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ORIGINAL PAPER

Risk assessment of traffic-related air pollution in a world heritage city

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Abstract To support environmental risk management in a world heritage city, this paper presents high spatial-resolution maps of air pollutants for the Macao Peninsula. In particular, the risk of exposure to traffic-related nitrogen dioxide pollution for the 22 world heritage monuments in the Historic Center of Macao was assessed. The air-pollution mapping was performed by a building-based air quality model system, in which the traffic-related air pollutions at 5,965 receptor points in the Macao Peninsula were modeled and the average spatial resolution was 727 receptors/km^2. The results indicate that under the conditions of the evening peak hour and the north wind direction sector 0–20°, air quality in the Macao Peninsula is the worst. About 14.1% of the modeled nitrogen dioxide concentrations at the 5,965 receptor points exceed the national ambient air quality standard for scenic spot of 120 μg/m^3 in China. Two world heritage monuments, i.e., the "Leal Senado" Building and the Cathedral, are exposed to excessively high nitrogen dioxide concentrations of 135.9 and 121.1 μg/m^3, respectively. The results in this paper could help decision makers to develop effective strategies to protect the world cultural heritages in Macao for future human generations to appreciate and enjoy.

Keywords Air quality modeling · Cultural heritage · Environmental risk management · Geographical information system

Introduction

Macao is the first place in China open to the West in the sixteenth century. For the preservation of its dramatic mixing of eastern and western cultural relic sites, the Historic Center of Macao has been awarded "World Cultural Heritage" status by the United Nations Educational, Scientific and Cultural Organization in 2005. After the reunification with mainland China in 1999, Macao has experienced a tremendous economic boom. By 2007, the city enclave had become the largest gambling hub in the world and the richest place in Asia in terms of gross domestic product (GDP) per capita. However, the rapid economic development has brought with it associated environmental and social problems (Tang and Sheng 2009).

The urban form of Macao is extremely compact due to population growth and the shortage of land resources. The United Nations World Prospects Report (2004 revised) listed Macao as the No. 1 most densely populated region in the world. In 2011, the population density of the Macao Peninsula is 50,602 inhabitants/km^2. There are 108,178 motorcycles and 85,777 light vehicles, with an increasing rate of 88.3 and 63.7%, respectively, over the past decade (DSEC 2011). The high population density and the lack of control over the number of vehicles cause ever-worsening air quality that endangers the reputation of Macao as a World Cultural Heritage site (De la Fuente et al. 2011; Sheng and Tang 2011a, b). For this reason, there is a need for air-pollution mapping to support effective urban planning and risk management.

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Effective environmental risk management needs to be supported by accurate mapping of air pollutants (Vienneau et al. 2009; Lahr and Kooistra 2010). Studies have shown that the air pollution in an urban area has a complex spatial pattern and levels can vary significantly over small distances (Malakootian and Yaghmaeian 2004; Jerrett et al. 2005; Simkhada et al. 2005; Wilson and Zawar-Reza 2006; Skene et al. 2010; Yassin 2009, 2011). To capture the complex spatial variation of air pollution in an urban area, some researchers have developed geographical information system (GIS)-based models to estimate air-pollution levels at high spatial resolution. Among these, deterministic models based on dispersion modeling include ADMS-Urban (McHugh et al. 1997; Carruthers et al. 2000), AirGIS (Jensen 1998; Jensen et al. 2001, 2009; Berkowicz et al. 2008), AERMOD (Kesarkar et al. 2007), STEMS-Air (Gulliver and Briggs, 2011), and others (Elbir 2004; Tang and Wang 2007; Guerrero et al. 2008; Elbir et al. 2010). In particular, a deterministic building-based air quality model system for Macao has been developed by the authors (Tang and Wang 2007; Sheng and Tang 2011a, b). The system integrates the operational street pollution model (OSPM) (Berkowicz 2000), digital maps of the road network, building layout and topographic information, an urban landscape model, and the GIS. The building-based model system has the feature that the street configuration and traffic data can be automatically extracted building by building and therefore, the complex spatial variation of traffic emission, urban geometry, and air pollution can be captured.

This study applied the model system developed by the authors to generate high spatial resolution maps of air pollutants for the Macao Peninsula. The urban areas and populations at potential risk of exposure to traffic-related air pollution were identified. Particularly, the risk for the World Heritage monuments in the Historic Center of Macao was assessed. The results could help decision makers to develop effective strategies to improve air quality and protect the World Cultural Heritages in Macao. The highly compact urban form of the Macao Peninsula may make the findings very relevant to urban planners as they prepare for higher population densities in cities throughout the world. The work presented in this paper was conducted in Macao during 2010 to 2011.

