ENVIRONMENTAL SCIENCE & POLICY 15 (2012) 38–47

Available online at www.sciencedirect.com

SciVerse ScienceDirect

journal homepage: www.elsevier.com/locate/envsci

Valuing the health risks of particulate air pollution in the Pearl River Delta, China

Desheng Huang, Jianhua Xu, Shiqiu Zhang *

Institute of Environment and Economy, College of Environmental Sciences and Engineering, Peking University, Beijing, 100871, PR China

ARTICLE INFO

Keywords:
Economic loss
Particulate matter
Health effect
Valuation
Pearl River Delta

ABSTRACT

The Pearl River Delta (PRD) in Southern China is a region where the manufacturing industry is rapidly developing, accounting for about 10% of the gross domestic product (GDP) with 4% of China's population. The economic development in this region is accompanied by severe air pollution that poses harm to people's health and causes economic loss. This paper estimates the adverse health effects of particulate matter pollution in the PRD by using a log-linear exposure–response function, and monetizes the morbidity effect by using the cost of illness (COI) method and the mortality effects by using both the amended human capital (AHC) method and the results of contingent valuation (CV) study. The results show that in 2006 the total economic loss of the health effects from PM_{10} pollution in PRD is 29.21 billion Chinese yuan by using CV results and COI method, which is equivalent to 1.35% of the regional GDP, and is 15.51 billion Chinese yuan by using AHC and COI methods, which is equivalent to 0.72% of the regional GDP. The economic loss due to premature death and chronic respiratory disease accounts for more than 95% of the total loss. Despite the uncertainties, the results clearly show the severity of the health effects and economic loss incurred by particulate matter pollution in PRD; the results further point to the need for developing environmentally friendly industry, and provide a benchmark for comparing alternative options to reduce air pollution.

1. Introduction

The Pearl River Delta (PRD)[1] Economic Zone consists of nine prefecture-level cities (Fig. 1), located in Guangdong, a southern coastal Chinese province adjacent to Hong Kong. The PRD is well-known as a manufacturing center supplying a wide variety goods ranging from toys, home appliances to electronics and communication equipments to all over the world (Enright and Scott, 2005). As the forerunner of China's economic reform, this region has made tremendous economic progress since the reform and opening policy was adopted about 30 years ago. From 1978 to 2007, PRD's gross domestic product (GDP) has been increasing at an average annual rate of 21.2%. In 2006, PRD produced 10.16% of the total national GDP in an area 0.43% of the total land (Statistics Bureau of Guangdong Province, 2007; National Bureau of Statistics of China, 2007). These achievements were accomplished by developing high energy- and resource-intensive industries. As an unwanted by-product, the air quality in the PRD cities deteriorated and the PRD has been suffering from acid rain, ozone pollution and particulate matter pollution. Especially, severe haze pollution has descended routinely into the PRD in recent years, greatly impairing the health of the population and the visibility throughout the region (Wu et al., 2007b; Huang et al., 2008; Deng et al., 2008; Xie et al., 2011). The

* *Corresponding author*. Tel.: +86 10 62764974; fax: +86 10 62760755.
E-mail addresses: hds@pku.edu.cn (D. Huang), jianhua.xu@pku.edu.cn (J. Xu), zhangshq@pku.edu.cn (S. Zhang).

[1] The Great Pearl River Delta consists of Hongkong, Macao and the PRD Economic Zone. Here we only focus on the PRD Economic Zone, which is part of the Guangdong province.

1462-9011/$ – see front matter
doi:10.1016/j.envsci.2011.09.007

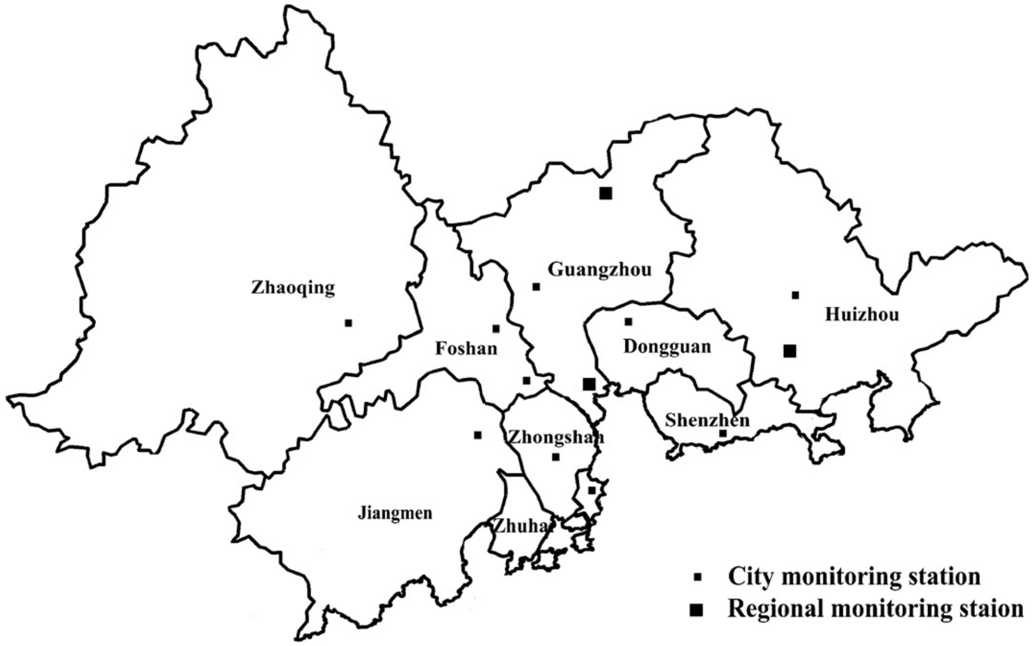

Fig. 1 – The Pearl River Delta and its nine cities which are Guangzhou, Shenzhen, Zhuhai, Foshan, Jiangmen, Dongguan, Zhongshan, Huizhou and Zhaoqing, as well as the locations of air quality monitoring stations (the picture is revised from the report by Guangdong Provincial Environmental Protection Monitoring Centre and Environmental Protection Department, Hongkong (2006)).

