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Impact of Ozone Pollution on Human Health and Economic Loss Assessment

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Abstract: The problem of ozone (O_3) pollution in the air has become increasingly prominent in recent years, and the health effects of O_3 pollution on people have attracted more attention. O_3 is the primary pollutant with the highest over-limit rate in the Guangdong-Hong Kong-Macao Pearl River Delta. Based on the data of O_3 concentration, exposed pollution, baseline mortality, and hospitalization rate monitored by the Pearl River Delta Regional Air Quality Monitoring Network (PRD-RAQMN) in Shenzhen. This study evaluates the impact of O_3 pollution on human health and economic loss in Shenzhen from 2006 to 2018 by using the relative risk model, benefit conversion method, and disease cost method. The annual mean value of daily 8 h maximum concentration of O_3 in Shenzhen shows an overall significant upward trend from 2006 to2018, with an average annual value range of 70 to 190.92 μg/m^3 and an average value of 112.89 μg/m^3. The number of death and hospitalization caused by O_3 pollution increases significantly, and the incidence of respiratory system diseases is higher than that of circulatory system diseases. However, the mortality caused by circulatory system diseases was higher than that caused by respiratory system diseases. The economic loss of health caused by O_3 pollution increased yearly, with an annual average economic loss of82.46 million RMB, reached 658.31 million RMB in 2018, accounted for 0.0272% of Shenzhen's GDP in 2018.

Keywords: Ozone, Health Effects, Economic Loss, Shenzhen

1. Introduction

With the continuous acceleration of global industrialization and urbanization, the impact of urban air pollution on human health, economy, and society is becoming more and more important, so it has been paid great attention to by all countries and relevant organizations in the world. In recent years, many studies have been carried out on the effects of air pollution and population health as a reference basis for formulating and assessing relevant environmental policies. According to the global gender and environment outlook published by the United Nations Environment Programme in 2006, air pollution was one of the main factors leading to environmental and health problems in both developed and developing countries [1]. Global burden of disease (GBD) [2] reported that the disability-adjusted life year (DALY) caused by O_3 was 4.1 million people/year in 2015 [3]. Compared with the results in 2006, the number of deaths worldwide associated with particulate pollution and ozone (O_3) pollution increased significantly and reached 4.09 million (95%CI: 3.62-4.58 million) and 0.23 million (95%CI: 0.09-0.38 million) in 2016, respectively. The mortality of residents increased by 0.26% (95%CI: 0.15%-0.37%) with every 10 μg/m^3 increased in O_3.

Studies showed that O_3 has a typical biological toxic effect, which could cause inflammation of cardiovascular system and respiratory system as well as system oxidation stress response [4]. Since 2005, the results of several cohort studies suggested that long-term O_3 exposure has a potential link with mortality, and mainly affected the mortality of respiratory and cardiovascular diseases [5, 6]. There was a significant positive correlation between the increase of environmental O_3 concentration and the increase of incidence [7]. The most commonly used health terminal in this kind of research is the number of hospital admissions or emergency visits for asthma, respiratory infection and other respiratory diseases. Relevant literature found that there was a positive correlation between the change of O_3 level and the admission amount of respiratory diseases in a large number of cities [8]. Nuvolone et al. [9] found that the concentration of O_3 every increased 10 μg/m^3 caused the number of coronary artery deaths in hospitals to increase by 6.3% (95%CI: 1.2%~11.7%), and women, the elderly and patients hospitalized increased for cerebrovascular diseases would face high risks.