Materials and methods

Building-based air quality model system

This sub-section provides a brief description of the prototype building-based air quality model system developed by the authors. The model system has a high spatial resolution down to individual buildings along both sides of the street. It is a deterministic model system based on the OSPM and has been evaluated in Macao (Tang and Wang 2007). Interested readers could consult the paper by the authors (Tang and Wang 2007; Sheng and Tang 2011a, b) for more details.

The OSPM model is a parameterized model for flow and dispersion conditions in street canyons (Berkowicz 2000; Berkowicz et al. 2008). Concentrations of exhaust gases are calculated as the sum of the direct contribution from traffic and the recirculation part of the pollutants in the street. The direct contribution is calculated by a plume dispersion model and the recirculation by a box model. In the plume model, the emission field is treated as a number of infinitesimal line sources aligned perpendicular to the wind direction at the street level. It is assumed that the wind direction at street level is a mirror reflection of the wind above roof level. The air pollution is determined by the emission density (per street length and per time), street width, wind speed at the street level, and mechanical turbulence. The mechanical turbulence is assumed to be generated by the wind and by the traffic in the street. When the wind speed is low, the traffic-induced turbulence dominates. For nitrogen oxides, the OSPM model also takes into account simple photochemistry between nitric oxide (NO), nitrogen dioxide (NO_2), oxygen (O_2), and ozone (O_3).

In the prototype model system, an urban landscape model has been developed to integrate the OSPM with the ArcView GIS and automatically extract the street configuration data and traffic data from digital maps. When the urban landscape model is executed, a target building polygon is selected from the cadastral map in ArcView. Based on the coordinates of the vertices of the target building polygon, the boundary segments of the building polygon are obtained. If the boundary segment faces a street aligning parallel to it, it is treated as a building façade which is exposed to direct traffic air pollution and a target receptor point is created in the middle of the boundary segment. The spatial-related input data (street configuration data and traffic data) around the target receptor point are then extracted from the cadastre, road network, and terrain maps for the OSPM.

The modeling results of the OSPM, which include the gaseous concentrations of carbon monoxide (CO), NO, NO_2 and benzene are then stored in the attribute fields of the target point feature created in a receptor point map. The spatial-related input variables are also stored in the attribute fields of the receptor point. When all the buildings in the cadastral map are selected and manipulated, the urban landscape model stops the execution. All the modeling results in front of the building façades at roadside can then be accessed from the receptor point map in ArcView. The statistical/spatial relationships of the input values and output results can also be investigated.

Input variables

The input variables for the OSPM include street configuration, meteorological data, urban background concentrations, traffic data, and vehicular emissions.

The street configuration data are spatial data that describe the physical street environment surrounding a target receptor point. The data include street width, street length, street orientation, building locations, and building heights, which can be automatically extracted from the cadastre, road network, and terrain maps by the urban landscape model.

Meteorological data include wind speed, wind direction, temperature, and global radiation. Urban background concentrations include those of CO, NO, NO_2, and O_3. The meteorological data and urban background concentrations were obtained from the background monitoring stations of the Macao Meteorological and Geophysical Bureau in the Macao Peninsula.

Traffic data required by the OSPM include traffic volume, composition, and speed. The data were obtained by manual traffic counts on major urban trunk roads and district distributors during the evening peak period (18:00–19:00) on working days in 2010. Diurnal variations on typical traffic roads such as Rua de Campo and Rua da Ribeira do Patane were also observed in an hourly basis. In this study, the traffic composition included five categories of vehicles, i.e., motorcycle, passenger car, taxi, truck, and bus. The category of motorcycle was not included in the original version of the OSPM but was added in this study because motorcycles contribute around half of the traffic volume on majority of the roads in the Macao Peninsula.

The vehicle emission factors are essential input parameters in air quality modeling. In the Macao Peninsula, vehicle emissions are complex due to traffic congestions with rapid exchange of idle, acceleration, cruise, and deceleration modes. To support air quality modeling and management, it is crucial to obtain vehicle emission of individual vehicle during traffic congestion in urban “hot spots” in Macao. The vehicle following measurement under traffic congestion conditions had been conducted by the authors in the urban hot spots in the Macao Peninsula in 2004. A total of 178 vehicles were followed individually and the gaseous emissions (CO, HC, NO, CO_2, and O_2) from each preceding vehicle were measured with high-time resolution so that fluctuations in the emissions can be seen readily during vehicle acceleration, cruising, deceleration, and idling. Based on the measurement, the emission factors for five categories of vehicles, i.e., motorcycle, passenger car, taxi, truck, and bus, had been calculated. The details of the vehicle following measurement and the calculation of the emission factors have been reported by Tang and Wang (2006).

