ASSESSMENT OF 3D POPULATION DISTRIBUION UNDER TRAFFIC IMPACTS USING GIS AND FINE-RESOLUTION DTMs

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ABSTRACT: Pollution exhibits significant variations horizontally and vertically within cities; therefore, the size and three-dimension spatial distribution of population is a significant determinant of urban health. This paper presents a novel methodology, three-Dimensional dIgital Geography (3DIG) methodology, for investigating both horizontal and vertical distributions of population under traffic impacts. 3DIG integrates application of Geographic Information System (GIS) and fine-resolution Digital Terrain Models (DTM). 5 meter resolution DTMs were employed to obtain the building stories in residential areas of Taipei metropolis; the vertical distribution of population at different stories were obtained accordingly. In addition, the potentially affected populations at different floors within five specified buffer zones under traffic impacts were estimated with GIS. Field survey validation indicated model results were reliable and accurate. The results showed that 97.9% (6.4 million) of the Taipei population lives within 50 m and 0.8 million (12.3%) residents live on the first or second floor within 5 m from municipal roads. This study demonstrates that 3DIG is a versatile methodology capable of identifying potentially high-exposure population and useful for various researches and policy planning in which the three-dimensional spatial population distribution is the central focus.

1. INTRODUCTION

Previous epidemiological studies reported that residents living near major roads experienced more chronic respiratory symptoms, such as lung problems or an increase in asthma (Edwards et al, 2001). The distance of a residence from roadways determines the levels of traffic-generated pollutants outside the residence, which infiltrate indoors posing threats to the health of the exposed residents. Most of the previous studies focused on the spatial distribution of pollutants rather than the exposed population. To assess horizontal variations of pollutants, Geographic Information System (GIS) have been widely applied to air pollution mapping at different geographic scales and to assess health impacts as a function of distance from emission sources in epidemiological studies (Aguilera et al, 2008; Henderson et al, 2007). Fail to consider vertical distance of residences from roadways may result in misclassification of subjects' exposure which would reduce the power of detecting the differences in health endpoints of traffic exposure. Therefore, assessing vertical distribution of population is an important issue in exposure science and environmental epidemiology. In population modeling, demographic databases together with supplementary data such as land-use types in GIS, called "dasymetric mapping", provide more detailed spatial information than the census data (Sleeter 2008). Among them, only one publication (Lwin and Murayama 2009) estimated three-dimensional (3-D) distribution of population. However, their approach demanded detailed governmental databases such as the number of floors, height of buildings, footprint area of buildings, and so on. In many countries, those detailed data are not available. Moreover, it required a lot of efforts and resources to handle those detailed data as the number of studied buildings goes up. Therefore, it might not be applicable to a large-scale study. Till now, no research provides an effective method to assess 3-D population distribution in large-scale spatial domains.

A novel methodology, three-Dimensional dIgital Geography (3DIG) methodology, is presented in this study to estimate the size of the potential exposed population within different buffer zones, considering both horizontal and vertical distributions of residences around the roadways. 3DIG is constructed using GIS and fine-resolution Digital Terrain Models (DTM). Taking Taipei metropolis (Fig. 1) as a model example, this paper applies 3DIG to assess the number of population horizontally and vertically in close proximity to traffic, thus the potential exposed population under traffic impacts. The obtained results can provide exposure scientists and environmental epidemiologists the 3-D distribution of potential exposed population and assist urban planners and environmental health professionals in evaluating the potential environmental health benefits of pollution mitigation policy for protecting urban health.

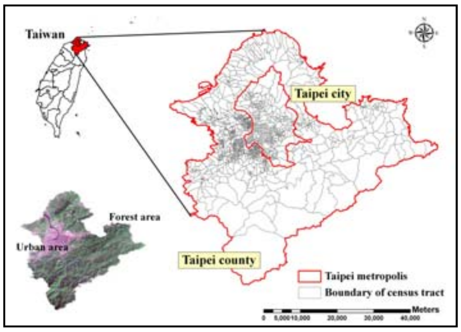

Fig. 1. Location of the study area

2. MATERIALS AND METHODS

2.1 Materials

Both DEM and DSM with 5m resolution processed from aerial photos taken in 2004-2005 were used; the horizontal and vertical variations in urban area are less than 0.5m and 0.7m, respectively (SSC, 2010). The demographic database of all 1520 census tracts in 2009 obtained from the respective Household Registration Office. The national land-use inventory generated based on 1/5,000 scale aerial photos collected in 2008 was acquired. Three sub-types of construction type, pure residential, commercial-residential, and industrial-residential zones, were selected from the database. Polygon patterns of municipal roads (defined as any roads wider than 4m but excluding highways and expressways) in Taipei metropolis were also extracted from the database.

2.2 Three-Dimensional dIgital Geography methodology (3DIG)

The procedures of 3DIG are described in details as follows.