primary culprit of haze is particulate matter (PM) (Huang et al., 2008; Wu et al., 2007a; Zhang et al., 2008). PM is comprised mostly of metals, dust, organic chemicals, sulfates and nitrates, is a mixture of small solid particles and liquid droplets, which is either directly emitted from fossil fuel combustion, industrial processes, construction activities, and various transportation sources or formed secondarily via various chemical and physical processes in the atmosphere. In the PRD, the major sources of PM are wind-blown dust and industrial activities followed by coal-fired power plants and vehicular emissions; in the individual PRD cities, these are the major PM emission sources as well, but the contributions of these sources in the different cities are somewhat different reflecting the different development strategies of them.

The associations of exposure to PM pollution and increases in premature mortality and the various morbidity effects have been well-documented (Dockery et al., 1993; Pope et al., 1995; Brunekreef and Holgate, 2002; Li et al., 2003; Jia et al., 2004). The major concerns on human health include mortality, bronchitis, asthma, respiratory and cardiovascular hospital admissions, and outpatient visits. The economic loss from health effects incurred by PM at sectoral levels and at different geographical locations has been estimated in China. Ho and Jorgenson (2007) estimated the total national health damage due to PM pollution to be 117 billion Chinese yuan, or 1.6% of GDP in 1997. Particularly, this study estimated the health damage incurred by PM contributed from the different sectors. The World Bank (2007) estimated the health cost of urban PM pollution in China in 2003 which was 157 billion Chinese yuan by using amended human capital (AHC) method and 520 billion Chinese yuan by using the value of statistical life (VSL), equivalent to 1.2% and 3.8% of the 2003 national GDP, respectively. Yu et al. (2007) estimated that the health cost of PM_{10} pollution over 659 Chinese cities was 170.3 billion Chinese yuan by using AHC method, which was equivalent to 1.02% of the 2004 national GDP. Zhang et al. (2007) estimated that the health cost of PM_{10} in Beijing from 2000 to 2004 ranges from 1.67 to 3.66 billion Chinese yuan by using adjusted VSL from previous studies, which was equivalent to 5.58–7.06% of Beijing's GDP. Despite the inherent uncertainties in estimating and monetizing health damage, these numbers approximate the magnitude of health cost incurred by PM pollution; to date, no studies on estimating the economic cost of health effect incurred by PM pollution in PRD, the main manufacturing center in China, have been conducted yet.

About 4% of China's population resides in the PRD, where the PM pollution is among the most severe anywhere in China (Zhang et al., 2008). As the living standards improve and people's environmental awareness grows, the demand for cleaner air increases in PRD as indicated by the large number of complaints about air pollution in recent years (SEPA, 2008). In this research, we monetize the health effects of PM pollution in PRD for two reasons: (1) to justify the proposal and implementation of more stringent air pollution abatement strategies, and (2) to provide a benchmark for selecting alternative control options to reduce air pollution. Although $PM_{2.5}$ is reported to be the part most strongly associated with the health effects (Kan et al., 2007; Pope et al., 2002; Schwartz et al., 1996; Xie et al., 2009), we select PM_{10} with $PM_{2.5}$ being part of it as the target pollutant given PM_{10} instead of $PM_{2.5}$ is monitored in the current routine monitoring practice. We select 2006 as the study year mainly because PM_{10} data is available for the PRD cities and the PM pollution in this area has not been significantly changed since then (Wan et al., 2011).

The following sections introduce the methods that are used to estimate and monetize the health effects of PM pollution in PRD, describe the data and parameters that are chosen, discuss the results and uncertainties, and finally, conclusions drawn.

2. Methods

Following the general approach used for health damage assessment (Tietenberg, 2005), we identify the health outcomes associated with the exposure to PM_{10} pollution and the exposed population, estimate the adverse health effects by using appropriate exposure–response functions, and monetize the estimated health effects with various valuation methods.

2.1. *Estimating the health effects*

According to epidemiological study results, exposure to PM_{10} may cause a wide range of respiratory, systemic and cardiovascular effects. In this paper, we only select those health outcomes that can be quantitatively estimated and monetized, including chronic and acute mortality, chronic bronchitis, acute bronchitis, asthma, outpatient visits (pediatrics and internal medicine) and respiratory and cardiovascular hospital admissions. Neglected are the health outcomes that are hard to assess such as decreased lung function, pain and suffering, restricted activity days and other sub-clinical symptoms. It is understood that omitting these health outcomes may lead to the underestimation of the health cost to some extent.