Results and discussion

With the building-based model system, a total of 5,965 receptor point entities were created automatically in front of individual buildings along both sides of the streets in the Macao Peninsula. As the area of lands in the Macao Peninsula is only 8.2 km^2 (excluding the 1.1 km^2 of a reservoir and two lakes), the average spatial resolution was 727 receptors/km^2. In addition, as the street configuration and traffic data can be extracted building by building, the influence of the complex urban geometry and traffic conditions on air pollution exposures at human respiration height can be taken into account. Human exposures in a city can then be investigated at the address level.

In this study, 18 sets of meteorological conditions and urban backgrounds in different wind direction sectors have been considered in air quality modeling, see Table 1. The data were obtained from the background monitoring stations of the Macao Meteorological and Geophysical Bureau. The number of effective measurement days in 2010 was 360 days. In each wind direction sector, the measurements of wind direction, wind speed, global radiation, temperature, NOx, NO_2, and O_3 during the evening peak hour 18:00–19:00 were averaged and the results are given in Table 1. It is found that the dominated wind direction sector is 80–100°, which was observed on 27.8% of effective measuring days in 2010. While there is no record in the wind direction sectors of 200–220° and 240–260°. The wind speeds are in the range of 1.1–3.3 m/s and the global radiations are in the range of 0.0–12.4 W/m^2. The global radiations are relatively low as values refer to the radiations in the evening. As the Macao Peninsula is located in the sub-tropical region, the temperatures are in the range of 17.7–31.0°C. For urban backgrounds, NOx and NO_2 concentrations are in the range of 21.7–121.2 μg/m3 and 14.8–90.3 μg/m^3, respectively. While O_3 concentrations are in the range of 25.3–168.2 μg/m^3.

Statistical results for modeled NO_2 concentrations under different meteorological conditions and urban backgrounds in the 18 wind direction sectors are shown in Table 2. It is found that when winds blow from the south direction of 180–200°, the air quality in the Macao Peninsula is the best. The average, minimum, and maximum values of NO_2 concentrations at the 5,965 receptor points are, respectively, 20.8, 15.2, and 47.7 μg/m^3, which are the lowest among the 18 wind direction sectors. This could be explained by the fact that the Macao Peninsula and its outer islands face the South China Sea in the south and the urban

Table 1 Meteorological conditions and urban backgrounds

Wind direction sector (degree)	Frequency (%)	Average wind direction (degree)	Average wind speed (m/s)	Average global radiation (W/m^2)	Average temperature (°C)	Average NO_x (μg/m^3)	Average NO_2 (μg/m^3)	Average O_3 (μg/m^3)
0–20	1.7	12.8	1.7	0.5	21.5	121.2	90.3	44.7
20–40	2.5	33.7	1.7	2.2	22.4	96.1	74.0	47.7
40–60	1.4	42.6	1.4	0.0	18.0	91.2	73.6	45.1
60–80	1.7	69.0	2.5	1.9	21.9	94.0	70.2	30.6
80–100	27.8	90.8	2.2	1.6	22.1	77.5	56.9	52.7
100–120	16.1	108.7	2.0	4.4	24.3	54.5	42.3	59.7
120–140	2.5	134.6	1.5	6.8	25.8	35.1	25.7	37.7
140–160	4.2	159.3	2.2	0.9	24.6	28.3	21.5	39.0
160–180	9.7	174.5	1.9	10.2	28.1	25.8	17.2	41.8
180–200	8.6	185.6	2.6	12.4	29.2	21.7	14.8	25.3
200–220	0.0	–	–	–	–	–	–	–
220–240	0.6	223.0	1.1	6.9	29.6	29.2	22.7	39.4
240–260	0.0	–	–	–	–	–	–	–
260–280	1.7	269.5	2.1	6.0	27.8	30.0	15.8	32.9
280–300	1.1	290.0	1.8	2.1	31.0	49.7	38.7	168.2
300–320	12.2	315.3	2.5	0.5	18.0	107.4	68.6	44.7
320–340	4.4	336.0	3.3	0.0	17.7	84.0	50.5	47.3
340–360	3.9	354.9	2.6	0.2	21.9	76.4	60.9	65.2

