologic associations between ambient concentrations and health effects depend on the correlation between ambient concentrations and exposure to ambient-generated PM (Pope et al., 1995; Beeson et al., 1998; Moschandreas and Saksena, 2002). However, this approach may lead to important uncertainties as population exposures are also influenced by indoor environments and time activity patterns (European Union, 1995; Boudeta et al., 2001; Nerrierea et al., 2005). A number of studies have reported the poor correlations between ambient concentrations and human exposure to PM (Lai et al., 2004; Adgate et al., 2002). Therefore, directly using ambient air concentrations directly to assess population exposure calls for some caution, especially when indoor PM level is higher than outdoors, as is the case for many people in rural area of China.

Indoor air pollution from solid fuel use in developing countries is estimated to be the eighth leading health risk worldwide (WHO, 2002), which is also true in China. Coal, wood, and other bio-fuel such as crop residues and dung remain the primary heating and cooking fuels in rural areas, small cities, and in less developed peri-urban areas of large

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cities. Several studies have implied that indoor PM pollution is much more serious as compared to outdoor (Qin et al., 1991; Cai et al., 2000; Li et al., 2001; Pan et al., 2001). The indoor PM_{10} levels of different areas in China varied between 340 and 853 μg/m^3 in these studies, and all the results indicated that indoor air pollution could potentially constitute a large share of the actual human exposure.

These reported PM concentrations in different microenvironments are not sufficient for exposure assessments. Population exposure should be estimated by combining the pollutant concentrations in different microenvironments with time activities of relevant population groups (Abt et al., 2000; Dimitroulopoulou et al., 2001; Burke et al., 2001). A few studies have been carried out to estimate the total integrated exposures for Chinese people in Anqing (Pan et al., 2001), Hong Kong (Chau et al., 2002), and Beijing (Wu et al., 2003), by multiplying the average micro-environmental PM concentrations by the total time spent in each microenvironment (ME). These papers provided a general overview of exposure patterns in the three cities studied. To provide a more detailed picture of exposure, detailed information on PM_{10} concentrations in different microenvironments and time activity patterns for different demographic subgroups should be investigated. From this information one can better understand who is at risk, where they live, the fuel they use, and the level of particulates to which they are exposed. The geographical dimension should also be included by taking advantage of Geographical Information System (GIS), which encompasses storage, retrieval, analysis and display of spatial–geographical data. GIS can provide efficient methods for determining exposure indices and has been used in some exposure studies for developed countries to illustrate the health risk zones for policy making of air pollution control and health risk management (Jensen, 1998; Kousa et al., 2002; Nuckols et al., 2004).

Accordingly, this study aims to develop a modeling approach to make detailed population exposure estimates of PM with information on spatial PM concentrations in both indoors and outdoors, population distributions, and time activity patterns, and to apply this exposure model to find the level of daily exposure for different age population groups, to identify the spatial distribution of level of exposure, and to map the health risk in Chongqing, one of the four municipalities directly under the jurisdiction of the central government in China which is well known for its severe air pollution in 1990s. The exposure estimates presented here provide a basis for more precise targeting of intervention policies, demonstrated through exposure reduction by adopting cleaner fuel in rural households, nonetheless it is not intended to quantify the cost and benefit of exposure reduction under pollution control strategies.

2. Materials and methods

In this study, the human exposure expression depends on three input variables: population of each demographic group in each residential area, pollutant concentration and its constituents at each microenvironment, and time spent in each of these microenvironments by the given demographic group. Therefore, the approach in this work is as follows: (1) map the population density of the stratified demographic group; (2) calculate the PM_{10} concentrations in each grid; and (3) overlay the PM_{10} concentration on the population density map to determine the effect of air quality on the population. All the work related with geographical information was carried out with MapInfo Professional 7.0.

2.1. Study area and demographic information

Chongqing, the metropolis of southwest China, is located at north latitude 28°10′–32°13′ and east longitude 105°11′–110°11′. As a large commercial and industrial center covering an area of 0.0824 million square kilometers, the municipality of Chongqing is 470 km wide from east to west and 450 km long from north to south (Chongqing Statistical Bureau, 2004), as shown in Fig. 1. Chongqing includes nine urban districts (the so-called city zone) and another 31 counties around them. In this study, a grid system with 3 × 3 km resolution and totally 9150 grids was designed to cover the whole area.

The database of the fifth Census on population, which identifies the sex (male and female), age (0–14, 15–64, and over 65 years) and the percentages of non-agriculture population for each urban district or county, was used to estimate the population density at grid level. In the year 2000, the total population of Chongqing is 30.5 million, in which 22% are non-agricultural. For the city zone, the population density of each grid cell was assumed to equal the density at street or block level where the grid is located, while uniformly the average value of the county where the grid is located for other counties. For those grids which intersect several different streets/blocks/counties, the average density was calculated using the proportion of values from the covered areas.

The geographical distribution of the population density in Chongqing is shown in Fig. 1. The highest population densities were found mainly in the western area, especially Jiangbei, Yuzhong, Beibei, and Shapingba districts in the city zone, and Dazu, Yongchuan, Bishan, and Hechuan counties. The average population density in these regions was beyond 600 persons/km^2, with the highest 10 000 persons/km^2 in the most urbanized parts of Jiangbei and Yuzhong districts. In the middle-east region, population density was relatively high in Changshou and Dianjiang counties, while lower than 500 persons/km^2 for the rest.

