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Evaluating population exposure to N, N-dimethylformamide in a small industrial area accounting for population movement*

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Abstract: Population exposure to pollutants is important for studies on the exposure-response relationship. However, it is difficult to evaluate population exposure to non-conventional pollutants due to limited data on concentration levels and the movement patterns of inhabitants. In this study, an air dispersion model was used to simulate N, N-dimethylformamide (DMF) concentrations, as a proxy to monitoring concentrations. A total of 1289 randomly selected household representatives were surveyed to obtain information on movement characteristics. Subsequently, population movement patterns were combined with DMF concentration levels on maps of 100 m×100 m resolution to calculate population exposure. During 2008, the estimated population exposure to DMF ranged from 0.002 to 0.64 mg/m^3. The highest level of population exposure to DMF was found in the north and northwest sub-districts of the study area, ranging from 0.42 to 0.64 mg/m^3. The population exposure to DMF for different occupational groups indicated that retired people and farmers were vulnerable subpopulations among people highly exposed to DMF. This was mainly because they spent most time at home where the DMF concentration was high. As pollutant concentrations were divided into small grids, we found that exposure levels were substantially impacted by population movement characteristics.

Key words: Volatile organic compound, Dispersion model, Concentration distribution, Movement characteristics, Longwan
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1 Introduction

Population exposure to pollutants is an important component of epidemiological studies on the exposure-response relationship between pollutant exposure and health effects (Gilliland *et al.*, 2005; Needham *et al.*, 2005; Nieuwenhuijsen *et al.*, 2006; Choi *et al.*, 2008; Özkaynak *et al.*, 2008). Population exposure has been defined as ‘the event when a person comes into contact with a pollutant of a certain concentration during a certain period of time’ (Ott, 1982). It can be evaluated by combining information on pollutant concentration levels with population movement characteristics (i.e., the time spent on specified activities within relevant population groups) in the study area (Wang *et al.*, 2008; Delgado-Saborit *et al.*, 2009). Research has shown that pollutant concentrations obtained from widely distributed monitoring stations indicate different ambient air quality levels in urban area districts (Gehrig and Buchmann, 2003). As a result, monitored pollutant concentrations have been used to evaluate population exposure levels of entire urban areas (Burke *et al.*, 2001; Zeger *et al.*,

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2008; McCarthy *et al.*, 2009; Guay *et al.*, 2011). This method is suitable for conventional pollutants such as SO_2, NO_x, and PM_{10}, due to the wide distribution of monitoring stations. Furthermore, monitoring data collected on a daily basis across many years could be used for population exposure evaluation.

However, such monitoring stations do not usually monitor non-conventional pollutants, such as N, N-dimethylformamide (DMF) (CEPA, 1999). Therefore, data for non-conventional pollutants may be obtained only through temporary monitoring programs (Wei *et al.*, 2011). Recent research has shown that pollutant concentrations may vary greatly with respect to location and time (i.e., of day or year), even within the same urban area (Corburn, 2007). Pollutants emitted from industrial plants tend to disperse and consequently influence locations in close proximity to the emission source (Polidori *et al.*, 2010). The evaluation of population exposure using monitoring data obtained over the course of a few days may result in larger uncertainty in exposure levels due to the variability in pollutant concentrations in small areas.

Population movement characteristics are also an important consideration when evaluating exposure levels (Klepeis *et al.*, 2001). Because the timing of human activities may have a significant impact, some studies have evaluated population exposure levels based on the movement characteristics of the local population (Williams *et al.*, 2000). However, in these studies, variation in the concentration levels of pollutants was not taken into account. Several recent studies have calculated population exposure based on variation in both movement characteristics and pollutant concentrations, to obtain a more accurate indication of exposure levels. For example, Kousa *et al.* (2002) adopted the EXPAND model (exposure to air pollution, especially to nitrogen dioxide and particulate matter) to evaluate average population exposure to NO_2 levels in different micro-environments. Beckx *et al.* (2009) found differences between static and dynamic exposures after developing an activity-based population modeling approach to calculate population exposure to particulate matter. However, the focus of these studies was on conventional pollutants and persistent organic pollutants.

In the present study, we developed a method to evaluate population exposure to a non-conventional pollutant in a small industrial area. The Longwan district of Wenzhou city in China that represents a typical highly-concentrated synthetic leather industry region was selected as the case study area. Previous studies have indicated a range of negative health effects that are associated with exposure to DMF, particularly liver disease and cancer (Chivers, 1978; Levin *et al.*, 1987; Chen *et al.*, 1988; Fail *et al.*, 1998; Wrbitzky, 1999; Long and Meek, 2001; Chang *et al.*, 2004; Senoh *et al.*, 2004). An AMS/EPA Regulatory Model (AERMOD) was adopted to simulate the distribution of pollutant concentrations. As data on the activity of residents did not exist, we investigated the movement characteristics of 1289 randomly selected household representatives in the study area. We subsequently combined the two datasets to calculate the temporal and spatial distributions of population exposure to DMF with a resolution of 100 m×100 m in the Longwan case study area.