Table 2 Modeling results in various wind direction sector

Wind direction sector (degree)	Average NO_2 (μg/m^3)	Min. NO_2 (μg/m^3)	Max. NO_2 (μg/m^3)	Exceed NO_2 standard (>120 μg/m^3) (%)
0–20	111.7	99.3	139.8	14.1
20–40	95.8	81.2	132.3	0.5
40–60	93.7	79.4	131.9	0.3
60–80	82.6	72.3	110.7	0.0
80–100	76.1	60.1	111.1	0.0
100–120	59.0	44.3	104.7	0.0
120–140	37.3	26.6	68.5	0.0
140–160	31.6	22.9	67.1	0.0
160–180	28.2	18.4	64.6	0.0
180–200	20.8	15.2	47.7	0.0
200–220	–	–	–	–
220–240	36.4	24.4	83.7	0.0
240–260	–	–	–	–
260–280	26.8	17.2	63.9	0.0
280–300	68.8	43.4	179.0	4.0
300–320	91.3	76.3	116.1	0.0
320–340	65.3	54.1	91.3	0.0
340–360	77.7	66.3	118.0	0.0

background of NO_2 concentration in the wind direction sector 180–200° is the lowest among the 18 wind direction sectors (i.e., 14.8 μg/m^3, Table 1).

On the other hand, when winds blow from the north direction of 0–20°, the air quality in the Macao Peninsula is the worst. Comparing with the wind direction sector

180–200°, the wind speed in the north wind direction sector 0–20° is 35% lower and the background NO_2 is 6.1 times higher (Table 1). The lower wind speed leads to worse dispersion conditions while the higher background concentration of NO_2 leads to higher total concentration of NO_2. As a result, under the conditions of the north wind direction sector 0–20° and the evening peak hour, the average value of NO_2 concentrations at the 5,965 receptor points is 111.7 μg/m^3, which is the highest among the 18 wind direction sectors. In addition, about 14.1% of the receptor points are exposed to NO_2 concentrations which exceeded the national Ambient Air Quality Standard for Scenic Spot of 120 μg/m3 (GB3095-1996) (State of Environmental Protection Administration of China 1996).

Based on the modeling results at 5,965 receptor points, the distribution maps of NO_2 under the conditions of the dominated wind direction sector 80–100° and the north wind direction sector 0–20° are generated as shown in Figs. 1, 2, respectively. It is observed from Figs. 1, 2 that NO_2 concentrations are the highest in the high-rise residential areas, in the central business district (CBD), and along the inner circumferential routes, which attracted heavy traffic and thus induced intense vehicle emissions.

Figure 1 indicates that under the conditions of the dominated wind direction sector 80–100° and the evening peak hour, the modeled NO_2 concentrations at all the 5,965 receptor points do not exceed the national Ambient Air

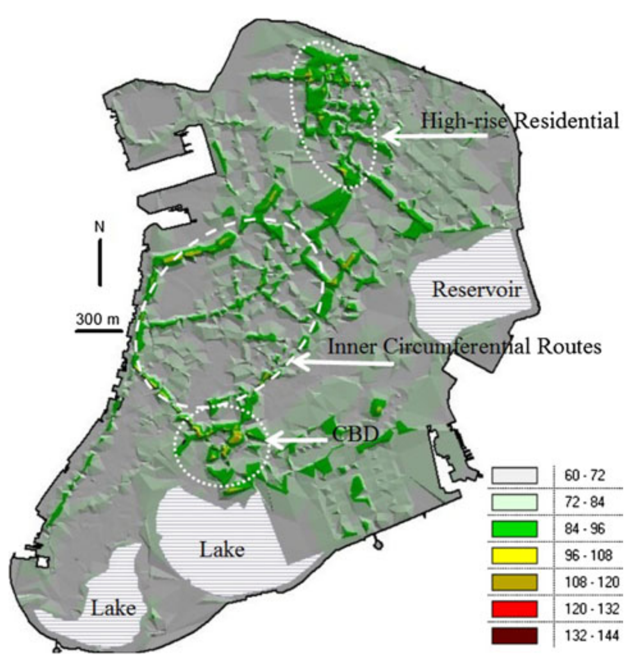

Fig. 1 Spatial distribution of NO_2 (μg/m^3) in dominated wind direction sector 80–100°