Selecting the exposure–response function is the core part because it greatly affects the magnitude of the eventual valuation results (Zou and Zhang, 2010). The incidence of morbidity or mortality among the population can be regarded as random events, and follows a Poisson distribution. Most epidemiologic studies linking air pollution with health effects use a relative risk model based on Poisson regression (Kan and Chen, 2004; Kan et al., 2004). Though most of them showed statistically significant and relatively linear associations between PM concentrations and health end-points, a log-linear function is more plausible and recommended for use to estimate the health effects for cities with high PM concentrations (WHO, 2006). Given the PM_{10} concentrations in the PRD cities are high, we therefore chose a log-linear exposure–response function according to the studies of Kan and Chen (2004), Kan et al. (2004) and Yu et al. (2007) to estimate the health effects in this paper.

The incidence of each health outcome under the actual PM_{10} pollution condition can be expressed as:

$$I = I_0 \times \exp(\beta \times (C - C_0)) \tag{1}$$

where C is the actual PM_{10} concentration, I is the incidence rate of the population exposed in the actual situation, C_0 is the baseline PM_{10} concentration, I_0 is the incidence rate of the population exposed in the baseline scenario, and β is the exposure–response coefficient. There are many factors affecting the health of the population, just name a few, nutrition status, accessibility to health service, exposure to polluted air, and smoking history. The health effects due to all the factors other than exposing to PM_{10} is the health effects when PM_{10} concentration is equal to C_0.

Then, the incremental incidence rate attributed to the actual PM_{10} pollution can be estimated by using the following equation:

$$\Delta I = I - I_0 = I \times \left(1 - \frac{1}{\exp(\beta \times (C - C_0))}\right) \tag{2}$$

The number of cases (E) with the specified health outcome attributed to PM_{10} pollution among the exposed population (P) can be estimated by using the following equation:

$$E = P \times I \times \left(1 - \frac{1}{\exp(\beta \times (C - C_0))}\right) \tag{3}$$

2.2. *Monetizing the health effects*

Welfare economics assumes that life (or health) has values like other goods and the values can be compared. Specifically, it assumes that individuals are rational and the various choices they make in their daily life involve the trade-offs between the changes in health risk and money or other economic goods that can be measured by money.

The economic loss due to the health damage attributed to PM_{10} pollution, denoted as L, can be estimated by using the following equation:

$$L = \sum_{i=1}^{M} L_i = \sum_{i=1}^{M} E_i \times Lp_i \tag{4}$$

where i is the index of health outcomes (e.g., bronchitis, asthma) attributed to PM_{10} pollution, M is the total number of types of health outcomes attributed to PM_{10} pollution, L_i is the economic loss of health outcome i across the population in the studied region, E_i is the estimated number of people with health outcome i due to PM_{10} pollution, and Lp_i the economic loss associated with one case of health outcome i.

The key is to determine the economic loss associated with one case of a certain health outcome, i.e., the value of health or life. Given that health and life are irreplaceable and have no market price, indirect approaches such as contingent valuation (CV) approach, human capital (HC) or amended human capital (AHC) approach, and the cost of illness (COI) approach are used for health valuation. Different valuation methods are used for the different health outcomes attributed to PM_{10} exposure. We use CV and AHC method to evaluate the economic loss of premature death and chronic bronchitis, and COI method to estimate the economic loss of other health outcomes, including acute bronchitis, asthma, outpatients and inpatients.

2.2.1. *Contingent valuation (CV) method*

CV method is a nonmarket valuation method that is widely used in environmental impact assessment and cost-benefit analysis (Venkatachalam, 2004). It can effectively measure the money that individuals are willing to pay for improving their own and others' safety or health. There are many studies conducted using CV method to estimate the value of life in general. However, there are only a few such studies conducted in a Chinese setting (Hammitt and Zhou, 2006; Wang and Mullahy, 2006) and none of them were conducted in the PRD, our study region. The valuation results obtained in other countries are not suitable for our estimation given the differences in economic and social development and people' perceptions about environmental problems across nations. As an alternative, we use the value of statistical life (VSL) obtained with the CV study conducted in Chongqing (a southwestern Chinese city) in 1998 by Wang and Mullahy (2006), and take into account the differences in residential income between cities and years, to estimate the VSL in the PRD cities.

$$\mathrm{VSL_{PRD}} = \mathrm{VSL_{CQ}} \times \left(\frac{I_{\mathrm{PRD}}}{I_{\mathrm{CQ}}}\right)^{e} \tag{5}$$

where $\mathrm{VSL_{PSD}}$, $\mathrm{VSL_{CQ}}$, I_{PSD}, I_{CQ}, and e represents the VSL of residents in the PRD cities in 2006, the VSL of residents in Chongqing in 1998, the yearly per capita income in the PRD cities in 2006, the yearly per capita income in Chongqing in 1998, and the income elasticity coefficient, respectively. The income elasticity coefficient is normally set to be 1.