2 Methodology

2.1 Study area

The Longwan district is located in Wenzhou city on the Yangtze River delta in eastern China, along the south coast of the East China Sea (Fig. 1). The Longwan district covers an area of 279 km^2 and has a population of 306 000, making it one of the three major urban areas of Wenzhou city. The climate of Longwan is subtropical maritime and humid. The Longwan synthetic leather industrial zone covers 1.13 km^2. It is the largest synthetic leather product zone worldwide, producing about 70% of China's synthetic

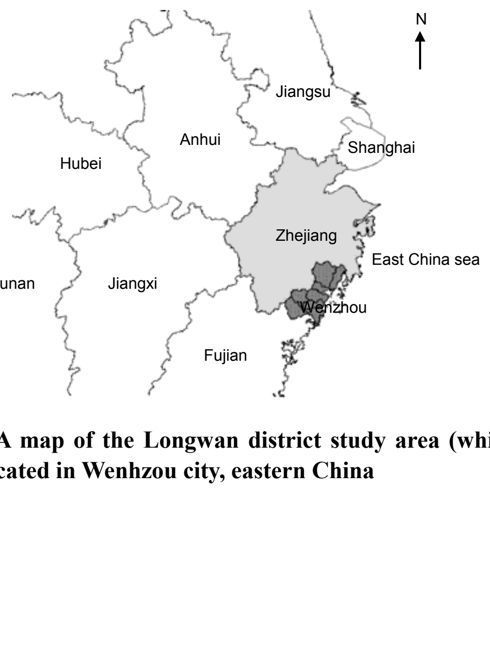

Fig. 1 A map of the Longwan district study area (white star), located in Wenhzou city, eastern China

leather goods and about 50% worldwide. The manufacture of synthetic leather in the study area began in 1986; hence, residents of the Longwan district have been exposed to DMF pollution for more than 20 years.

2.2 DMF concentration distribution

The study area was divided into 10 000 grid cells at a resolution of 100 m×100 m based on topographic data. The AERMOD was used to simulate the temporal and spatial distribution concentrations of DMF (Wei *et al.*, 2011). Basic input parameters of AERMOD include source location and parameter data, receptor locations, and meteorological data.

DMF emissions were divided into point or area sources. We considered point sources to be organized sources (i.e., emissions from chimney stacks ≤15 m), while emissions from factory workshops were considered to be area sources. The latitude and longitude of each point source were measured using a handheld global positioning system (GPS). The DMF emission rate was calculated by dividing the running time of 54 control factory facilities against DMF emissions. DMF emissions were estimated based on the mass balance of the manufacturing process according to the total DMF consumption (Wei *et al.*, 2011). Other information on each point source, such as chimney height and diameter, as well as emission exit velocity and exit temperature, was compiled during the investigation. For area sources, the latitude and longitude of the four corners of each workshop in all 54 factories were measured using a handheld GPS. The orientation angles of the rectangular area sources in degrees from north were calculated. Emissions were distributed with respect to the wet and dry production lines of each workshop and the emission rate was calculated by dividing the running time against DMF emissions. Other information on each area source, such as the length and width of each workshop, was compiled during the investigation.

The Fifth-Generation NCAR/Penn State Mesoscale Model (MM5) was used to simulate the meteorological data of the corresponding grids according to the latitude and longitude of the Longwan district (Isakov *et al.*, 2007). The simulated data of the meteorological parameters closely resembled that of the monitored data (Wei *et al.*, 2011). Other parameters, such as TOXICS (option to use air toxics options), HALFLIFE (optional half life used for exponential decay) and parameters required for dry and wet DMF deposition calculations, were also established.

2.3 DMF ambient concentration monitoring

To validate DMF simulated concentrations from the dispersion model, seven monitoring stations representing different urban communities within the study area were characterized. The monitoring sites were located in industrial (Stations 2, 3, 7), residential (Stations 1, 4) and commercial zones (Station 6), as well as along major roads (Station 5) (Fig. 2). We obtained information from the Wenzhou Environment Monitoring Center, which recorded DMF concentrations according to the national monitoring standard (MEP-GAQSIO, 2008). At each monitoring site, samples were collected hourly from 10:00 until 13:00, from March 28–29 and from July 9–10, 2007. This gave a total of 112 monitoring point results from these four days (i.e., 7 stations×4 h×4 d per station). The relative errors (REs) between the monitored and simulated DMF concentrations were evaluated using the following formula:

$$\mathrm{RE}=\frac{|C-C_0|}{C}\times 100\%, \tag{1}$$

where C and C_0 represent the monitored and simulated DMF concentrations, respectively.

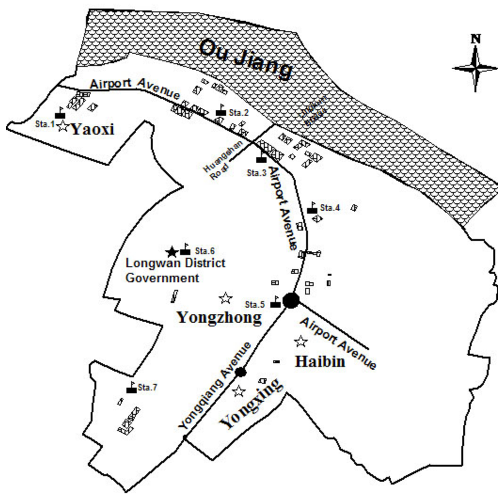

Fig. 2 A map of the four sub-districts (white stars), the industrial plants (indicated by rectangles) and the seven monitoring stations in the study area

2.4 Population distribution

Based on the simulated annual average DMF concentration of 2008, the primary area of DMF exposure was found to encompass four sub-districts (towns) within the Longwan district, including Yongzhong, Yongxing, Haibin and Yaoxi (Fig. 2). The total population of each of these sub-districts is 67265, 31771, 24417 and 29493, respectively. The total number of households in each of the four districts is 19981, 7991, 6471 and 8225, respectively. Statistical information on the sex, age range and jobs of household representatives of the resident population of each sub-district was assimilated (Longwan Municipal Statistics Yearbook, 2006). To obtain a GIS (geographic information system)-based population distribution of the study area, coordinates of each village center within the sub-districts were measured using a handheld GPS. According to the area and coordinates of each village, the grids (100 m×100 m) where each village was located were identified. Based on the investigation, homes were relatively evenly distributed in each village. Thus, the population was evenly divided into corresponding grids according to the location of the village where they lived.