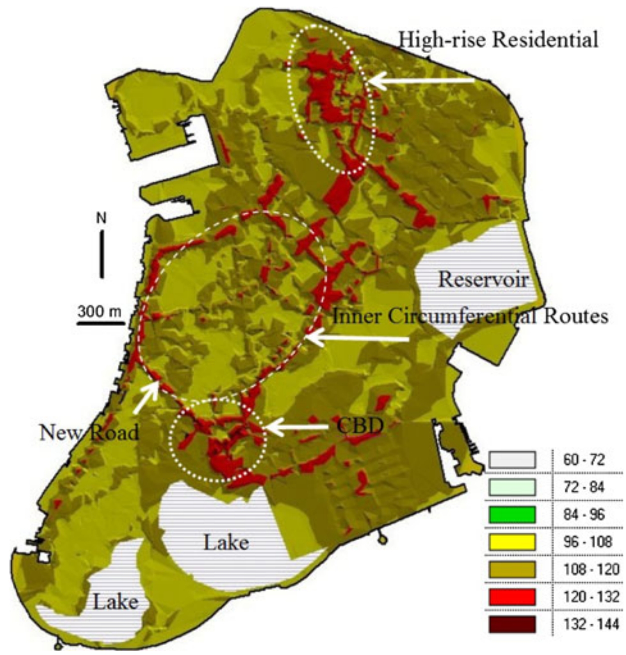

Fig. 2 Spatial distribution of NO_2 (μg/m^3) in north wind direction sector 0–20°

Quality Standard for Scenic Spot of 120 μg/m^3. However, under the conditions of the north wind direction sector 0–20° and the evening peak hour (Fig. 2), about 14.1% of NO_2 concentrations at the 5,965 receptor points in the Macao Peninsula exceed 120 μg/m^3. Particularly, about 0.5% of the receptor points have NO_2 concentrations higher than 132 μg/m^3, which exceeds 10% of the air quality standard of 120 μg/m^3. As seen from Fig. 2, the red and dark red areas are at a high risk of exposure to air pollution (NO_2 concentrations >120 μg/m^3). The worst air quality occurs in the CBD (NO_2 concentrations >132 μg/m^3).

In this study, the traffic-related NO_2 pollutions at the 22 World Heritage monuments in the Historic Center of Macao have been further investigated to support effective risk management and protection for the World Heritage. Figure 3 shows the spatial distribution of the 22 World Heritage monuments. The modeled NO_2 concentrations at the 22 monuments are given in Table 3. Under the conditions of the dominated wind direction sector 80–100° and the evening peak hour, NO_2 concentrations at all the monuments do not exceed the national Ambient Air Quality Standard for Scenic Spot (120 μg/m^3). The highest NO_2 concentration of 99.9 μg/m^3 (i.e., 83% of the allowed limit) is observed in the "Leal Senado" Building (No.9), followed by the St. Anthony's Church (No.19), the Cathedral (No.12), and the A-Ma Temple (No.1).

Under the conditions of the north wind direction sector 0–20° and the evening peak hour, the "Leal Senado" Building (No.9) and the Cathedral (No.12) are exposed to

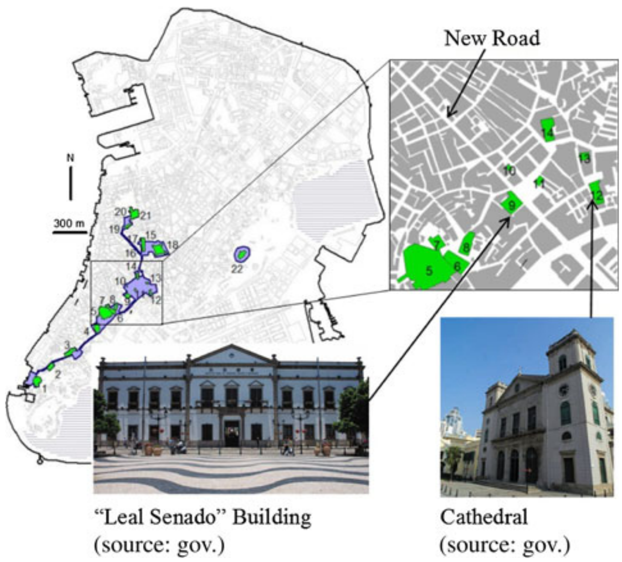

Fig. 3 Monuments in the Historic Center of Macao (*1* A-Ma Temple, *2* Moorish Barracks, *3* Mandarin's House, *4* St. Lawrence's Church, *5* St. Joseph's Seminary and Church, *6* Dom Pedro V Theatre, *7* Sir Robert Ho Tung Library, *8* St. Augustine's Church, *9* "Leal Senado" Building, *10* Sam Kai Vui Kun (Kuan Tai Temple), *11* Holy House of Mercy, *12* Cathedral, *13* Lou Kau Mansion, *14* St. Dominic's Church, *15* Ruins of St. Paul's, *16* Na Tcha Temple, *17* Section of the Old City Walls, *18* Mount Fortress, *19* St. Anthony's Church, *20* Casa Garden, *21* Protestant Cemetery, *22* Guia Fortress)