2.2.2. Human capital (HC) and amended human capital (AHC) method

In the HC approach, individuals are considered as the basic unit of human capital providing products and services. This approach measures the loss of life and health according to a general standard for assessing physical capital, usually represented as wage or labor capital. The HC approach merely takes the expected income loss as the loss from premature death. So there is an implicit assumption that value of life of individuals with different incomes is different, which often raises ethical concerns. To fix this, the amended human capital (AHC) approach was put forward, which use per capita GDP to measure the value of a statistical year of life (Eq. (6)). It estimates human capital from the perspective of the entire society, neglecting individual differences. AHC approach has advantages in data collection, and is currently widely used in life valuation. The estimated results by using HC or AHC are more conservative than those obtained with the CV method.

$$\mathrm{HCL} = \sum_{k=1}^{t} \mathrm{GDP}_k^{pv} = \mathrm{GDP}_0 \times \sum_{k=1}^{t} [(1+\alpha)/(1+r)]^k \tag{6}$$

where HCL represents the human capital or life value of individuals based on per capita GDP, t is the per capita loss of life years, GDP_k^{pv} is the per capita GDP in year k, GDP_0 represents per capita GDP in the baseline year, α is the growth rate of per capita GDP, and r is the social discount rate.

2.2.3. Cost of illness (COI) method

COI method directly estimates the minimum value of health damage by calculating various disease related costs, including pharmaceutical, diagnostic, treatment and hospitalization costs, and the loss of income or social loss of GDP due to illness. Cost of illness (COI) method is widely used to measure the cost of different diseases in various regions with different levels of economic and social development. We use the COI method to estimate the cost of acute bronchitis, asthma, outpatients and inpatients. The basic formula is as follows:

$$C_i = (C_{Pi} + \mathrm{GDP}_p \times T_{Li}) \times \Delta I_i \tag{7}$$

where C_i is the aggregated cost of health outcome i, Cp_i is the cost per case of medical treatment for health outcome i, GDP_p is the per capita GDP, T_{Li} is the working time loss due to disease i, and ΔI_i represents the increased number of cases of health outcome i attributed to PM_{10} pollution.

3. Results

In using the equations in Section 2 to estimate the health effects associated with exposure to PM_{10} pollution in the PRD cities in 2006 and monetize the health effects, we need the information on ambient PM_{10} concentration, baseline PM_{10} concentration, exposed population, exposure–response coefficients, and the economic loss per case of a certain health outcome. The inputs and results are detailed below.

3.1. Inputs

3.1.1. PM_{10} concentration

The hourly and annual average ambient PM_{10} concentrations in the nine PRD cities from January 1, 2006 to December 31, 2006 are provided by Guangdong Provincial Environmental Monitoring Center (data are available upon request); they operate 13 air quality monitoring stations across the PRD (Fig. 1). The distributions of PM concentrations across the PRD cities are shown in Fig. 2. It can be seen that PM concentrations in cities located at central and northeast PRD (e.g., Foshan, Dongguan and Huizhou), where manufacturing industry is dynamic, are higher than the PM concentrations in cities located at southeast PRD (e.g., Zhuhai), where tourism industry is booming.

The baseline PM_{10} concentration is set at zero. Generally, a threshold, derived from the lowest concentration at which individual's adverse health effects can be observed or the highest concentration at which individual's adverse health effects cannot be observed, is taken as the baseline concentration. However, a large number of studies show that there seem to be no health effect threshold concentration for ambient PM (Morgan et al., 2003; Pope, 2000). Thus, we set the baseline PM_{10} concentration at zero.

3.1.2. Exposure–response coefficients

The exposure–response coefficients are derived from the meta-analysis results of Kan and Chen (2002) and Xie et al. (2009), as shown in Table 1. Exposure–response coefficients obtained from cohort study in the study region are ideal for estimating the health effects due to PM pollution. No cohort studies in a Chinese setting have been reported yet. The results from the two American cohort studies, which are the Harvard Six Cities study (Dockery et al., 1993) and the American Cancer Society cohort study (Pope et al., 2002), are not applicable to the PRD, given that these studies were conducted in USA cities where the PM concentration were significantly lower than that in the PRD cities. Previous studies show that the relative risk curve gets flatter as PM

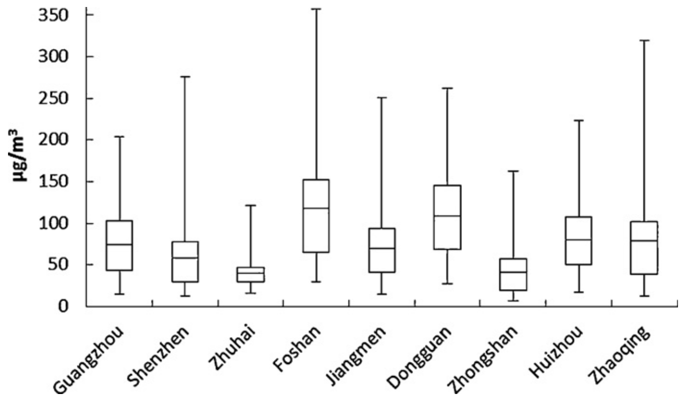

Fig. 2 – The distribution of PM_{10} concentrations in the nine PRD cities.

concentration increases and becomes horizontal as the PM_{10} concentration exceeds 100 μg/m^3 (Ostro, 2004; Cohen et al., 2004). The PM_{10} concentration in PRD ranges from below 10 μg/m^3 to 300 μg/m^3 and above, directly applying the coefficients of Pope's or Dockery's study is inappropriate. Therefore, we adopted the results of meta-analysis of well-selected studies in Chinese settings.