2.2.1 Estimating building floors using DEM and DSM

The building heights in the identified residential zones were obtained by subtracting the elevation values in DEM from those in DSM. Building height in each pixel was then divided by building floor height (ceiling height plus height of the utility layer if any) to derive the number of floors. In this study, floor height of each residential type was first assigned based on the reference values and field data (3.6m, 4.0m, and 4.2m for pure residential, commercial-residential, and industrial-residential zones, respectively). In addition, the first floor in the mixed residential buildings was generally used for industry or commerce while the upper levels are for residences, according to the building codes (NLSMC, 2009). Thus, a constant of "1" was subtracted from the estimated number of floors in mixed residential buildings to obtain the floors on which people actually live. Field surveys for the actual number of building floors in five randomly chosen census tracts were conducted to validate the model results. The estimation of building floors for each pixel is as follow.

$$F_i = \frac{Hdsm_i - Hdem_i}{h} \text{ (for pure residential areas)}$$
$$F_i = \frac{Hdsm_i - Hdem_i}{h} - 1 \text{ (for mixed residential areas)} \quad (1)$$

where F_i is the number of floors in pixel i, $Hdsm_i$ and $Hdem_i$ are elevation values recorded in DSM and DEM of pixel i, respectively. Each pixel is a 5m × 5m area. h is the floor height according to the residential type of this pixel. Number of floors in individual pixel area estimated from equation (1) may not be an integer. Thus, three approaches were adopted to round the decimals; they were: round down, round off, and round up approaches. The comparison of these three approaches was also used as our sensitivity analysis.

2.2.2 Assigning floor categories

In Taiwan, the number of floors of buildings is generally associated with the construction years. Residences built before 1940s and 1960s usually had two and four floors, respectively. High rise buildings were widely constructed after 1970 due to the rapid economic growth. Building types affect the efficiency of outdoor air infiltrating indoors. Therefore, we adopted two floors as an interval to classify the building floors into four categories: I, II, III, and IV, i.e. the first and second, third and fourth, fifth and sixth floors, and all floors higher than the sixth floor, respectively. The first floor is equivalent to the ground floor in this study.

2.2.3 Estimating vertical population distribution

Population in each floor category can be calculated by multiplying the total population in one area with the percentage of the population in that particular floor category in this area. To improve the overall accuracy, population of each floor category was first calculated for each census tract and then summed up for all census tracts. It was assumed that population is evenly distributed within each census tract. The calculation of population in different floor category is as follow.

$$PC_j = \sum_{k=1}^{1520} \frac{FL_{jk}}{F_k} \times P_k \ ; \ j = 1 \sim 4 \quad (2)$$

where PC_j (people) is the total population of floor category j in Taipei metropolis, FL_{jk} (layer) is the number of floors in floor category j of census tract k, F_k is the total number of floors of census tract k. The ratio of FL_{jk} (layer) and F_k (layer) represents the percentage of that specific floor category in the census tract. P_k (people) is the total population of census tract k.

2.2.4 Estimating population within buffer zones around roads

Buffer distances of 5, 10, 20, 50 and 100m were generated around the outside of road polygons. The total number of floor layers and the population of each floor category within different buffer zones were calculated by using zonal statistics in GIS. Moreover, defining "High Exposure Ratio" (HER) as the ratio of residents living on the first and second floors within 5m buffer zone to total residents; it was further applied to identify the spatial distribution of potential highly exposed population under traffic impacts within Taipei metropolis.

3. RESULTS

3.1 Estimation of building floors

The pure residential, commercial-residential, and industrial-residential zones account for 73.8%, 23.9%, and 2.3% of the total residential zones, respectively. The residential zones are densely distributed and surrounded by municipal roads; these three different residential zones are intertwined with each other. The total number of floors estimated using the round down, round off, and round up approaches were 10,475,550, 12,263,583, and 14,266,592 layers, respectively. As expected, the estimation of the round down approach is the lowest while that of the round up approach is the highest. The highest number of floors in the pure residential zone estimated by the round down, round off, and round up approaches were 31, 31, and 32, respectively. As part of our validation attempt, a field survey was conducted to examine the highest residential building. It was actually a 32-floor apartment complex, indicating that the round up approach was accurate in this estimation. The results of model validation indicated that, the number of floors obtained by the round down and round off approaches for all residential types were significantly underestimated ($p < 0.01$), in contrast to those of the round up approach ($p > 0.05$). In addition, regression was used to examine the model validation. The R^2 of all models range from 0.91 to 0.99; the values of the round down and round up approaches are slightly better than that of the round off approach. After careful deliberation of the aforementioned results, the round up approach was chosen since it provided the best estimates. Furthermore, from these results, it can be concluded that 3DIG with the round up approach provides accurate estimation of number of floors. Fig. 2 presents an example of 3D mapping of buildings with different number of floors using the round up approach.