2.2. Participant recruitment and data collection

In daily life, people move around and thus are exposed to various levels of pollutants in various locations. In this study, data were collected on time activity patterns, ambient PM_{10} levels, and hourly indoor (typical microenvironments) and corresponding outdoor PM_{10} levels.

To determine the time activity patterns of Chongqing people, a recall questionnaire investigation was conducted in Shapingba, Yongchuan, and Jiulongpo between January and March 2006. Questionnaires were sent to 270 families (180 urban and 90 rural), members of which were required to record the time they spent in different microenvironments ("kitchen," "bedroom," "living room," "school/work," "other indoors away from home," "transit" and "outdoors") with a 7-day period. The age groups chosen were youth under 15, adults 15–64 and elderly older than 65. The records with summations of time spent in various microenvironments for 1 day greater than 25 h or less than 23 h were considered misreporting and thus excluded from the analysis.

The outdoor PM_{10} concentrations for each month in 2004 are available at 10 ambient air quality monitoring stations in the city zone (there are two stations in Shapingba District) and 28 in the counties (there were no monitoring data in Chengkou, Wuxi, and Xiushan counties). The monitoring sites are located at fixed points on the terraces of the municipal buildings. In these sites, the Suspended Particulate Matter Beta Attenuation Mass Monitor (MP101M),[1] was used to measure ambient PM_{10} concentrations. This equipment determines the particulate concentration by measuring the amount of radiation a sample absorbs when exposed to a radioactive source. The maximum range of the instrument is 0–10 000 μg/m^3, while the lower detectable limit for PM_{10} (24 h average) is 0.5 μg/m^3.

[1] Environment.s.a Inc., France: http://www.environnement-sa.com/.

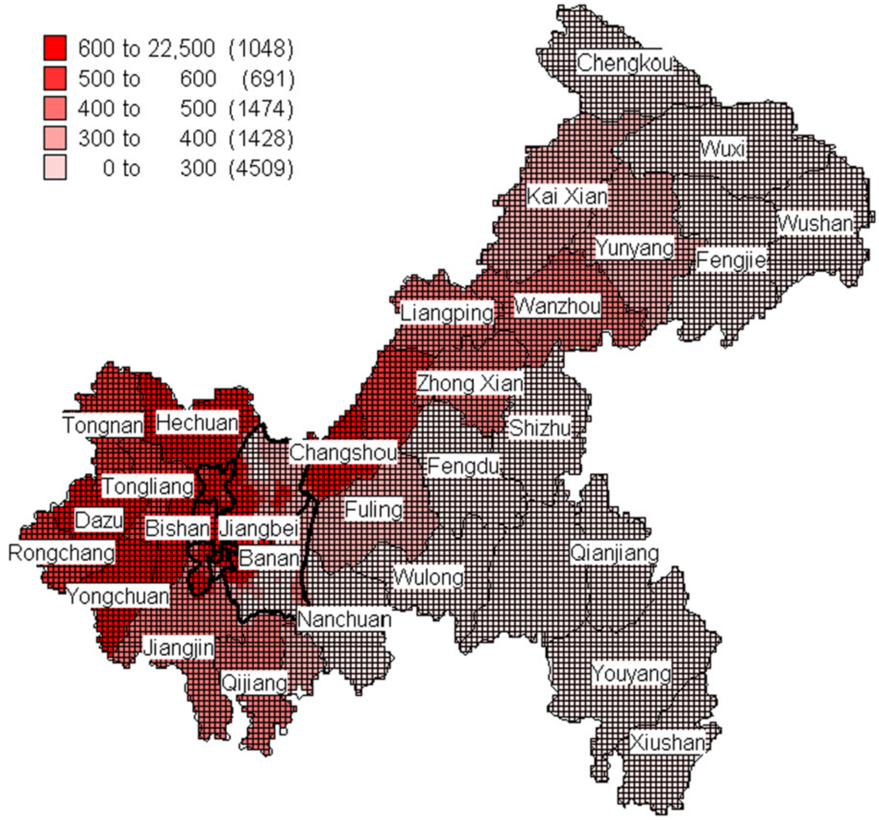

Fig. 1. Study area and geographical distribution of total population density (persons/km^2). The areas with solid borders are the city zone. Figures in brackets represent the number of grid cells.

Regarding indoor particulate air pollution, both indoor and corresponding outdoor hourly PM_{10} concentrations were measured simultaneously at 21 sites containing major indoor microenvironments (bedrooms, kitchens, living rooms, offices, and other indoors such as hospitals, as shown in Table 1) with MP101M, the same instrument applied in the ambient monitoring stations. The level in transits environment was estimated based on the measurement data reported in the literature (Chau et al., 2002). In the indoor measurement, the MP101M was placed on a table without any movement during the measurement period, and cigarette smoking was strictly controlled at public area sites but hardly at home. In the synchronous outdoor measurement, an ambient monitoring vehicle was applied which was at anchor closed to the microenvironment during the measurement period. The MP101M was fixed in the vehicle, with its sampling inlet staying in the air. Each measurement was conducted continuously for at least 24 h.

2.3. Calculation of ambient PM_{10} concentration at grid level

The spatial interpolation method was applied to estimate the concentration of pollutants at grid level. In this study, we used an inverse-distance squared neighbor scaling to calculate the pollutant concentration at each grid from the measured data in 38 monitoring stations. For example, the ambient PM_{10} concentration of grid i can be calculated as follows:

$$C_{i(\mathrm{ambient})} = \frac{\left(\sum_{j=1}^{38} \frac{1}{D_{ij}^2} \times C_j\right)}{\left(\sum_{j=1}^{38} \frac{1}{D_{ij}^2}\right)} \quad (1)$$

where D_{ij} is the distance of grid i from monitoring station j, C_j is the PM_{10} concentration measured at monitoring station j.