There are three studies using meta-analysis to integrate the epidemiological studies on the relationship between exposure to PM pollution and health effects in China: Kan and Chen (2002), Aunan and Pan (2004) and Xie et al. (2009). The health outcomes from Aunan and Pan (2004) do not match the health outcomes that we selected for health effect valuation. Therefore, based on the selected health outcomes that we want to assess, the exposure–response coefficients derived from two meta analysis, i.e. Kan and Chen (2002) and Xie et al. (2009), are selected for their corresponding health outcomes and applied to our estimation.

3.1.3. *Health information*

The mortality and the morbidity of each disease in the PRD cities are mainly estimated by using the data in the Health Statistical Yearbook of Guangdong Province 2007 (Department of Health of Guangdong Province, 2007) and the results of the 2000 population census of Guangdong province (Population Census Office of Guangdong Province, 2002). When the information for disease incidence rate in a city is not available, the average health information of Guangdong Province is used. The basic health information is listed in Table 1.

3.1.4. *Exposed population*

The exposed population is obtained from Guangdong Statistical Yearbook 2006 (Statistics Bureau of Guangdong Province, 2006). We include both the registered residents and non-registered residents, taking into consideration the large size of the migrating population in the PRD. The population is divided into two categories, children and adults, as shown in Table 2.

3.1.5. *Economic loss per case of a certain health outcome*

The economic loss per case of a certain health outcome as estimated by using the different valuation methods is shown in Table 3.

The economic loss per case of premature death is estimated by using CV and AHC methods. In using CV results, the VSL in the different PRD cities is derived from the VSL obtained with Chongqing subjects according to Eq. (5), which

Table 1 – Exposure–response coefficients (refer to Eq. (1)) and the incidence rate of each health outcome under the actual PM_{10} pollution condition.

Health outcome	Coefficients β (95% CI)	Reference	Incidence rate
Chronic effect			
All cause mortality	0.00148 (0.00038,0.00252)	Kan and Chen (2002)	–[a]
Chronic bronchitis	0.00505 (0.00183,0.0078)		0.00148
Acute effect			
All cause mortality	0.00046 (0.00013,0.00079)	Kan and Chen (2002)	–[a]
Acute bronchitis	0.00505 (0.00192,0.00904)		0.0372
Asthma	0.0019 (0.00145,0.00235)	Xie et al. (2009)	0.0094
Hospital admissions			
Respiratory disease	0.00124 (0.00086,0.00162)	Xie et al. (2009)	0.00797
Cardiovascular disease	0.00066 (0.00036,0.00095)		0.00325
Outpatient visits			
Internal medicine	0.00042 (0.00025,0.00061)	Kan and Chen (2002)	0.14856
Pediatrics	0.00047 (0.00017,0.00077)		0.54261

[a] All cause mortality rate for chronic and acute effect refers to the non-accident mortality as shown in Table 2.

Table 2 – Information on the exposed population and non-accident mortality in the PRD cities.

City	Population (persons)	Child (%) (<15 years old)	Adult (%) (≥15 years old)	Population density (persons/km^2)	Non-accident mortality (%)
Guangzhou	9,496,800	14.91	85.09	1277	3.5734
Shenzhen	8,277,500	9.21	90.79	4239	0.0734
Zhuhai	1,415,700	16.39	83.61	839	1.2734
Foshan	5,800,300	14.19	85.81	1507	3.3834
Jiangmen	4,102,900	18.38	81.62	430	3.5834
Dongguan	6,560,700	7.65	92.35	2662	1.9534
Zhongshan	2,434,600	13.65	86.35	1352	2.7634
Huizhou	3,706,900	19.90	80.10	332	2.3634
Zhaoqing	3,676,000	26.55	73.45	247	3.5434

was US$34,458 in 1998. In using the AHC method, the human capital (the value of individuals' life) is estimated according to Eq. (6) by setting the loss of years of life for an individual, the growth rate of per capita GDP and the social discount rate to be 14 years, 10.89%, and 8%, respectively, following Han et al. (2006) and the Health Statistics Yearbook of China and Guangdong Province.

The economic loss per case of asthma and acute bronchitis is assumed to be equal to the cost of medical treatment per case of asthma and acute bronchitis, respectively. Tang et al. (2000) surveyed 71,867 asthmatics in Guangdong Province where the PRD is located in 1999 and found that the average medical cost per case of asthma was 634.2 Chinese yuan. The average medical cost per case of asthma in 2006 in the PRD cities is derived from this 1999 value, adjusted by using disposable per capita incomes in the different years. The economic loss per case of acute bronchitis in 2006 in the PRD cities is derived from the medical cost per case of acute bronchitis in Shanghai (52.56 Chinese yuan) by Kan and Chen (2004), taking into consideration the difference in disposable income in these cities.

For chronic bronchitis, it is difficult to estimate its health cost by using the COI method since we do not know how often one needs to visit doctors. Viscusi et al. (1991) suggested an alternative approach to derive the revealed utility of living with a disease, and found that the utility of living with chronic bronchitis was about 0.68 of the utility of living in good health (Viscusi et al., 1991). That means if good health is scaled to equal 1 and death is scaled to equal 0, living a life with chronic bronchitis is equal to losing 32% of life. Thus, this number can be converted to the value of a statistical case of chronic bronchitis by multiplying the VSL by 0.32.

In estimating the cost per case of outpatient and inpatient care in the PRD cities, the cost per case of medical treatment for health outcome is obtained by using the average cost for outpatient and hospital admission and the average duration of stay from Guangdong Health Statistical Yearbook 2007. The work time loss for outpatient is assumed to be 0.5 days; the work time loss for inpatient is set to be 9.5 days for respiratory disease and 11.5 days for cardiovascular disease.