Air pollution not only affects people's health but also affects the economy. The central framework of environmental-economic accounting system (SEEA-2012) was issued by the United Nations Commission on environmental and economic accounting and has been recognized as the first international statistical standard of environmental-economic accounting [10]. The physical terminal of health loss caused by air pollution includes the total number of premature deaths of urban residents, the number of inpatients in the respiratory and circulatory system, and the number of patients with chronic bronchitis. The economic loss accounting terminal includes the economic loss caused by premature death, hospitalization, off work, and the long-term disability of chronic bronchitis patients. To assess the economic loss of air pollution to human health, the willingness to pay method (WTP) was used in western developed countries [11]. However, the disease cost method and the revised human capital method were used in developing countries with an incomplete market economy [12]. The technical specification for health risk assessment of air pollution population proposed a general model for health risk assessment. In this general model, the data of air pollution in various concentration ranges relates to epidemiological parameters, such as the relative risk of health outcomes caused by air pollution exposure of the target population, the baseline incidence of health outcomes ($1/10^5$), the proportion of population attributable risk, and the calculation of diseases incidence rate, hospitalization rate, and the mortality due to air pollution exposure. Then combined with the size of the exposed population, the number of cases or deaths attributable to air pollution exposure could be estimated. Zmirou et al. [13], Patankar & Trivedi [14], and Zhang et al. [15] used the economic burden of disease to assess the medical expenses caused by exposure to particulate air pollution in three metropolitan areas of France, Mumbai city of India, and 111 cities of China. Wei et al. used the Poisson regression model, modified human capital method and disease cost method to evaluate the acute health damage effect, early death economic loss and hospitalization, illness and outpatient economic loss of $PM_{2.5}$ exposure of Xi'an residents, respectively [16].

In recent years, the haze phenomenon characterized by a high concentration of fine particles ($PM_{2.5}$) and photochemical smog characterized by O_3 has been highlighted in the air pollution of urban agglomerations in Chinadue to the rapid development of urbanization, industrialization, and the rapid increase of vehicle ownership. Air pollution has entered the era of mixed pollution and the problem of O_3 pollution has become increasingly prominent. The concentration of $PM_{2.5}$ in most areas showed a significant downward trend and the assessment objectives basically achieved with the release and implementation of the "ten atmospheric regulations". However, the pollution of O_3 was increasingly prominent at the same time. The Pearl River Delta (PRD) region is an important urban agglomeration area with rapid economic development in China. Photochemical smog is one of the main air pollution problems in the PRD of its low latitude [17]. The comparative study of O_3 concentration in the pilot cities in China showed that the pollution of O_3 in the pilot cities of the PRD was prominent and higher than that in the pilot cities in the north [18]. The concentration of O_3 in the pilot cities of the PRD could be nearly twice as high as that in the pilot cities of the north. According to statistics, the proportion of days of O_3 concentration exceeding the standard increased and the proportion of cities meeting the standard decreased in 338 cities of China from 2015 to 2017. The concentration of O_3 in some areas exceeded the new standard level II concentration limit (160 μg/m^3). The proportion of O_3 in the main pollutant days in Beijing, Tianjin and Hebei was second only to $PM_{2.5}$ and has a large increase. In the PRD and the Yangtze River Delta, O_3 replaced $PM_{2.5}$ as the primary pollutant throughout the year in 2014 and 2017, respectively [19]. O_3 is currently the primary air pollutant with the highest rate of excess in the PRD. In the past decade, the overall trend of the annual average concentration of O_3 in the air has continued to rise, and the health effects of the population caused by O_3 pollution have received increasing attention. However, there is a lack of long-term studies on the health effects and economic losses of O_3 pollution. In view of the above factors, this study uses the data of O_3 concentration monitored by the PRD Regional Air Quality Monitoring Network (PRD-RAQMN), exposed population, baseline mortality, and hospitalization rate from 2006 to 2018, and uses the relative risk model and other evaluation methods to evaluate the impact of O_3 pollution on human health and economic loss in Shenzhen in the past 13 year.