2.4. Calculation of daily exposure and population weighted exposure of PM_{10}

Exposure to particulate air pollution is the product of PM_{10} concentration in each microenvironment multiplied by the time spent by an individual in that microenvironment. Given the grid i, the classical equation for an individual's daily exposure is as follows:

$$E_i = \sum_{j=1}^{n} E_{ij} = \sum_{j=1}^{n} \left(f_{ij} \times C_{ij}\right) \quad (2)$$

where E_{ij} is the exposure of an individual in microenvironment j, f_{ij} is the fraction of the day that the individual spend in microenvironment j, and C_{ij} is the average PM_{10} concentration in microenvironment j when the individual is in that microenvironment.

A population can be divided into groups of individuals with some common characteristics. Eq. (3) was applied to calculate the daily exposure for the group k.

$$\mathrm{PE}_{ik} = \mathrm{PE}_{ik} \sum_{j=1}^{n} \left(f_{ij} \times C_{ij}\right) \quad (3)$$

where P_{ik} is the population living in grid i belonging to demographic subgroup k.

To estimate the individual and population exposure, IO ratios (indoor/outdoor concentration) for various microenvironments when people are normally present in the microenvironments were calculated based on the data measured in Section 2.2. For example, we only used daytime concentration to assess the IO ratios of office since usually there are few people working there during night. With IO ratios, PE was calculated with Eq. (4):

$$\mathrm{PE}_{ik} = P_{ik} \times C_{i(\mathrm{ambient})} \sum_{j=1}^{n} \left(f_{ij} \times \mathrm{IO}_j\right) \quad (4)$$

Table 1
Indoor and outdoor PM_{10} field measurements

Period	Date	District/ county	Urban/ rural	Indoor ME
May 2005	17th–18th	Jiangbei	Urban	Office
	18th–19th, 21st–22nd	Yuzhong	Urban	Hospital
	22nd–24th	Yuzhong	Urban	Guest room at home
	24th–25th, 28th–29th	Shapingba	Urban	Guest room at home
	25th–28th Aug	Shapingba	Urban	Office
Aug–Sep 2005	23rd–25th Aug	Nan'an	Urban	Company area
	25th–26th Aug	Jiangbei	Urban	Dormitory/ bedroom
	29th–30th Aug	Shapingba	Urban	University classroom
	30th Aug–1st Sep	Yubei	Urban	Indoor at home
	1st–3rd Sep	Beibei	Urban	Dormitory/ bedroom
	8th–10th Sep	Beibei	Rural	Office
Mar 2006	10th–11th	Shapingba	Urban	Guest room at home
	12th–14th	Shapingba	Urban	Classroom
	14th–15th	Shapingba	Urban	Office
	15th–17th	Yuzhong	Urban	Kitchen
	17th–19th	Jiulongpo	Rural	Indoor at home
	19th–21st	Jiulongpo	Rural	Bedroom
	19th–20th	Jiulongpo	Rural	Kitchen
	20th–21st	Jiulongpo	Rural	Kitchen
	21st–22nd	Jiulongpo	Rural	Kitchen
	25th–27th	Yuzhong	Urban	Hospital

where $C_{i(\text{ambient})}$ is the outdoor concentrations calculated from Eq. (1) and IO_j is the IO ratio in microenvironment j.

We also calculated the population weighted exposure (PWE). The PWE for a given population is the daily average exposure weighted by the population groups included. It can either be calculated for a given demographic subgroup, and thus represents the group's average daily exposure in the study area; or it can be estimated for a combination of groups or all groups and thus represent the average daily exposure of the entire population in study area. To calculate the PWE for different demographic subgroups, we used the equation:

$$\mathrm{PWE}_{ik} = \frac{1}{P_{ik}} \mathrm{PE}_{ik} \tag{5}$$

where P_{ik} is the total population of group k.

3. Results

3.1. Time activity patterns

Through the recall questionnaire, 774 valid cases (525 in urban areas and 249 rural) were obtained. The mean times spent in various microenvironments for the 7-day period by the different age groups are listed in Table 2. Since no obvious discrepancy was found between males and females during the investigation, the result was gender-independent. High standard deviations were found in almost all microenvironments except in the bedroom, showing rather large differences among individuals. As opposed to urban people, rural people in Chongqing spent less time in the school/office but more in the kitchen and outdoors. Comparatively, youngsters spent more time in schools, adults spent more time outdoors, and older people spent more time at home.

3.2. Calculated ambient PM_{10} concentration at grid level

In 2004, the averaged annual ambient PM_{10} concentrations varied from 53 μg/m^3 (Wulong County) to 200 μg/m^3 (Pengshui County). Winter was more seriously polluted than summer. In 2005, the monthly mean of PM_{10} concentration varied from 62 μg/m^3 (Wulong County) to 264 μg/m^3 (Pengshui County) in January, and 9 μg/m^3 (Wulong County) to 146 μg/m^3 (Changshou County) in July. Fig. 2 shows the average PM_{10} concentrations calculated for each grid cell using Eq. (1). In 2004, PM_{10} levels were highest in the city zone and some adjacent counties, such as Changshou, Fuling, Nanchuan, Wansheng, Qijiang, and Pengshui. The situation in winter (January 2005) was quite similar to that, while large parts of northeast had relatively high PM_{10} levels in summer (July 2005), showing a clear seasonal difference.