3.2. *Results*

3.2.1. *Health effects of PM_{10} pollution*

Table 4 shows the various health effects attributed to PM_{10} pollution in the PRD cities in 2006. It can be seen that about 12,800 premature deaths, 21,600 cases of chronic bronchitis, 496,900 cases of acute bronchitis, 55,000 cases of asthma, 292,200 outpatient visits and 38,500 hospital admissions in 2006 can be attributed to PM_{10} pollution in the PRD. The number of premature deaths due to long-term exposure is more than 3 times that due to short-term exposure, which is consistent with the implication of Kan et al. (2005). The number of cases of acute bronchitis is overwhelmingly larger than that of the chronic bronchitis. Further analysis shows that although the absolute number of adult outpatient visits is significantly greater than that of the children outpatient visits, children are about 1.5 times more likely to be impacted by air pollution taking into consideration of the population sizes of children and adults respectively. The number of hospital

Table 3 – Economic loss per case of health outcomes in the PRD cities (Chinese yuan).

City	Premature death (million)		Chronic bronchitis (million)		Acute bronchitis	Asthma	Outpatient		Inpatient	
	VSL	AHC	VSL	AHC			Adult	Child	Respiratory	Cardiovascular
Guangzhou	1.54	1.08	0.49	0.35	1512	1113	1122	708	12,253	12,598
Shenzhen	1.75	1.19	0.56	0.38	1512	1113	1130	674	7444	7824
Zhuhai	1.37	0.90	0.44	0.29	1512	1113	1015	672	7248	7534
Foshan	1.51	0.86	0.48	0.28	1512	1113	951	621	9282	9558
Jiangmen	1.24	0.39	0.40	0.13	1512	1113	635	484	6501	6627
Dongguan	1.87	0.68	0.60	0.22	1512	1113	688	428	4924	5140
Zhongshan	1.47	0.72	0.47	0.23	1512	1113	964	688	4967	5198
Huizhou	1.08	0.43	0.34	0.14	1512	1113	535	371	6364	6501
Zhaoqing	0.90	0.24	0.29	0.35	1512	1113	418	326	5019	5095

Table 4 – Health effects attributed to PM_{10} pollution in the PRD cities in 2006, mean value (95% CI).

City	Premature death[a]	Premature death[b]	Chronic bronchitis	Acute bronchitis	Asthma	Outpatient	Inpatient
Guangzhou	3554 (952, 5826)	1130 (337, 1929)	4416 (1800, 6208)	106,427 (46,395, 163,112)	11,590 (9026, 14,051)	61,005 (32,389, 90,572)	8078 (5476, 10,574)
Shenzhen	52 (14, 85)	15 (4, 26)	3196 (1274, 4572)	70,895 (30,300, 111,169)	7568 (5876, 9202)	39,447 (20,914, 58,654)	5248 (3549, 6886)
Zhuhai	105 (28, 176)	31 (9, 54)	389 (150, 569)	9176 (3745, 15,121)	935 (721, 1145)	4757 (2513, 7100)	640 (431, 845)
Foshan	3164 (868, 5077)	996 (300, 1686)	3870 (1680, 5185)	88,960 (41,569, 127,382)	10,390 (8185, 12,458)	56,868 (30,367, 83,905)	7388 (5056, 9581)
Jiangmen	1442 (385, 2370)	454 (135, 776)	1801 (729, 2547)	42,964 (18,638, 66,252)	4656 (3623, 5648)	24,451 (12,978, 36,314)	3241 (2196, 4245)
Dongguan	1666 (451, 2705)	488 (146, 828)	3670 (1538, 5047)	78,958 (36087, 115,052)	8956 (7027, 10,779)	48,215 (25,690, 71,304)	6313 (4305, 8214)
Zhongshan	397 (104, 662)	117 (35, 201)	675 (261, 988)	15,358 (6365, 24,900)	1589 (1228, 1942)	8151 (4312, 12,151)	1093 (736, 1440)
Huizhou	977 (263, 1598)	310 (93, 529)	1821 (748, 2544)	43,613 (19,159, 66,291)	4786 (3732, 5796)	25,297 (13,439, 37,534)	3343 (2269, 4372)
Zhaoqing	1429 (384, 2338)	1130 (337, 1929)	1779 (729, 2491)	40,519 (18,034, 61,056)	4506 (3522, 5443)	24,028 (12,783, 35,598)	3161 (2150, 4125)
Total	12,786 (3449, 20,837)	15 (4, 26)	21,617 (8909, 30,151)	496,870 (220,292, 750,335)	54,976 (42,940, 66,464)	292,219 (155,385, 433,132)	38,505 (26,168, 50,282)

[a] Premature deaths attributed to the chronic impact with long-term exposure.
[b] Premature deaths attributed to the acute impact with short-term exposure.

admissions due to respiratory disease is more than 4 times that due to cardiovascular disease, implying that reducing PM_{10} concentration would gain significant benefit from avoiding respiratory disease in the PRD region.