2.5 Movement characteristics

In everyday life, people often move around and as a result are exposed to different levels of air pollutants in different places (i.e., micro-environments). Based on the living habits of residents, four micro-environment categories were selected, including residence (i.e., home), traveling to/from occupation, site of occupation (e.g., office, workshop, school), and other (e.g., entertainment places).

To investigate the movement characteristics of people in 2008 in the study area, an on-site questionnaire was conducted from May to August 2009. Inhabitants living in their current residence for at least five years were included. People from 1289 households were interviewed in the Longwan area, representing 3% of all households in the study area (Mao, 2005).

According to the previous simulated DMF annual average concentration distribution, Yongzhong and Yongxing were on a lower DMF concentration level while Haibin and Yaoxi were on a higher DMF concentration level. Therefore, more households were investigated in Haibin and Yaoxi, in order to obtain detailed movement characteristics of people who live in the higher DMF concentration level areas. All respondents were interviewed using a standardized questionnaire that requested basic individual information (i.e., age, sex, occupation, home address, work location, etc.), residential history and work history. Respondents were asked to recall daily activities to record movement characteristic information. This included the average number of trips each day, travel time of each trip, trip mode, trip purpose, destination and time spent in each micro-environment category. Occupations were divided into worker, farmer, student, teacher, staff, self-employed worker, unemployed, house worker, retired and other. Occupational workers at the synthetic leather factories were excluded because our study focused on DMF exposure in the environment not in the workplace.

A total of 1289 people were surveyed. The numbers of questionnaires completed by representatives of households in the Yongzhong, Yongxing, Haibin and Yaoxi sub-districts were 276, 124, 350 and 443, respectively. Another 96 questionnaires which were completed by people who work in the study area but who live outside it were eliminated.

2.6 Population exposure evaluation

Individual exposure to the pollutant was calculated by multiplying the pollutant concentration by the residence time in each micro-environment. Based on our surveys, people of the same occupation were found to have similar movement characteristics. They spent similar times at home and in the workplace. The locations of their workplaces were also centralized or distributed regularly. Hence, population exposure was primarily calculated with respect to occupation categories. This method could also be used for exposure calculation based on other categories such as age or sex. Population exposure was calculated as follows, with Eq. (2) being based on an equation from Loh *et al.* (2007):

$$E_j = \left(\sum_{i=1}^{n} (C_{ij} \times t_{ij}) \right) / T, \tag{2}$$

$$E_m = \sum_{j=1}^{n} (E_j \times \eta_j), \tag{3}$$

where E is the population exposure to DMF (mg/m^3); C is the DMF concentration of the micro-environment (mg/m^3); t is the time spent in the micro-environment (h); T is the total amount of exposure time (h); η is the population weighted by occupation category (%); i is the micro-environment classification, j is the occupation category, i, j=1, 2,…, n; and m is the grid.

In the absence of data for indoor DMF monitoring concentrations, we assumed that the DMF concentrations indoors (i.e., home, office, workshop, school) were the same as those outdoors. We used the average DMF concentration of the total area as the DMF concentration of the micro-environment for traveling to/from their occupations. As we obtained the detailed addresses of the workplaces of the respondents, the workplaces were assigned to their corresponding grids on maps of 100 m×100 m resolution. The DMF concentration of the micro-environment was adopted from the average DMF simulated concentration of the corresponding grids where the micro-environment was located. So, the population exposure was weighted mainly by their time at home and in the workplace.

3 Results and discussion

3.1 Comparison of simulated and monitored DMF concentrations

The results of simulated and monitored DMF concentrations at each monitoring station on March 28–29 and on July 9–10, 2007, are shown in Figs. 3 and 4. Overall, the RE of simulated versus monitored data for seven stations was below 50% for 64 of the survey hours, accounting for 57% of the total monitoring points. An RE exceeding 200% was recorded for 8 of the survey hours, accounting for 7% of the total monitoring points. In total, 93% of the REs of simulated versus monitored data were within the range of 0.48%–189.4%. To evaluate the air pollutant dispersion modeling results, it was important that the variation of the simulated data closely matched that of the monitored data. Figs. 3 and 4 clearly show that the simulated concentrations of all seven monitored stations produced results that were similar to those of monitored concentrations and could be used for population exposure assessment.