3.3. Indoor concentration level and IO ratios

Indoor PM_{10} concentration was generally higher than outdoor in both rural and urban areas, and rural indoor particulate pollution was more serious than urban due to poor cooking and heating conditions, especially in the kitchen. The urban outdoor air pollution was generally higher than the rural, however, the urban population, to a larger extent, used cleaner

Table 2
Time (h) spent in different MEs by age group

	Urban						Rural					
Age	0–14		15–64		>65		0–14		15–64		>65	
N	187		327		11		84		151		4	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Kitchen	0.3	0.5	1.3	1.2	2.1	1.4	1.0	1.0	2.5	1.9	4.3	2.8
Bedroom	9.5	1.5	10.0	2.0	11.1	1.4	10.7	1.2	10.8	2.4	11.4	2.2
Living areas	2.2	1.5	3.2	2.1	6.6	1.9	2.5	1.5	2.4	1.9	2.5	1.6
School/office	8.4	3.1	3.6	3.6	0.2	0.8	6.1	1.9	0.1	0.5	0.0	0.0
Other indoors	0.6	0.9	1.6	2.4	1.1	1.6	1.6	1.6	2.0	2.5	2.3	2.3
Transits	1.0	0.9	1.2	1.4	0.2	0.3	1.0	0.8	1.0	2.1	0.1	0.1
Outdoors	2.0	2.8	3.1	3.7	2.7	2.5	1.2	1.5	5.2	3.1	3.5	2.3

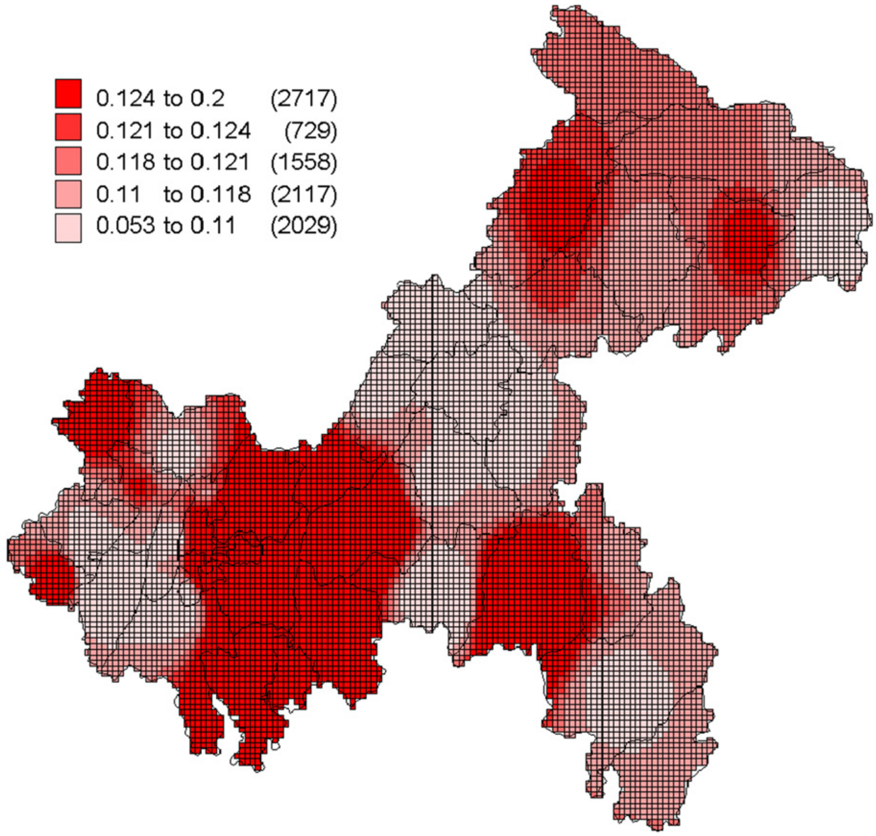

Fig. 2. Geographical distribution of ambient PM_{10} concentration in 2004 (unit: mg/m^3). Figures in brackets represent the number of grid cells.

fuels in the households. Therefore, the difference between indoor and outdoor in urban areas was not as large as in rural areas. As illustrated in Fig. 3, IO ratios for PM_{10} were observed to range between 0.15 and 7.65 for urban, and 0.40 and 22.46 for rural. The highest IO ratios were found in kitchens at cooking times, while the lowest were found in bedrooms during the night for both urban and rural areas. The extremely high IO ratio (22.46) observed in a rural kitchen was caused by the process of letting the coal smolder in the stove with poor ventilation, which is quite common in rural areas. From the measurement and analysis results, it can be seen that fuel combustion and ventilation conditions are obviously important factors determining the indoor particulate level. In indoor environments without apparent indoor sources the outdoor particles contributed to about 66–80% to the indoor PM_{10}. Another factor contributing to indoor PM levels is human activity. In the absence of smoking, the more people in the room, the higher the indoor concentrations. This was typical in the office in daytime and at hospitals. The mean IO ratios with standard deviation we used for exposure estimates are shown in Table 3.