By analyzing the health effects due to PM pollution in the individual PRD cities, it can be found that (1) the attributable number of premature deaths (due to both acute and chronic exposure) in Guangzhou and Foshan are the largest and are significantly greater than that in other cities, and (2) the attributable number of cases of all diseases in Guangzhou, Foshan, Shenzhen and Dongguan are greater than that in Zhuhai and Zhongshan. The size of the population, the age structure, the PM_{10} concentration, and all the other factors affecting people's health (e.g. accessibility to health service, nutrition status, etc.) all contribute to these differences.

3.3. *Economic loss of health effects*

Table 5 shows the economic loss of each health outcome as estimated by using CV, AHC and COI methods. The total economic loss of health effects of PM_{10} pollution in nine PRD cities in 2006 is 29.214 (9.552, 45.013) billion Chinese yuan by using CV and COI, equivalent to 1.35% (0.44%, 2.08%) of the total regional GDP, and is 15.508 (5.153, 23.846) billion Chinese yuan by using AHC and COI, equivalent to 0.72% (0.24%, 1.10%) of the regional GDP. Among all the health effects, the economic loss of premature death and chronic bronchitis accounts for more than 95% of the total loss. Though our estimation is lower than other similar studies conducted in China in terms of the proportion of economic loss incurred by PM pollution to local GDP, such as Kan and Chen (2004), Kan et al. (2004), Yu et al. (2007), World Bank (2007) and Zhang et al. (2007), our results show that ambient particulate matter pollution in the PRD is severe and causes significant economic loss.

Comparing the economic loss from health effect due to exposing to PM_{10} pollution in the nine different cities, it can be found that Guangzhou, Foshan and Dongguan suffer the greatest loss from PM_{10} pollution in 2006, while Zhuhai and Zhongshan suffer the least, which is similar to the results of the physical health effects. Besides the factors affecting the number of cases of the various health effects due to exposing to PM_{10} pollution, the economic development status (as indicated by the per capita GDP) and medical expenses in the different cities all contribute the differences in the aggregated economic loss due to PM_{10} pollution.

The economic loss of the same health outcome estimated by using the CV method is greater than that estimated by using the AHC method. This is reasonable as the CV method is based on investigation of individual willingness to pay for reducing the risk of death or diseases and reflects all the loss of individual welfares caused by death or diseases (including time cost and income loss, medical expenses, pain suffering), while the AHC method is based on per capita GDP which only considers the loss of individual contribution to the productivity of the society.

4. Discussion and conclusions

Uncertainty arises in estimating both the health effects and monetary valuation. In estimating the health effects, the incomplete health outcomes, choice of the exposure–response functions and coefficients, selection of baseline PM_{10} concentration, and assumption in the exposure of the population all result in uncertainties. In estimating the monetary value of the health effects, uncertainties are inevitable in using VSL derived from survey and the benefit transfer method.

The health effects of PM are not completely understood yet, and there are many uncertainties in using epidemiological or

Table 5 – Economic loss of health effects attributed to PM_{10} pollution in the PRD cities in 2006, mean value (95% CI) (in million Chinese yuan).

City	Premature death[a]		Premature death[b]		Chronic bronchitis		Acute bronchitis	Asthma	Outpatient visits	Hospital admissions
	CV	AHC	CV	AHC	CV	AHC	COI	COI	COI	COI
Guangzhou	5474	3849	1740	1223	2176	1531	161	13	61	99
	(1467,8972)	(1032,6310)	(519,2971)	(365,2090)	(887,3059)	(624,2152)	(70,247)	(10,16)	(34,90)	(67,130)
Shenzhen	90	61	26	18	1791	1219	107	8	39	39
	(24,149)	(16,101)	(8,45)	(5,31)	(714,2562)	(486,1744)	(46,168)	(7,10)	(22,58)	(27,52)
Zhuhai	144	94	43	28	170	111	14	1	4	5
	(38,241)	(25,157)	(13,74)	(8,48)	(66,250)	(43,163)	(6,23)	(0.8,1.3)	(2,6)	(3,6)
Foshan	4782	2728	1506	859	1872	1068	135	12	49	69
	(1312,7673)	(748,4377)	(454,2548)	(259,1454)	(812,2508)	(463,1431)	(63,193)	(9,14)	(27,71)	(47,89)
Jiangmen	1790	568	564	179	716	227	65	5	14	21
	(478,2941)	(152,933)	(168,963)	(53,305)	(289,1012)	(92,321)	(28,100)	(4,6)	(8,21)	(14,28)
Dongguan	3113	1129	912	330	2194	796	119	10	30	31
	(843,5055)	(306,1832)	(274,1548)	(99,561)	(920,3018)	(333,1094)	(55,174)	(8,12)	(16,43)	(21,41)
Zhongshan	582	287	171	84	317	156	23	1.8	7	5
	(153,970)	(75,478)	(51,294)	(25,145)	(123,463)	(60,228)	(10,38)	(1.4,2.2)	(4,11)	(4,7)
Huizhou	1052	420	333	133	627	250	66	5	12	21
	(283,1720)	(113,687)	(100,569)	(40,227)	(257,876)	(103,350)	(29,100)	(4,6)	(7,18)	(14,28)
Zhaoqing	1280	343	395	106	510	137	61	5	9	16
	(344,2094)	(92,561)	(118,673)	(32,180)	(209,714)	(56,191)	(27,92)	(4,6)	(5,14)	(11,21)
Total	18,307	9479	5690	2961	10,373	5494	751	61	226	308
	(4941,29816)	(2559,15437)	(1705,9686)	(887,5041)	(4278,14463)	(2261,7674)	(333,1135)	(48,74)	(124,332)	(209,402)

[a] Premature deaths attributed to the chronic impact with long-term exposure.
[b] Premature deaths attributed to the acute impact with short-term exposure.

toxicological studies to derive exposure–response functions and coefficients. No cohort studies, which are considered to be the basis of estimating the health effect on long-term exposure to PM, are reported in a China setting. We use meta-analysis results of cross-sectional study in China instead. The results of the meta-analysis on the health effects due to PM exposure in other places may not be appropriate for PRD, given the population structure and the activity-time pattern of the population from different places could be quite different.