As shown in Fig. 4, the ratio of DMF concentrations of simulated and monitored data distribute

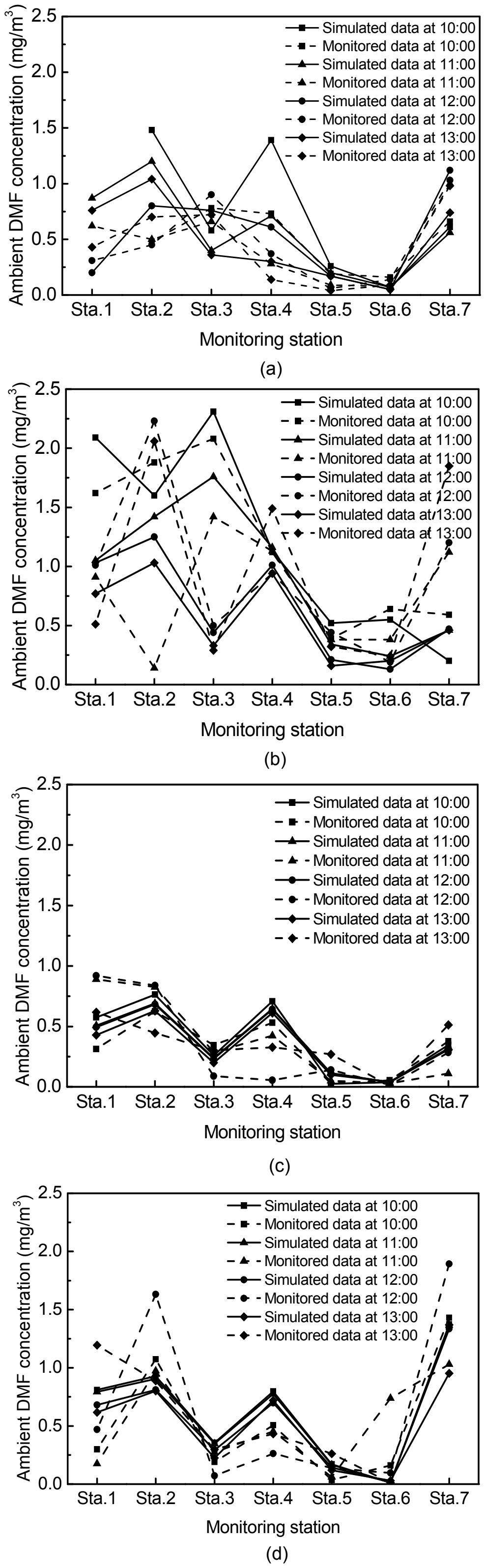

Fig. 3 Ambient DMF concentrations of simulated and monitored data from 10:00–13:00 on (a) March 28, 2007, (b) March 29, 2007, (c) July 9, 2007, and (d) July 10, 2007

near two sides of $y=x$ axle. The simulation data is accurate and reliable, which can be used in the future prediction.

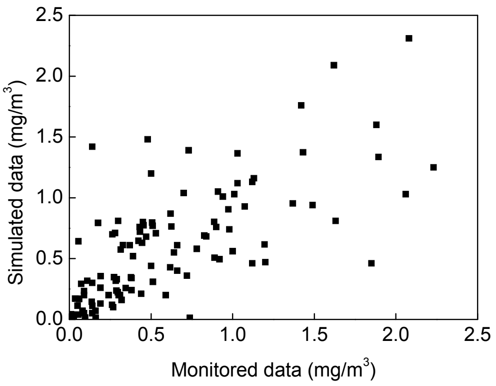

Fig. 4 Scatter plot of simulated and monitored data for each monitoring station
The monitored DMF concentration at Station 1 at 10:00 on March 28, 2007 was missed due to a device malfunction

3.2 Annual average and daily concentrations of DMF

During 2008, the annual average distribution of DMF concentration ranged from 0.006 to 1.6 mg/m^3 (Fig. 5a). DMF concentration categories of 0–0.2, 0.2–0.4 and 0.4–1.6 mg/m^3 (high concentration level) accounted for 92.47%, 4.97% and 1.94%, respectively, of the total grid area. The grids with the highest DMF concentrations (those marked dark blue) corresponded to the locations of the synthetic leather factories, accounting for 0.62% of total grid area. Fig. 5a also shows that high DMF concentrations were distributed in the vicinity of the synthetic leather factories, decreasing from the center of emission sources. The study indicated three high DMF concentration regions in the study area (Fig. 5a, sites A, B and C), in which the annual average DMF concentrations were (1.58±0.02), (1.09±0.03) and (1.51±0.04) mg/m^3, respectively. The DMF concentrations of these three sites in different months were within the ranges of 0.19–2.60, 0.15–0.69 and 0.63–2.24 mg/m^3, respectively (Fig. 5b). Fig. 5b also shows a higher DMF concentration in March, April and September, and a lower DMF concentration in January and February.

There were 26 factories within a 900 m radius of site A, which is located in the synthetic leather factory zone. Within a 900 m radius of sites B and C, there were seven and four synthetic leather factories, respectively. The DMF concentrations of these three sites appeared to be a direct result of the emission from the synthetic leather factories. At sites A and B, the highest daily DMF concentration was on September 1, while at site C it was on April 1. The lowest DMF daily concentration at each of the three sites was on February 2, February 6 and April 20, respectively. This variation in the concentration level depended primarily on individual factory production rates and ambient weather conditions in the study area. For example, March, April, September and October usually comprise the peak seasons of production, while February, May, June and July are the low seasons. Hence, DMF emissions were impacted by the factory production rates during these months. The low daily DMF concentration recorded at site C on April 20 may have been due to weather conditions, such as strong wind.