3.4. Daily exposure and population weighted exposure

Daily personal exposure (PE) and population weighted exposure (PWE) in Chongqing was calculated using Eqs. (4) and (5). The calculation results indicate that PE in Chongqing was 687 (range: 119–40 576), 748 (range: 136–50 987) and 505 (range: 20–25 273) persons mg/m^3 in 2004 (annual average), January 2005, and July 2005, respectively, and PWE 211 (range: 95–358), 229 (range: 110–472) and 155 (range: 16–256) μg/m^3, respectively.

The geographical distribution of daily exposures for year 2004 was illustrated in Fig. 4. As shown in Fig. 4(a), west and middle-north parts of Chongqing had the highest daily exposures in 2004 due to both high population density and high PM_{10} level. Regarding PWE, the geographical distribution was quite similar to the ambient PM_{10} concentration (Fig. 4(b)). The average PWE levels were very high in Chongqing. The areas with a PWE over 150 μg/m^3 accounted for 98.9% of the study area, while 5.6% of the area had PWE values above 250 μg/m^3. Yubei and Ba'nan districts in the city zone, Changshou, Fuling, Nanchuan, Qijiang, and Wansheng counties around the city zone, Tongnan County in the west, Pengshui County in the southeast, and Kaixian and Fengjie counties in the northeast had the highest PWE, and thereby the highest health risk. Jiangbei, Yuzhong, and Nan'an districts in the city zone, and Rongchang in the west, Wuxi and Chengkou counties in the northeast had the medium health risk. Other areas were of relatively low PWE. The seasonal variation was strong. High health risk zones covered much larger area in winter (i.e. January 2005) than in summer (July 2005). The areas with a PWE over 150 μg/m^3 and 250 μg/m^3 in winter accounted for 98.0% and 18.9% of the study area, respectively, while 71.5% and 0.0% in summer. In winter, the distribution pattern of PWE was quite similar with that in

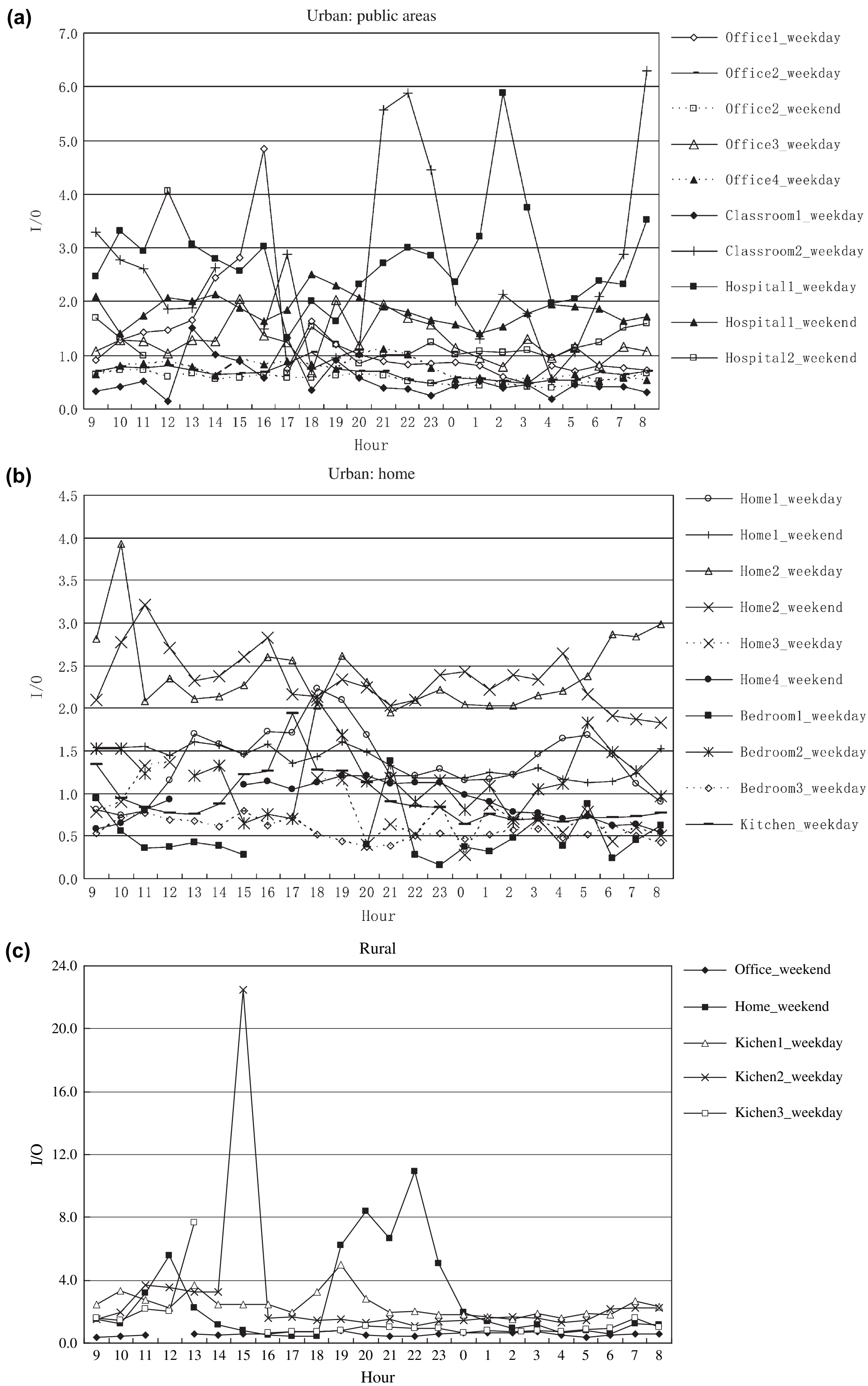

Fig. 3. Diurnal changes of PM_{10} indoor/outdoor ratios for various indoor MEs.