2. Research Methods

2.1. Estimation Method

The exposure effect coefficient between air pollution and health effect obtained from pollution epidemiology could be used to evaluate health risk. Based on the proportional hazard model of Poisson regression, the health effect value model formula under a certain O_3 concentration is obtained [20], as shown in Eq. (1).

$$E = E_0 \times \exp[\beta \times (C - C_0)] \quad (1)$$

$$\Delta E = E - E_0 \quad (2)$$

$$\Delta E = E \times \{1 - 1/\exp[\beta \times (C - C_0)]\} \quad (3)$$

$$I_i = P \times \Delta E = P \times E \times \{1 - 1/\exp[\beta \times (C - C_0)]\} \quad (4)$$

Where E_0 represents the health effect value at reference concentration, and E is the actual health effect value at actual concentration, such as mortality and hospitalization rate. P and β are exposed population and exposure effect coefficient, respectively. C and C_0 are the actual concentration and reference concentration, respectively. The change of health effects due to O_3 pollution could be calculated from Eq. (1). Finally, I_i caused by O_3 pollution could be calculated from Eq. (4).

The exposure effect coefficient between O_3 pollution and health terminal reflects the change of mortality and hospitalization rate of the circulatory system and respiratory system diseases for every 10 $\mu g/m^3$ increase in O_3 concentration. This study retrieved epidemiological studies related to the health effects of O_3 exposure at home and abroad to obtain relevant exposure effect coefficients, as shown in Table 1.

Table 1. *Exposure-response coefficient values of O_3 and various healthy terminals.*

Category	Health effect endpoint	Exposure-response coefficient (%)		Source
		β	95%CI	
Death	Circulatory system death	0.7	0.57~0.86	Liao Zhiheng et al. [17]
	Respiratory system death	0.64	0.47~0.86	Liao Zhiheng et al. [17]
Hospitalization	Circulatory system death	0.13	0.05~0.21	Wang et al. [21]
	Respiratory system death	0.22	0.15~0.29	Wang et al. [21]

Note: 95%CI represents a 95% confidence interval.

The U.S. Environmental Protection Agency (1997), the World Health Organization (2000), and the Ministry of Ecology and Environment of China revised the O_3 concentration standards, all of them used the maximum concentration of 8h per day. Therefore, the maximum concentration of 8h per day of O_3 was selected as the exposure index of O_3 concentration in this study. The selection of reference concentration reference of O_3 is very important in the evaluation of the effect of O_3 pollution on human health. The environmental background value given by the World Health Organization was mostly selected as the threshold value of O_3 pollution in the evaluation of O_3 pollution [17, 22]. According to the World Health Organization, the background concentration of O_3 in the earth's near-surface atmosphere was 70 $\mu g/m^3$ (calculated by the maximum concentration of 8 h per day, C_0=70 $\mu g/m^3$) [23].

The economic loss of O_3 pollution in the atmosphere is not only related to the concentration of O_3, but also to the exposed population, economic level, and medical expense of the whole society. The health economic loss of O_3 pollution could be divided into economic loss caused by premature death and the cost of hospitalization and labor caused by circulatory and respiratory diseases. In this study, the benefit conversion method and disease cost method were used to estimate the above two types of economic losses, respectively.

(1) The economic loss of premature death estimated by benefit conversion method

The economic loss caused by the premature death of residents is estimated by the method of benefit conversion [20]. The method is as follows:

$$W_{BJX} = W_{BJ2016} \times (I_{BJX}/I_{BJ2016})^e \quad (5)$$

Where W_{BJX} and W_{BJ2016} are the unit economic cos of premature death in year X and 2016 in Beijing (W_{BJ2016}=1197584 RMB) [24], respectively. I_{BJX} and I_{BJ2016} are the per capita disposable income in year X and 2016 in Beijing, respectively. The income elasticity coefficient is e and sets as 1.

$$W = W_{BJ} \times (I/I_{BJ})^e \quad (6)$$

$$C_{death} = I_i \times W \quad (7)$$

Where W and W_{BJ} are the unit economic cost of premature death in Shenzhen and Beijing, respectively. I and I_{BJ} are the per capita disposable income in Shenzhen and Beijing, respectively. C_{death} stands for the economic loss of premature death. The economic loss of premature death could be calculated from Eq. (6) and Eq. (7).