excessive high NO_2 concentrations of 135.9 and 121.1 μg/m^3, which exceed the national Ambient Air Quality Standard for Scenic Spot of 120 μg/m^3. In particular, the NO_2 concentration at the "Leal Senado" Building (No. 9) exceeds 13% of the allowed limit. Originally built in 1784, the building was Macao's original municipal chamber, a function it maintains to the present. The building is located on the New Road, which is part of the inner circumferential routes at present (Fig. 2). As shown in Fig. 3, the New Road is a long straight road passing through the historical area with narrow and complex curvature road network. The complex curvature road network was developed in an organic style of urban development by Portuguese explorers in the hilly historic area in the sixteenth century. At that time, people usually walked to destinations and thus the roads were designed for pedestrian use. In 1918, the Portuguese removed a small hill and some buildings to build a wider and straight New Road to facilitate modern vehicle transport passing through the historical area. Today's drivers select the straight New Road rather than the other complex curved roads to pass through the historical area, which leads to a significantly higher traffic volume (greater than 1,500 vehicles per hour) and hence, the worst air quality at the "Leal Senado" Building (No.9) among the 22 World Heritage monuments.

Table 3 NO_2 concentrations at the World Heritage monuments

World heritage monuments	NO_2 (μg/m^3)	
	Wind sector 80–100°	Wind sector 0–20°
1. A-Ma Temple	78.9	115.8
2. Moorish Barracks	75.1	110
3. Mandarin's House	78.8	111.4
4. St. Lawrence's Church	69.4	113
5. St. Joseph's Seminary and Church	73	114
6. Dom Pedro V Theatre	71.7	105.6
7. Sir Robert Ho Tung Library	70.4	110.1
8. St. Augustine's Church	69.5	109.7
9. "Leal Senado" Building	99.9	135.9
10. Sam Kai Vui Kun (Kuan Tai Temple)	68.7	106.5
11. Holy House of Mercy	68.4	105.3
12. Cathedral	84.8	121.1
13. Lou Kau Mansion	69.4	107.7
14. St. Dominic's Church	68.7	105.8
15. Ruins of St. Paul's	66.5	108.2
16. Na Tcha Temple	67.6	103
17. Section of the Old City Wall	67.6	103
18. Mount Fortress	76	108.5
19. St. Anthony's Church	93.8	107.8
20. Casa Garden	67.4	104.2
21. Protestant Cemetery	68.5	106.4
22. Guia Fortress	69.3	107.3

Conclusion

This study has applied a building-based air quality model system to generate high spatial resolution maps of traffic-related NO_2 based on the modeling results at 5,965 receptor points in the Macao Peninsula. The results indicate that under the conditions of the evening peak hour and the north wind direction sector 0–20°, air quality in the Macao Peninsula is the worst. About 14.1% of the modeled NO_2 concentrations at the 5,965 receptor points exceed the national Ambient Air Quality Standard for Scenic Spot of 120 $\mu g/m^3$. The CBD, the high-rise residential areas, and the inner circumferential routes are at a high risk of exposure to traffic-related air pollution (NO_2 concentrations $>120\ \mu g/m^3$). The worst air quality occurs in the CBD (NO_2 concentrations $>132\ \mu g/m^3$).

The risk of exposure to traffic-related NO_2 pollution for the 22 World Heritage monuments in the Historic Center of Macao has been further assessed. The results indicate that under the conditions of the evening peak hour and the north wind direction sector 0–20°, two monuments (i.e., the "Leal Senado" Building and the Cathedral) are exposed to excessive high NO_2 concentrations of 121.1–135.9 $\mu g/m^3$. The worst air quality occurs at the "Leal Senado" Building among the 22 World Heritage monuments.

According to the United Nations, World Heritage is the designation for places on earth that are of outstanding universal value to be protected for future human generations to appreciate and enjoy. The results in this paper could help decision makers to develop effective strategies to improve air quality and protect the World Cultural Heritages in Macao.

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