3.3 GIS-based population distribution

The population of the study area was divided into four levels, with categories of 0–40, 40–90, 90–140 and 140–500 persons/grid, respectively (Fig. 6). The population was unevenly distributed across the entire study region with a higher population in Yongzhong and Yongxing. In total, there were 203 grids where the population exceeded 140 persons/grid.

When the population distribution parameters were integrated with the annual average DMF concentration levels, it was found that most people in the study area did not live in the highest concentration areas. On the other hand, high population densities (exceeding 90 persons/grid) occurred in regions of low DMF pollution (below 0.2 mg/m^3).

3.4 Movement characteristics

People's ages ranged from 7–88. The age range of the study population was divided into five categories (0–10, 11–20, 21–30, 31–60, and over 60 years old) and each category accounted for 3%, 22%, 21%, 47% and 7% respectively, of total population (Table 1).

A total of 365 self-employed workers completed the questionnaire, accounting for 31% of the survey participants. Students accounted for 22% and workers for 19% of participants. The least surveyed groups comprised teachers and retired, with 2% and 3% of participants, respectively (Table 2) (p.801).

The mean period of time spent daily in each micro-environment by people in different

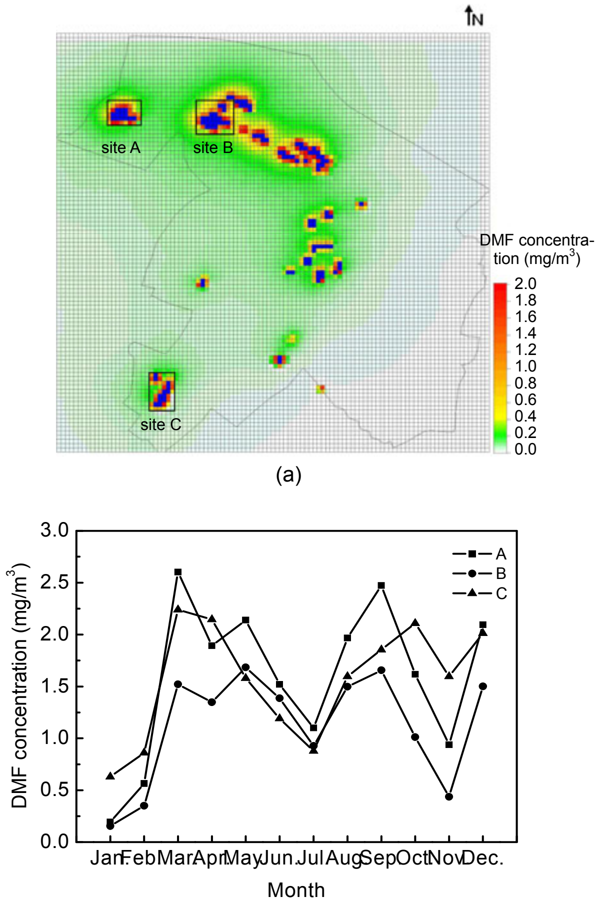

Fig. 5 (a) The 2008 annual average DMF concentration (mg/m^3) at a resolution of 100 m×100 m in the Longwan district study area (dark blue grids show the locations of the synthetic leather factories with DMF concentrations >2.0 mg/m^3). The DMF concentration level is indicated by the key; (b) The DMF concentration in different months of 2008 at the three sites indicated as A, B and C in (a)

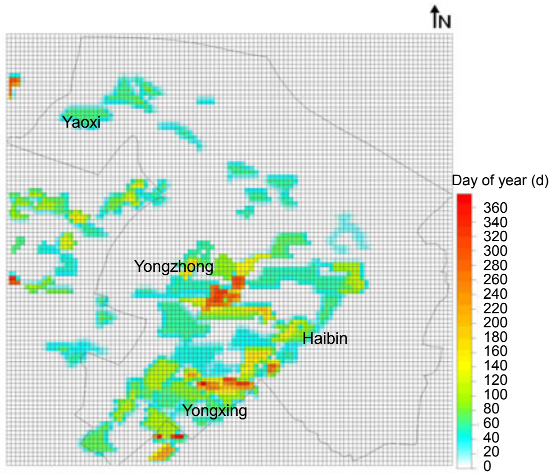

Fig. 6 The population distribution (152946) within the Longwan study area using GIS. The number of people per grid is indicated by the key

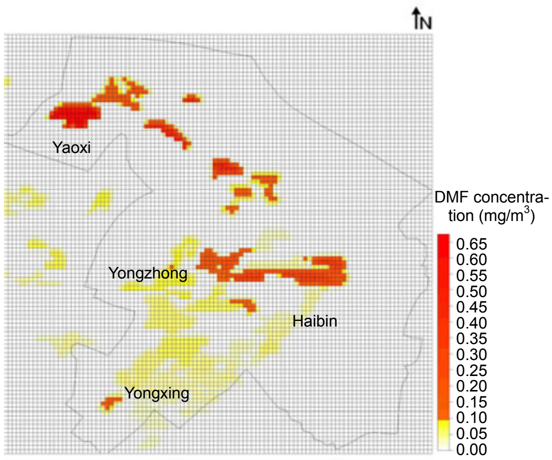

Fig. 8 The annual average population exposure to DMF concentrations in 2008 in the Longwan study area

Table 1 Age distribution of the survey household representatives in the Longwan study area