(2) The economic loss of hospitalization estimated by the disease cost method

The economic loss of hospitalization caused by O_3 pollution could be calculated by the method of disease cost, as Eq. (8).

$$C_{hospitalization} = (C_{pi} + GDP_P \times T) \times I_i \quad (8)$$

Where $C_{hospitalization}$ and C_{pi} are defined as the economic loss of hospitalization and hospitalization cost per unit case of health terminal, respectively. GDP_p is the daily average of per capita GDP in Shenzhen, and T represents the number of days in the hospital.

2.2. Data Source and Description

The date of O_3 daily 8 h maximum concentration annual average value was from the monitoring result report of PRD-RAQMN from 2006 to 2018 [25]. The data of disease terminal mortality, hospitalization rate, unit case hospitalization cost, and hospitalization were from the summary of health statistics in Shenzhen [26]. The data of the exposed population and GDP were from the statistical yearbook of Shenzhen [27]. The annual disposable income of Shenzhen [28] and Beijing were derived from the Guangdong Statistical Year book and the Chinese Statistical Yearbook [29], respectively. The statistics of mortality, hospitalization rate, and resident population in Shenzhen from 2006 to 2018 were shown in Table 2.

In the monitoring results report of PRD-RAQMN from 2006 to 2018, the annual value of daily 8 h maximum concentration of O_3 was not directly given in the monitoring results report from 2006 to 2013 [30]. Through adopted the rate of daily average value, daily 8 h maximum value, and daily 1 h maximum value was 8:15:20, the annual average value of 8 h maximum concentration of O_3 was calculated according to the daily average concentration in the monitoring results. The annual average value of 8 h maximum concentration of O_3 from 2014 to 2018 which was given in the monitoring results report was directly used in this study.

Table 2. *Morality and hospitalization rate of circulatory and respiratory disease in Shenzhen from 2006 to 2018.*

Year	Mortality rate (/million)		Hospitalization rate (/million)		Permanent population (/million)
	Circulatory	Respiratory	Circulatory	Respiratory	
2006	1.626	0.484	37.197	82.896	87.110
2007	1.759	0.486	40.586	87.437	91.237
2008	1.914	0.465	45.414	89.482	95.428
2009	1.926	0.411	52.309	110.740	99.501
2010	1.468	0.450	58.675	118.794	103.702
2011	1.694	0.460	64.300	116.058	104.674
2012	1.700	0.496	67.807	115.410	105.740
2013	2.775	0.345	75.982	134.620	106.289
2014	2.740	0.379	80.898	128.950	107.789
2015	2.662	0.418	83.557	124.437	113.787
2016	3.280	0.829	86.924	139.240	119.084
2017	3.222	0.812	95.564	141.014	125.283
2018	3.431	0.810	105.182	142.633	130.266

3. Results Analysis

3.1. Characteristic Analysis of O_3 Exposure Concentration

As shown in Figure 1, the concentration of O_3 showed an obvious upward trend from 2006 to 2018. According to the date of O_3 concentration monitored by PRD-RAQMN Shenzhen Ground Monitoring Station from 2006 to 2018, the concentration of O_3 in 2008 was in line with the benchmark value. given by the world health organization and was 70 $\mu g/m^3$. However, the concentration of O_3 in other years were exceeded the standard. The annual average range of daily 8 h maximum concentration of O_3 was 70~190 $\mu g/m^3$, with an average value of 112.89 $\mu g/m^3$. The annual average of daily 8 h maximum of O_3 reached the maximum value of 190.92 $\mu g/m^3$ in 2017 and increased 120.92 $\mu g/m^3$ compared to the lowest value of 70 $\mu g/m^3$ in 2008.