Fig. 2. Example of 3D mapping of buildings with different number of floors

3.2 Vertical population distribution using 3DIG

Sensitivity test was applied with three decimal-rounding approaches in order to assess the possible variation in population estimation resulted from variation in floor estimation. With the round up approach as the reference, the largest differences from the other approaches in categories I, II, III, and IV were -4.3%, -0.7%, 4.3% and 0.7%, respectively. It shows that there were only small differences in vertical distribution of population estimations among the three approaches, suggesting that these results were not sensitive to the minor variations in floor estimation. Additionally, the total population estimated in Taipei metropolis (6,538,161) was only 0.88% higher than the actual population numbers (6,481,081), again indicating the accuracy of our approach. The results of population estimation in each floor category indicated that 2,669,475 (42.3%), 2,186,424 (32.7%), 1,086,151(16.0%) and 596,111(9.0%) residents in Taipei metropolis live on the first/second, third/fourth, fifth/sixth, and higher floors, respectively.

3.3 3D population distributions under traffic impacts

Table 1 presents the potential exposed population within the specific buffer distances from road traffic. More than half of the residences (54.3%) were horizontally located within 10m from the municipal roads. Around 98% of the residential buildings were under road-traffic influence within 50m buffer zones; higher risks of cardiopulmonary diseases were observed within this distance (50m) from roads (Hoffmann et al., 2007). The results show that there are 2.7, 2.1, 1.0, and 0.57 million Taipei residents living within the 50m buffer zones for the four categories, respectively. Totally, 97.9% (6.4 million) of the Taipei population lives within 50 m. More alarmingly, about 0.8 million people live on the first or second floor within 5m from the municipal roads; these are the potential highly exposed population affected the most by the traffic emission. There are 22 census tracts with HER > 0.5, indicating more than half of their residents are potentially exposed to high pollutant levels from direct traffic emission. Figures 3(a)(b) shows HER distribution of different towns in Taipei metropolis. These graphs present vertical attributes (population in different floors) in bar charts with colors indicating different HER quartiles. It shows that half of the towns in Taipei city and county with more than 13.9 and 12.1% of residents living on the first and second floors within 5m buffer zones, respectively; the highest HER (23%) occurs in one town of Taipei city. Ranking HER and the size of potential highly exposed population can identify the towns under significant traffic impacts.

Table 1. Vertical distribution of population in four floor categories within different buffer zones from road-traffic. Number in the parentheses indicates the percentage of the total population in Taipei metropolis

	Floor category				
	Ⅰ	Ⅱ	Ⅲ	Ⅵ	Sum
Buffer distance	(1F and 2F)	(3F and 4F)	(5F and 6F)	(7F and up)	
5m	801573 (12.3%)	664054 (10.2%)	301280 (4.6%)	96298 (1.5%)	1863204 (28.5%)
10m	1495014 (22.9%)	1254994 (19.2%)	590927 (9.0%)	212439 (3.2%)	3553374 (54.3%)
20m	2284481 (34.9%)	1886013 (28.8%)	910898 (13.9%)	398705 (6.1%)	5480098 (83.8%)
50m	2686574 (41.1%)	2113130 (32.3%)	1032697 (15.8%)	566761 (8.7%)	6399162 (97.9%)
100m	2739778 (41.9%)	2133357 (32.6%)	1041547 (15.9%)	587213 (9.0%)	6501896 (99.4%)

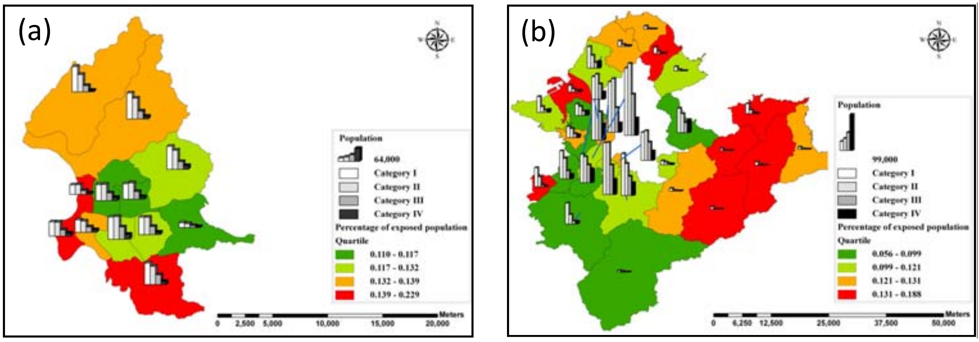

Fig. 3. Spatial distribution of the high exposure ratio (HER) in different towns of (a) Taipei city and (b) Taipei county.

4. **CONCLUSIONS**

This study presents a novel 3DIG methodology which integrates GIS techniques and fine-resolution digital terrain models to assess the size and distribution of the potentially affected populations at different floors within five specified buffer zones under traffic impacts**.** In addition, 3DIG can be employed to assess the population size affected by other pollution sources such as restaurants and community mechanical shops, which is important to prioritize pollution control and mitigation strategies for different sources in different areas. In summary, 3DIG is a useful tool for researches and policies on environmental health. This study demonstrates that 3DIG is a versatile methodology for air pollution management, epidemiology studies, and urban and transportation planning to evaluate environmental health impacts. It can also be applied to risk assessment for flood and applications in which the three-dimensional spatial distribution of population is the central focus.

5. REFERENCES

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