Sub-district	Population number (percentage)				
	0–10	11–20	21–30	31–60	>60
Yongzhong	12 (4%)	87 (32%)	62 (22%)	106 (38%)	9 (4%)
Yongxing	4 (4%)	65 (52%)	25 (20%)	30 (24%)	0 (0%)
Haibin	11 (4%)	77 (22%)	82 (23%)	159 (45%)	21 (6%)
Yaoxi	1 (0.2%)	34 (8%)	84 (19%)	269 (60%)	55 (12.8%)
Total	28 (3%)	263 (22%)	253 (21%)	564 (47%)	85 (7%)

occupational categories is shown in Fig. 7. Those under the 'house worker' category spent an average 21 h at home and 3 h doing other activities, such as shopping. Farmers usually worked on farmland in close proximity to their homes, hence these two categories were combined with an average of 20 h spent at home. Retired people spent time on outside activities such as socialising, playing chess or exercising in the nearby village, hence they spent an average of 4 h outside home. Students and teachers had similar movement characteristics. They spent an average of 9 h at school and about 13–14 h at home each day. Furthermore, due to the proximity of school to home,

Table 2 The occupation categories of the Longwan study area survey household representatives

Sub-district	Population number (percentage)									
	Worker	Farmer	Student	Teacher	Staff	Self-employed	Unemployed	House worker	Retired	Other occupation
Yongzhong	37 (13%)	3 (1%)	91 (33%)	7 (3%)	10 (4%)	94 (34%)	6 (2%)	14 (5%)	4 (1%)	10 (4%)
Yongxing	8 (6%)	1 (1%)	67 (54%)	1 (1%)	15 (12%)	28 (22%)	2 (2%)	1 (1%)	0 (0%)	1 (1%)
Haibin	69 (20%)	6 (2%)	84 (24%)	6 (2%)	4 (1%)	109 (30%)	9 (3%)	43 (12%)	10 (3%)	10 (3%)
Yaoxi	118 (27%)	31 (7%)	24 (5%)	4 (1%)	6 (1%)	134 (30%)	20 (5%)	53 (12%)	18 (4%)	35 (8%)
Total	232 (19%)	41 (3%)	266 (22%)	18 (2%)	35 (3%)	365 (31%)	37 (3%)	111 (9%)	32 (3%)	56 (5%)