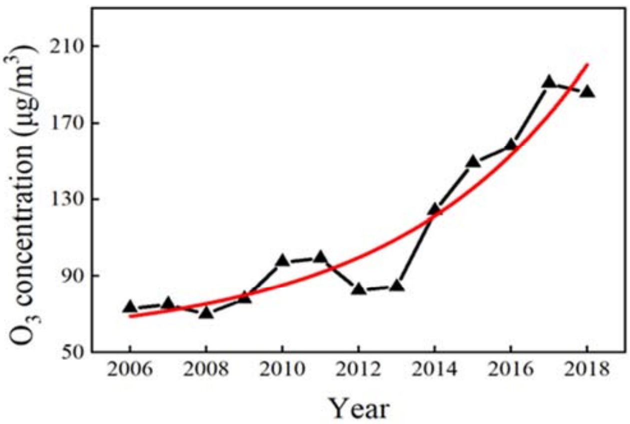

Figure 1. *The change of annual average of daily 8 h O_3 concentration in Shenzhen from 2006 to 2018.*

3.2. Health Effects of O_3 Pollution

By substituting the date of related health terminal mortality and hospitalization rate in Shenzhen from 2006 to 2018 into Eq. (4), the attributable death and hospitalization health effect values were obtained, and the results were shown in Figure 2.

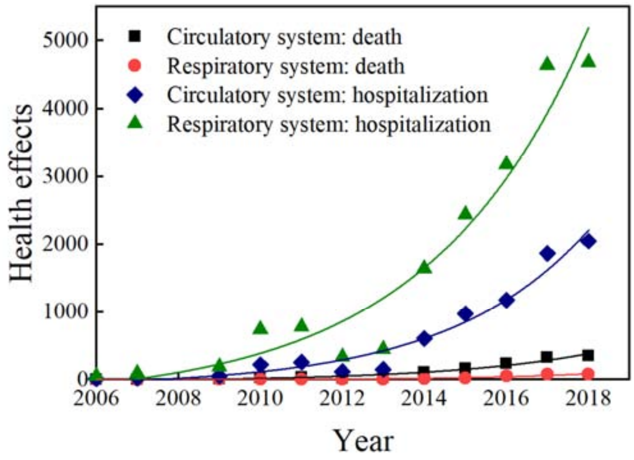

Figure 2. *Health effects of O_3 pollution in Shenzhen.*

According to the evaluation results, 66 cases were attributed to death and hospitalization in 2006 (95%CI: 41~91), and 7150 cases were attributed to death and hospitalization in 2008 (95%CI: 4335~9943). Then the number of attributable deaths and inpatients increased yearly, and the increasing trend was basically consistent with the increasing trend of O_3 concentration. In 2008, the cases of circulatory system attributable premature death (348 cases, 95%CI: 285~424) accounted for approximately 82.26% of total attributable deaths (423 cases, 95%CI: 341~524), which indicated that O_3 pollution mainly affected human circulatory system. From 2006 to 2012, the number of deaths attributed to circulatory system and respiratory system in Shenzhen was 100 (95%CI: 81~122) and 25 (95%CI: 18~34), respectively, and then the number of deaths attributed to circulatory system and respiratory system in PRD was 1894 (95%CI: 1546~2319) and 1128 (95%CI: 830~1508), respectively. The number of deaths attributed to the circulatory system and respiratory system in Shenzhen accounted for 5.28% and 2.22% of the 13 cities in the PRD, respectively. The number of attributable deaths and inpatients calculated was 0 in 2008, due to the concentration of O_3 not reached the reference concentration.

In terms of health categories, the number of deaths attributed to the circulatory system and respiratory system was 1311 (95%CI: 1074~1599) and 271 (95%CI: 201~361) in 2006~2018, respectively. And the number of hospitalizations attributed to the circulatory system and respiratory system was 7506 (95%CI: 2807~12081) and 19214 (95%CI: 13141~25249), respectively. It showed that the circulatory diseases caused by O_3 pollution were more difficult to cure than respiratory diseases, and the hospitalization of respiratory diseases was higher than that of circulatory diseases.