Table 3
IO ratios for exposure estimates

MEs	Kitchen		Bedroom		Living area		Office		Other indoors		Transits[a]	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Urban	1.58	1.68	0.89	0.41	1.39	0.74	1.45	0.92	1.21	0.39	2.50	–
Rural	4.49	9.79	1.70	1.00	2.96	2.99	1.01	0.23	1.21	0.39	1.00	–

[a] Estimated from measurement results in Beijing.

the whole year, while the areas with high PWE in summer were found mainly in the northeast part of Chongqing, such as Wuxi, Wushan, Fengjie, and Kaixian counties. The most urbanized areas such as Jiangbei and Yuzhong districts in the city zone did not have such a high PWE, meaning they were less polluted in summer.

Regarding the age, PWEs for different age subgroups were all above 150 $\mu g/m^3$ (annual average). Among all the age subgroups, the PWE for the elderly was the highest (the PWE for the elderly in winter even exceeded 250 $\mu g/m^3$), followed by adults and then the youth, mainly due to that elderly people tend to spend more time in indoors (kitchen and living area) where relatively high PM_{10} levels prevail, especially in rural areas.

To abate the potential population exposure of indoor air pollution, switching to clean fuels is recommended, for example, substitution of coal or biomass with natural gas or electricity as cooking fuel in the countryside. We made a rough assessment of the benefits from this abatement measure by reevaluating the PM_{10} exposure in rural areas applying the same IO ratios for rural areas as that in the city zone. That is, all solid fuels in rural would be replaced with clean fuels, for example, natural gas or electricity. Although the outdoor particulate level might be subsequently affected by the implementation of this measure, we believed the effect was small and thus could be negligible. The estimated results are shown in Fig. 5. After fuel replacement, PWE for the whole population in 2004 is estimated to decrease by 36% to 57–213 $\mu g/m^3$, and the areas with PWE over 150 $\mu g/m^3$ would cover only 12.3% of the whole study region. The exposure levels in most rural areas are estimated to have large reductions, resulting in the city zone and Changshou, Fuling, Nanchuan, Qijiang, and Wansheng counties becoming the highest health risk zones.

4. Discussion

4.1. Model implications

The human exposure model, which integrates the demographic data, time activity patterns, and both outdoor and indoor PM levels into GIS at city scale, was applied to Chongqing and indicated the large impacts of indoor air pollution on exposure assessment, as well as great applicability of GIS on municipal air pollution control management.

Human exposure would be underestimated if high levels of indoor air pollution were not considered in this study. In 2004, the average ambient PM_{10} for the whole city was 120 $\mu g/m^3$, only about 57% of the estimated exposure in this study (211 $\mu g/m^3$). The ratio of average ambient PM_{10} to estimated exposure was 55% and 58% for January and July 2005, respectively, showing no significant difference between winter and summer. To further explore the ‘‘indoor’’ significance on

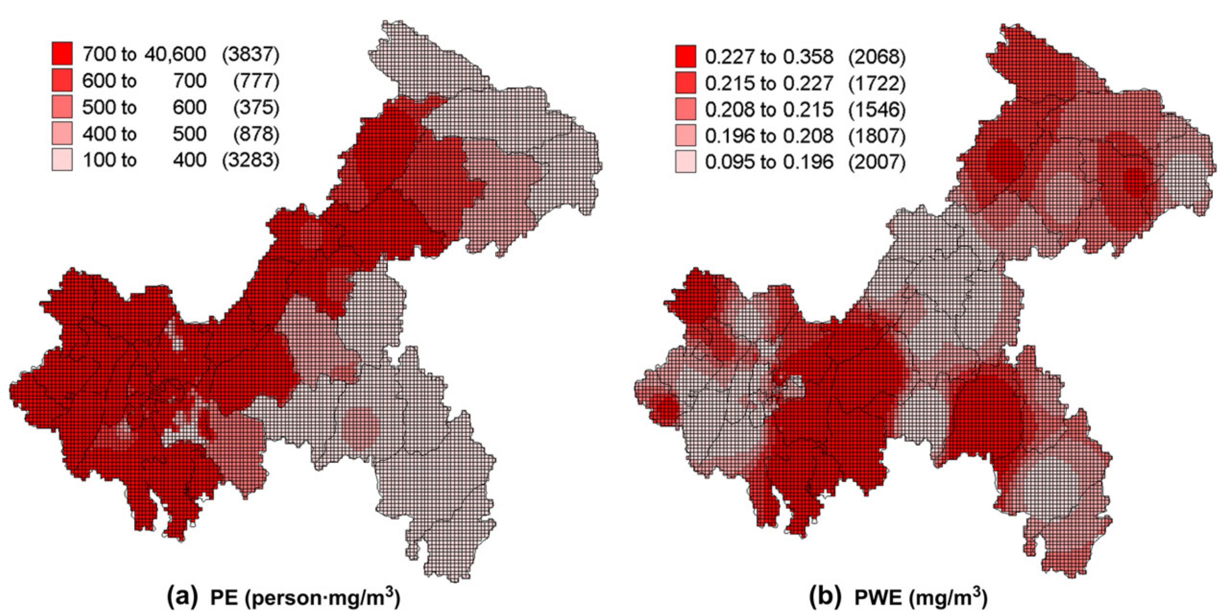

Fig. 4. Geographical distribution of daily personal exposure (PE) and population weighted exposure (PWE) of PM_{10} in Chongqing 2004. The exposure is estimated based on indoor and outdoor pollution levels and time activity patterns for the different groups. Figures in brackets represent the number of grid cells.