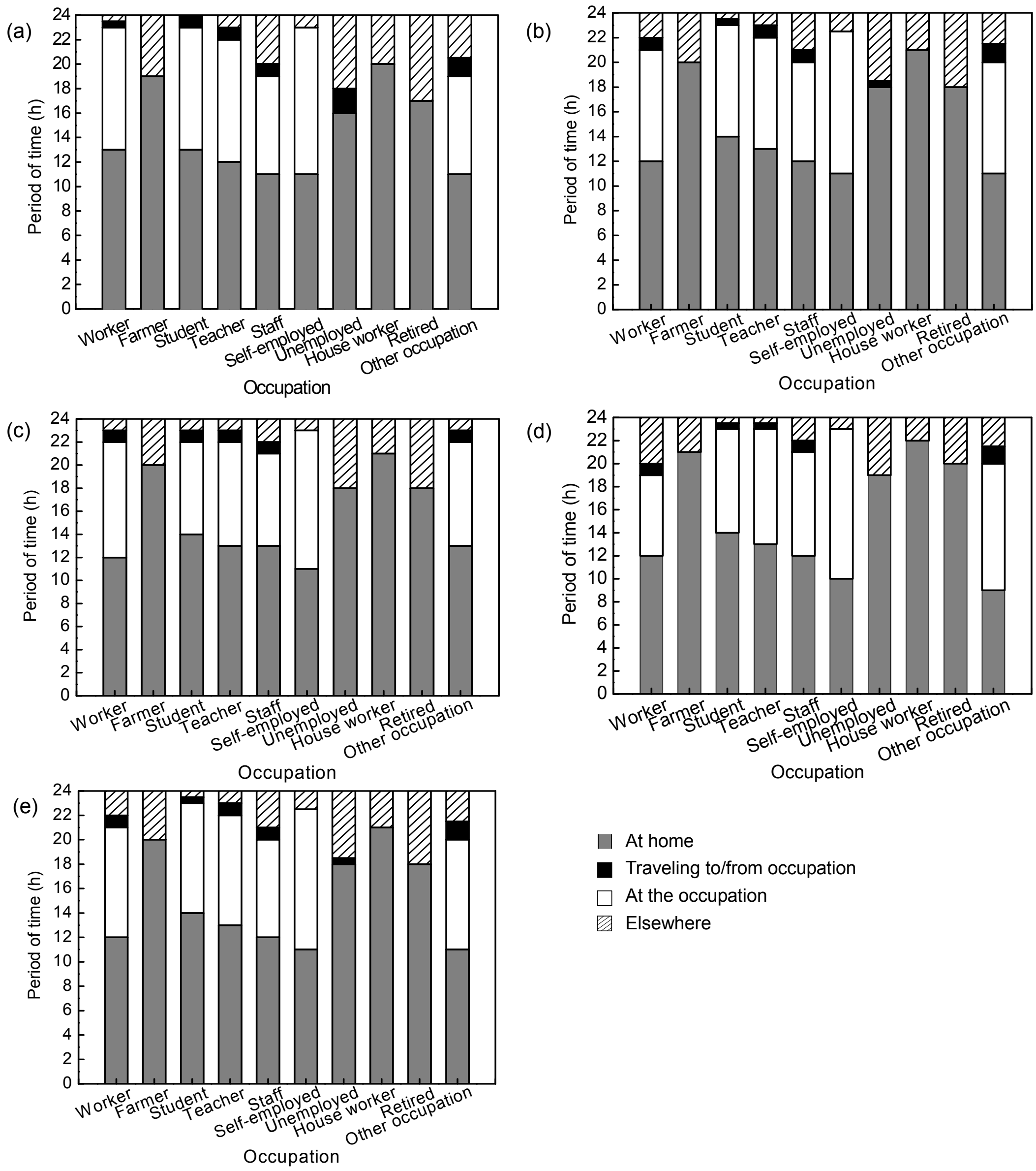

Fig. 7 The period of time spent each day in different micro-environments by the survey household representatives (1289 participants) in (a) Yongzhong, (b) Yongxing, (c) Haibin, (d) Yaoxi and (e) the total of all four sub-districts combined

about 0.5–1 h was spent on transit daily. For factory workers, about 7–11 h was spent at the workplace, and another 12 h was spent on resting, of which 2 h were spent on entertainment outside of the home. Self-employed workers were the largest group of the study. Most operated a shop close to their home or in the center of the sub-district. The shop opened for about 10–12 h and the self-employed workers remained at home at other times during the day.

3.5 Annual average and daily population exposure to DMF

The geographical distribution of annual average population exposure to DMF is illustrated in Fig. 8 (p.800). The calculated results indicate that the annual average population exposure to DMF in 2008 ranged from 0.002 to 0.64 mg/m^3. The average level of the annual population exposure in the study area was 0.09 mg/m^3. The population exposure was divided into two levels: relatively low exposure in which population exposure was below or equal to 0.09 mg/m^3 (yellow grids in Fig. 8), and relatively high exposure, in which population exposure was above 0.09 mg/m^3 (red grids in Fig. 8). In total, the relatively high population exposure covered 23% of the study area. According to the population distribution, 21% of the total population lived in this area. 79% of the total population lived in the relatively low exposure area. Due to higher DMF concentrations caused by synthetic leather emission sources, the highest population exposure to DMF was found in the northwest and north regions of the study area, with exposures of 0.64 and 0.42 mg/m^3, respectively. This differed from the spatial distribution of DMF concentrations, which indicated the presence of three high DMF concentration regions, including a site in the southwest.

The average population exposure in the four sub-districts of Yongzhong, Yongxing, Hanbin and Yaoxi were 0.05, 0.03, 0.09 and 0.19 mg/m^3, respectively. The distribution of daily population exposure to the pollutant in each of the four sub-districts in 2008 is shown in Fig. 9. The results indicate that population exposure exceeded 0.09 mg/m^3 for a total of 54, 26, 107 and 200 d of the year in the Yongzhong, Yongxing, Haibin and Yaoxi sub-districts, respectively.

3.6 Annual average population exposure to DMF by occupation category

The annual average population exposure to DMF of people in different occupations in 2008 ranged from 0.034 to 0.082 mg/m^3 (Fig. 10). The exposure of

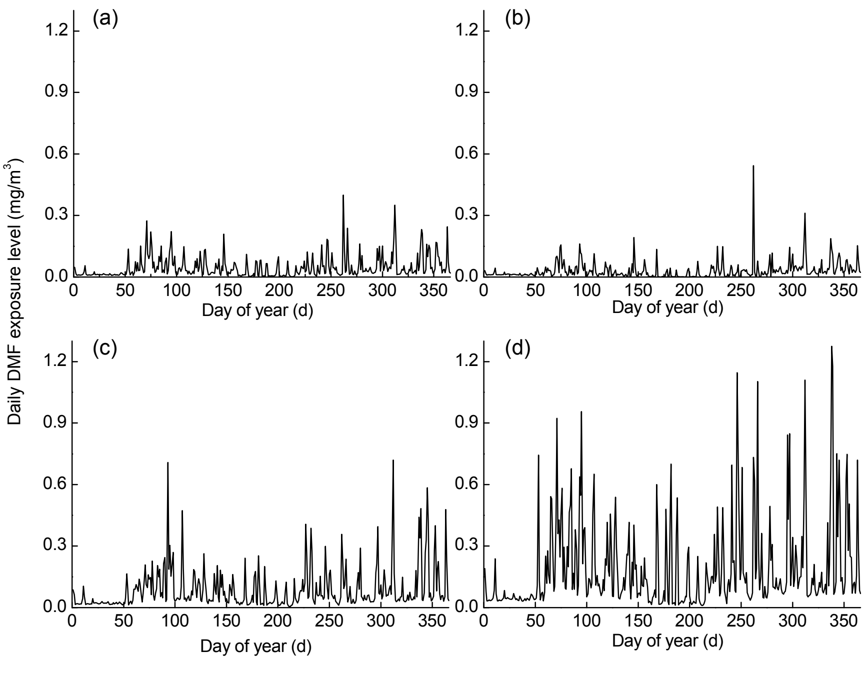

Fig. 9 The daily population exposure to DMF concentrations in each of the four Longwan sub-districts during 2008
(a) Yongzhong; (b) Yongxing; (c) Haibin; (d) Yaoxi

retired people was the highest, with an average level of 0.082 mg/m^3. Population exposure of farmers was the second highest (0.065 mg/m^3). Based on the investigation, retired people and farmers were distributed mainly in the sub-districts of Haibin and Yaoxi, which had higher DMF concentrations than the other two sub-districts. Furthermore, according to the movement characteristics of retired people and farmers, they spent over 18 h at home each day. Thus, the higher population exposure of these two categories is due mainly to the higher DMF concentrations in the micro-environment where they live. Population exposure of people in the unemployed, house worker, worker, other occupation, teacher and self-employed categories was between 0.042 and 0.064 mg/m^3. Students and staff had the lowest population exposure to DMF (0.034 mg/m^3).