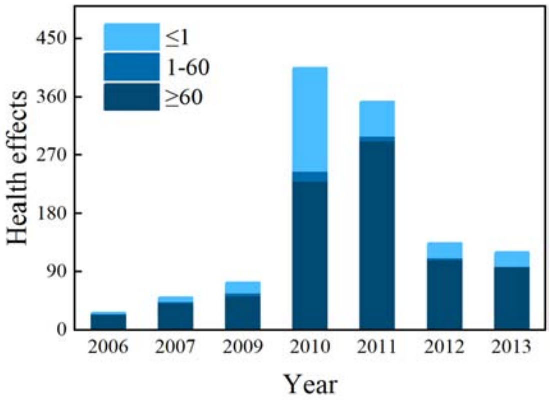

Figure 3. *Health effects of circulatory system diseases in different age groups.*

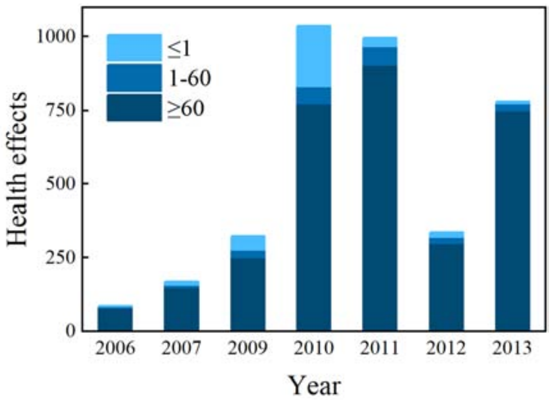

Figure 4. *Health effects of respiratory system diseases in different age groups.*

3.3. Health Effects of O_3 Pollution in Different Age Groups

The attributed death was divided into the age group ≤1-year-old, the age group from 1 to 60 years old, and the age group ≥60 years old according to the death dates of all age groups in the summary of health statistics of Shenzhen city. The health effects of the circulatory system and respiratory system diseases were shown in Figure 4 and Figure 5, respectively. Only, the situation from 2006 to 2013 was analyzed in this study because of the limited date. The health effects of the circulatory system and respiratory system in the age group ≥60 years old accounted for 86.88% and 78.75% of the total, respectively, indicating that people aged ≥60 years old were more affected by O_3 pollution. In addition, the mean value of circulatory system health and respiratory system health were 458 cases and 120 cases, respectively, indicating that cardiovascular diseases mainly exist in the elderly population. Because of the aging cardiovascular for the elderly, the risk of disease increases. The age group ≤1-year-old was also greatly affected by O_3 pollution because of its poor resistance. The health effects of the circulatory system and respiratory system accounted for 7.42% and 17.76% of the total, respectively. And the mean health effects were 45 cases and 39 cases, respectively.

3.4. Health and Economic loss of O_3 Pollution

The health and economic loss of O_3 pollution in Shenzhen from 2006 to 2018 was calculated by Eqs. (5) - (8). As shown in Table 3, the health economic loss caused by O_3 pollution was very large, and the average economic loss was 82.46 million RMB/ year. The economic loss reached 658.31 million RMB (95%CI: 502.37-827.86 million RMB) and accounted for 0.0272% (95%CI: 0.0207~0.0346%) of Shenzhen's GDP in 2018. The estimate of average economic loss was lower than the estimate of other major cities calculated by Zeng et al.[19]. This phenomenon could be attributed to that Shenzhen is a new city with a relatively young population, so the mortality rate was relatively low.