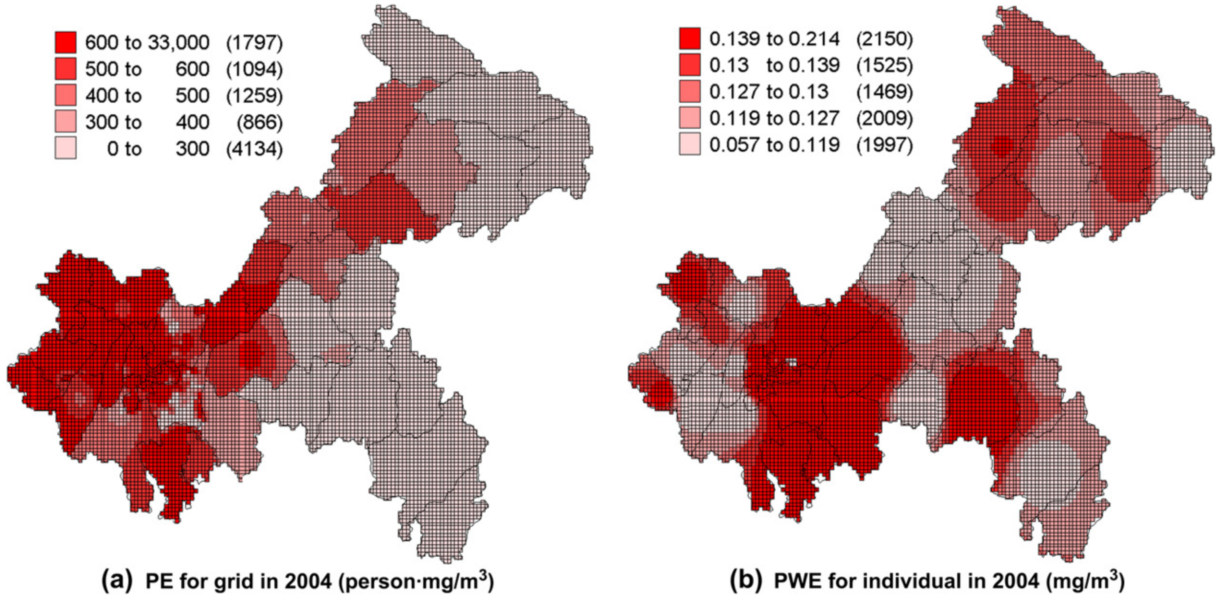

Fig. 5. Geographical distribution of daily personal exposure (PE) and population weighted exposure (PWE) of PM_{10} in Chongqing when all the solid fuels in rural are replaced with clean fuels. Figures in brackets represent the number of grid cells.

PWE, contributions of different microenvironments to PWE were analyzed and shown in Fig. 6. It is evident that indoor PM_{10} contributed most to PWE among all the population subgroups, especially for the rural areas, while outdoor PM_{10} contributed only 7−11%, demonstrating the importance of the indoor pollution sources. Coal combustion coupled with poor ventilation in rural areas can be considered a serious health risk factor for the residents.

Geographical information systems (GISs) are powerful tools for exposure assessment and have been widely used to support both air pollution epidemiology and air quality management policy. Jensen (1998) mapped human exposure to traffic air pollution in Denmark with ArcView in order to improve assessment of health impacts and support risk management. Kousa et al. (2002) applied MapInfo to evaluate the population exposure to NO_2 in Helsinki (Finland) by combining the predicted concentrations, information on people's activities and location of the population. In this study, digital maps of Chongqing were also used for grid modeling of human exposure at city scale. The GIS approach and the resulting maps obtained can be used as an efficient tool for planning various air pollution control strategies and air quality management for Chongqing, such as the delineation of control areas, the siting of development projects and transport routes, and selection of monitoring sites.

Although direct monitoring method has been applied to evaluate personal exposures in developed countries (Rojas-Bracho et al., 2000), the indirect model developed in

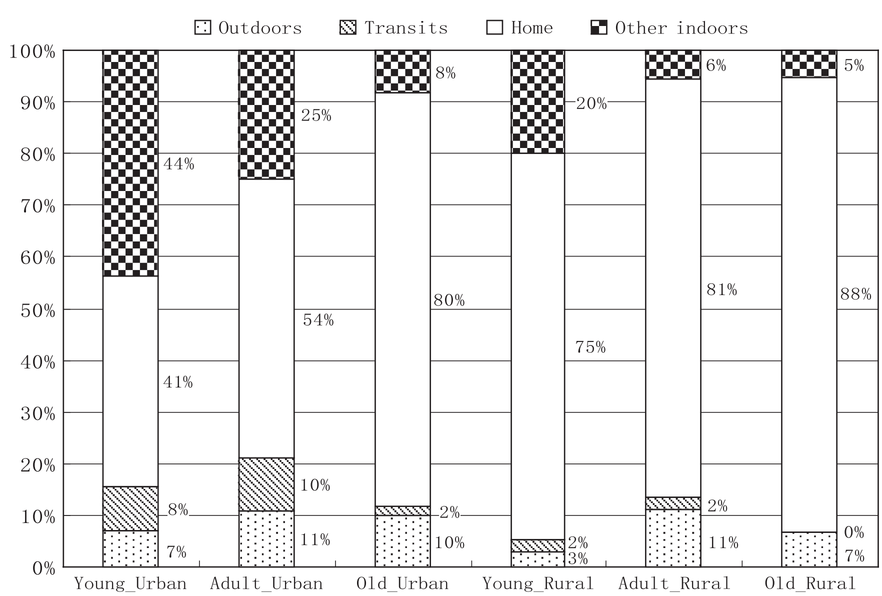

Fig. 6. Contributions of microenvironments to PWE for different demographic groups.