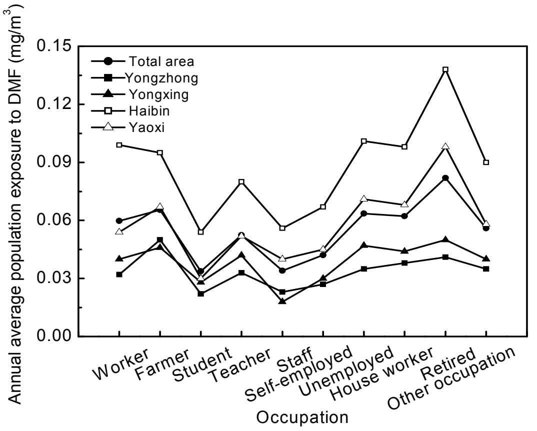

Fig. 10 Annual average population exposure to DMF in 2008 by occupation category

4 Conclusions

In this study, we developed a method to evaluate population exposure to a non-conventional pollutant in a small industrial area and account for the impact of population movement. We used the AERMOD to simulate the distribution of DMF concentrations, as a proxy for monitored concentrations, in order to evaluate population exposure levels. We investigated the movement characteristics of 1289 household representatives in the study area to obtain a human time-activity dataset. Based on the temporal and spatial distributions of the pollutant and human movement characteristics, population exposure to DMF at a resolution of 100 m×100 m was calculated. The simulated results showed that the annual average DMF concentrations in 2008 ranged between 0.006 and 1.6 mg/m^3. Annual concentrations of three high DMF emission regions in 2008 were 1.6 (north), 1.12 (northwest) and 1.56 mg/m^3 (southwest). The annual average DMF concentrations of 1.85% of the total Longwan study area exceeded high concentration levels (0.4 mg/m^3). The range of annual average population exposure to DMF in 2008 was from 0.002 to 0.64 mg/m^3. Interestingly, the regions of the highest population exposure to DMF were not identical to the regions of the highest DMF concentration. The highest population exposure to DMF was found in the north and northwest regions of the study area, where the population exposure was 0.64 and 0.42 mg/m^3, respectively. Therefore, due to high population exposure, health risks were also higher in these two regions. The annual average population exposure also indicated that there may be a higher health risk in Yaoxi and lower health risk in Yongzhong and Yongxing. The daily distribution of population exposure showed that Yaoxi had the highest health risk, while Haibin had a medium health risk and Yongzhong and Yongxing had the lowest health risk.

The annual average population exposure to DMF of different occupations in 2008 ranged from 0.034 to 0.082 mg/m^3. Retired people and farmers were vulnerable subpopulations exposed to a higher health risk and with the highest population exposures of 0.082 and 0.065 mg/m^3, respectively. The higher population exposures of these two categories were mainly because they spent most time at home where DMF concentration was high. Students and staff had the lowest population exposure to DMF (0.034 mg/m^3). Hence, the health risk to these people was the lowest of all.

Based on simulated DMF concentrations, without taking population movement characteristics into consideration, the study showed that the DMF concentration was higher than 0.2 mg/m^3 in 160 grids. When taking population movement characteristics into consideration, the DMF concentration was higher than 0.2 mg/m^3 in 151 grids. For 39% of all grids, the difference between DMF concentrations and population exposure was more than 50%. This is because pollutant concentration varied in different grids, while the exposure of people varied with respect to the micro-environment, based on their different activities during the course of the day. Therefore, there was a substantial impact of pollutant concentration and movement characteristics on the evaluation of population exposure. Hence, to improve the accuracy of population exposure evaluations, the inclusion of population movement characteristics is essential.

Our research has shown that simulated pollutant concentrations were correlated with those of monitored concentrations, and as such could be used as a substitute for population exposure evaluation. This method could also be applied to evaluate population exposure of a wide range of other pollutants. At present, research on the relationship between DMF exposure and health effects has been limited to occupational workers (Wang *et al.*, 2004). In such studies, DMF concentrations were monitored in the workshop, and the subsequent health effects such as liver disease and/or other symptoms were studied (Shieh *et al.*, 2007). However, the relationship between long-term DMF exposure and health effects in the non-occupational population requires consideration. Furthermore, the air quality standard for long-term exposure to DMF remains undesignated. The population exposure levels calculated in this study could be used to establish relationships between long-term human exposure to DMF and consequent health effects, as well as a basis for establishing ambient DMF air quality standards.

In our work, we did not monitor indoor DMF concentrations but assumed they were the same as outdoor concentrations. In fact, indoor levels of pollutant were different from outdoor levels and people spent most of their time indoors. This assumption would increase the uncertainty in population exposure assessment. Therefore, further research is needed on the relationship between indoor and outdoor concentrations of DMF to reflect more accurately actual population exposure.

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