The economic losses of the circulatory system and respiratory system were 1661.23 million RMB (95%CI: 1286.61~2092.50 billion RMB) and 482.85 million RMB (95%CI: 347.87~639.22 million RMB) from 2006 to 2018, respectively. The number of inpatients was far more than the number of deaths according to the above, but the economic loss of death accounted for 77.5% of the total economic loss. Therefore, the economic loss was mainly caused by premature death. The attributable economic loss was 3.2 million RMB (95%CI: 2.47~4.09 million RMB) in 2006, while it reached 658.31 million RMB (95%CI: 502.37~837.86 million RMB) in 2018, an increase of 95.6%. Combined with Figure 1 and Figure 5, it could be seen that the attributable health economic loss increased yearly with the aggravation of O_3 pollution. In 2018, the economic loss of health caused by the death of the circulatory system and respiratory system increased by 454.73 million RMB and 98.37 million RMB, respectively. And the economic loss of health caused by the hospitalization of the circulatory system and respiratory system increased by 53.46 million RMB and 48.55 million RMB, respectively. It could indicate that the economic loss caused by the death of the circulatory system increased the most.

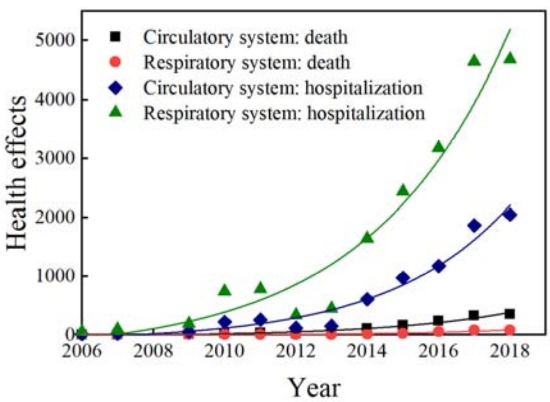

Figure 5. *Health and economic loss assessment of O_3 pollution in Shenzhen.*

Table 3. *Evaluation of Health and Economic Losses of O_3 Pollution in Shenzhen (100 Million RMB).*

Year	Mortality		Hospitalization		Sum
	Circulatory	Respiratory	Circulatory	Respiratory	
2006	0.0225	0.0061	0.0015	0.0019	0.0320
2007	0.0429	0.0108	0.0029	0.0035	0.0601
2008	0.0000	0.0000	0.0000	0.0000	0.0000
2009	0.0703	0.0137	0.0073	0.0092	0.1005
2010	0.2143	0.0601	0.0326	0.0409	0.3479
2011	0.3004	0.0746	0.0419	0.0485	0.4654
2012	0.1451	0.0388	0.0198	0.0226	0.2263
2013	0.3007	0.0342	0.0278	0.0335	0.3962
2014	1.0227	0.1295	0.1191	0.1322	1.4035
2015	1.6582	0.2386	0.2058	0.2137	3.0319
2016	2.5904	0.6002	0.2770	0.2865	3.7541
2017	3.9539	0.9143	0.4492	0.4378	5.7552
2018	4.5698	0.9898	0.5361	0.4874	6.5831
Sum	14.8912	3.1107	1.7210	1.7177	22.1562

4. Discussion

4.1. Selection of Health Effect

The choice of the health effect terminal of air pollution should follow the principle of the most sensitive effect, which could sensitively and accurately reflect the adverse effects of certain air pollutants on the health of the population [31]. However, the selection of such health effect endpoints is often difficult and complicated. The influence of air pollution on human health was complex, which included acute effects and chronic effects. The toxic mechanism of O_3 pollution to human health was not clear. On the other hand, O_3 may cooperate with other pollutants in the atmosphere, and the characteristics of health hazards are complex, so it is difficult to select health terminals. In this study, the death and hospitalization of the respiratory system and circulatory system diseases as health effects were selected to evaluate their economic loss. This study evaluated the risk of early death and hospitalization caused by O_3 pollution and did not calculate other health effects such as outpatient service. Therefore, the health effects of O_3 pollution may be underestimated.