this study are still very useful for human exposure estimation and decision making for air pollution control at city scale, especially for those developing cities with limited data available. Besides Chongqing, there are also human exposure results reported from other regions in China. A study in Hong Kong applied indirect method and found the average personal exposures for different demographic groups ranged from 114 $\mu g/m^3$ to 130 $\mu g/m^3$ (Chau et al., 2002). This range is far lower than our modeling estimates in Chongqing. In poor rural areas, however, particulate pollution is aggravated due to the use of coal and biomass as cooking and heating fuels. Pan et al. (2001) carried out a study in rural Anqing, Anhui province, and found the mean personal exposure of PM_{10} was above 500 $\mu g/m^3$ while outdoor concentration was lower than 300 $\mu g/m^3$, which is consistent with the results in this study.

4.2. Limitations

Though indoor pollution contributed considerably to the human exposure in Chongqing, the correlation between the ambient and PWE for different districts/counties was rather significant ($R^2 = 0.616$; $p < 0.01$). The main reason is that due to limited data from field measurements and questionnaire investigation, uniform IO and time activity pattern for each microenvironment were applied in the PWE calculation at grid levels without considering the sub-region difference, and thus the percentage of non-agriculture population in each district/county became the key factor causing the differences between the ambient level and PWE. It is thus implied that field indoor measurements especially in countryside with different pollution status, as well as time budget investigation, need to be studied further in the future to correctly assess the contribution of the agricultural sector to PWE.

Regarding the relationship between indoor and outdoor pollutions, some studies implied that simple empirically determined coefficients can be utilized to estimate indoor particulate concentrations from the corresponding ambient pollution levels, since moderate to high correlation between indoor and outdoor PM concentrations was found (Adgate et al., 2002; Tsai et al., 2000). In this study, both indoor and outdoor measurements were taken to estimate the IO ratios in the study region. However, the IO ratio can be influenced by meteorological conditions such as temperature, humidity, and solar irradiation (Chan, 2002), which were not considered in our study. Furthermore, smoking was hardly controlled at home during the field tests, which might increase the uncertainty of results given that smoking is prevalent in both urban and rural areas.

To gather information on time activity pattern, several methods including focus groups, surveys, questionnaires and interviews, diaries and personal data loggers, direct observations, and videography can be used (Freeman and de Tejada, 2002). Questionnaire/interview method has been carried out to investigate the time activity patterns of different demographic subgroups in some other Chinese areas (Pan et al., 2001; Chau et al., 2002; Wu et al., 2003). The results of these studies were very similar to what we found in Chongqing (see Table 4). In our time activity patterns investigation, questionnaires were sent out through families. Only 2% of the total valid cases were obtained from the elderly, while the elderly account for 8% of total population in Chongqing. This implies some uncertainty in evaluating the time activity patterns for the elderly people. Seasonal factor, which might influence the time activity patterns (Leech et al., 2002), was also neglected in the study. However, given that Chongqing is located at the subtropical area close to Yangze River, we assume that the error of this assumption is not very large.

Table 4
Percentage of time spent at various MEs

Locations/MEs	Indoor at home (%)	Other indoors (%)	Transits (%)	Outdoors (%)
Rural Anqing	53	29	4	14
Rural Chongqing	63	17	4	16
Urban Beijing	44	42	3	11
Urban Hong Kong	58	31	7	4
Urban Chongqing	57	27	5	11

4.3. Future work

In this study, indoor air pollution contributed most to the human exposure in the countryside, and the simple scenario analysis of fuel switching suggested a significant health benefit *by* decreasing indoor air pollution levels in rural areas. However, this analysis represents an ideal situation and may encounter considerable hindrance when carrying into execution, for example, construction of natural gas and electrification network, and possible high economic costs. Low to medium cost measures such as development and dissemination of improved stoves, and switching to coal briquettes and washed coal might be more available in short term. In general, the political awareness about indoor air pollution and its broader societal impacts is still low, and rural household are switching to cleaner fuels at rather low rate. Therefore, more efforts should be made to (1) identify most viable options for clean renewable rural energy, their feasibility, and the associated costs; (2) estimate potential exposure reduction associated with the identified most viable options; (3) estimate health benefits from implementation of options according to the reduced population weighted exposure, exposure–response functions for health effects, and unit costs; (4) estimate the impacts on CO_2 emissions from a transition to clean biomass fuels; and (5) estimate cost-benefit ratios for options taking into account the different cost and benefit elements.

5. Conclusion

The human exposure model developed in this study indicated that indoor air pollution should be considered in epidemiology studies. The model can be transferred and applied in other cities with comparable exposure pressure in China and even other developing countries, while it would be necessary to consider the geographical difference and update local information and data in the model. To improve the modeling results in city scale, more surveys on microenvironment pollution level as well as time budget of different sub-regions are strongly suggested.

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