4.2. Determination of Threshold

Whether there is an impact threshold for air pollutants is an important issue in health impact assessment. Some studies showed that O_3 has no obvious threshold value. However, relevant toxicology studies indicated that the human body has certain self-regulation and adaptability to the impact of exogenous chemicals. When the exposure pollutant reached a certain concentration and exceeded its self-regulation, pathological changes and health damage may occur. Many epidemiological studies showed that the morbidity and mortality of the relevant population would change when air pollution reached a certain concentration. The Air Quality Guideline (AQG) [23] issued by the World Health Organization (WHO) considered that there was a critical value causing health hazards, and recommended that the atmospheric environmental quality standards in the guidelines be used as threshold values for O_3 air pollution research. Therefore, the value of environmental background of 70 $\mu g/m^3$ (calculated as the maximum concentration of 8 h per day) given by the WHO was selected as the threshold value of O_3 pollution in this study.

4.3. Determination of Exposure Effect Coefficient

The impact of air pollution on human health was expressed by a dose-response function of pollutants and health hazard terminals. The health damage assessment model of air pollution first studies the correlation coefficient between an air pollutant and corresponding health effect endpoint, the calculates the ratio of each unit of increase in air pollutant concentration leading to the corresponding health endpoint, such as the increase of population mortality or morbidity, which is the basis for the assessment of effect of population health. There were two methods to establish the dose-response relationship model of the health effects of air pollution. One is the method of environmental epidemiology, which is to carry out environmental epidemiology investigation and research in the areas that need to be calculated. At the same time, the corresponding air pollution monitoring data and relevant data are collected. Based on the data of various terminals of health effects and other confounding factors that endanger the health of the population, the data are statistically analyzed to obtain a statistical model and the correlation coefficient of the dose-response relationship between the two as the basis for effective evaluation. This method was divided into long-term cohort study and time-series study. Another is the basic method of health risk assessment, which is used to collect the data of relevant research literature at home and abroad. The dose-response relationship model of air pollutants and related health effect endpoints are obtained according to certain statistical methods. In this study, the exposure effect coefficient β between O_3 pollution and the health terminal was used to evaluate the health effect of O_3 pollution in Shenzhen.

4.4. Evaluation Method of Health Economic Loss

In assessing the premature economic loss caused by pollution, China often uses per capita GDP as the value of a statistical life year's contribution to GDP, namely the modified human capital method. It is estimated based on the loss cost of income and direct medical costs. The revised human capital method and the disease cost method is used to calculate the loss of premature death and the cost of disease, respectively. Therefore, the evaluation results obtained by the study should be the lowest value of health economic losses caused by air pollution.

5. Conclusion

Based on the analysis results, the following conclusions were drawn:

1. The annual average change of the daily 8 h maximum concentration of O_3 in Shenzhen showed an obvious upward trend from 2006 to 2018, with the annual average value ranging from 79 to 190.92 μg/m^3 and the average value of 112.89 μg/m^3. It reached the maximum value of 190.92 μg/m^3 in 2017, and increased 120.92 μg/m^3 compared to the lowest value of 70 μg/m^3 in 2008, with an increase rate of 172%.
2. The number of deaths and hospitalizations due to O_3 pollution increased yearly in Shenzhen from 2006 to 2018. The incidence of respiratory system diseases caused by O_3 pollution was higher than that of circulatory system diseases. However, the mortality caused by circulatory system diseases was far higher than that of respiratory system diseases. In addition, the group whose age is beyond 60 years old is the most risk group affected by O_3 pollution.
3. The health and economic loss of O_3 pollution increased yearly in Shenzhen from 2006 to 2018, and the average economic loss was RMB 82.46 million/year. The economic loss reached RMB 658.31 million (95%CI: 502.37-827.86 million) and accounted for 0.0272% of Shenzhen's GDP in 2018.

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