The threshold concentration of particulate matter is still inconclusive; WHO (2000) has proposed several feasible thresholds for environment impact assessment: zero, non-zero ''clean'' concentration, and background concentration of a site. Based on the meta-analysis on worldwide epidemiological studies, WHO (2006) carefully made an air quality guideline for ambient particulate matter for human health and safety, which indicated that the annual average PM_{10} concentration should not exceed 20 $\mu g/m^3$ and the 24-h average PM_{10} concentration should not exceed 50 $\mu g/m^3$. The choice of different baseline PM_{10} concentration is expected affect the results of health effect estimation and monetary valuation. If the baseline concentration is set at 20 $\mu g/m^3$ (annual average PM_{10} concentration) and 50 $\mu g/m^3$ (24-h average PM_{10} concentration), the total economic loss of the health effects attributed to PM_{10} pollution in the PRD cities in 2006 becomes 22,374 (7143, 34,939) million Chinese yuan by using CV and COI methods and 11,753 (3788, 18,334) million Chinese yuan by using AHC and COI methods. The corresponding values when zero is set to be the baseline concentration are 29,214 (9552, 45,013) million Chinese yuan and 15,508 (5153, 23,846) million Chinese yuan, respectively.

In conclusion, we estimate the adverse health effects of particulate matter pollution in PRD by using a log-linear exposure–response function, and monetize the morbidity effect by using the cost of illness (COI) method and the mortality effects by using both the amended human capital (AHC) method and the results of contingent valuation (CV) study. The results show that total economic loss of the health effects from PM_{10} pollution in PRD is 29.21 billion Chinese yuan by using CV and COI methods, which is equivalent to 1.35% of the regional GDP, and is 15.51 billion Chinese yuan by using AHC and COI methods, which is equivalent to 0.72% of the regional GDP. The economic loss due to premature death and chronic respiratory disease accounts for more than 95% of the total loss. Despite the uncertainties, the results imply the severity of the health effects incurred by PM_{10} pollution in the PRD. Aggressive actions are needed to alleviate the PM pollution problem and these research results provide a benchmark for choosing alternative air pollution abatement options.

Acknowledgements

The authors would like to thank the members of Environmental Economics and Policy Study Group, Peking University, including Zou Wenbo, Chen Xiaolan, Wu Dan, Xie Xuxuan, Wan Wei, Yu Jialing, Mu Quan, Yi Ru, Ma Xunzhou and Zhang Xiuli, for the simulating discussion and insightful suggestion. Special thanks are given to Dr. Leong Eugene for his effort in editing the paper. The research is supported by the Research Fund of National High Technology Research and Development Projects (''863'' Projects, Grant No. 2006AA06A309): Synthesized Prevention Techniques for Air Pollution Complex and Integrated Demonstration in Key City-Cluster Region (3C-STAR).

REFERENCES

Aunan, K., Pan, X., 2004. Exposure–response functions for health effects of ambient air pollution applicable for China – a meta-analysis. Science of Total Environment 329, 3–16.

Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. Lancet 360, 1233–1242.

Cohen, A.J., Anderson, H.R., Ostro, B., Pandey, K.D., Krzyzanowski, M., Künzli, N., Gutschmidt, K., Pope III, C.A., Romieu, I., Samet, J.M., 2004. Mortality impacts of urban air pollution. In: Comparative quantification of health risks: global and regional burden of disease attributable to selected major risk factors, World Health Organization, Geneva, p. 2.

Deng, X., Tie, X., Wu, D., Zhou, X., Bi, X., Tan, H., Li, F., Jiang, C., 2008. Long-term trend of visibility and its characterizations in the Pearl River Delta (PRD) region, China. Atmospheric Environment 42 (7), 1424–1435.

Department of Health of Guangdong Province, 2007. Health Statistical Yearbook of Guangdong Province 2007. Flower City Publishing House, Guangzhou.

Dockery, D.W., Pope III, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. The New England journal of Medicine 329 (24), 1753–1759.

Enright, M.J., Scott, E.E., 2005. China's quiet powerhouse. Far Eastern Economic Review 168 (5), 27–34.

Hammitt, J.K., Zhou, Y., 2006. The economic value of air-pollution-related health risks in China: a contingent valuation study. Environmental and Resource Economics 33 (3), 399–423.

Han, M., Guo, X., Zhang, Y., 2006. The human capital loss of air pollution in cities, China. China Environmental Science 26 (4), 509–512 (in Chinese).

Ho, M.S., Jorgenson, D.W., 2007. Sector allocation of emissions and damage. In: Ho, M., Nielsen, C. (Eds.), Clearing the Air: the Health and Economic Damages of Air Pollution in China. The MIT Press, London.

Huang, J., Wu, D., Huang, M., Li, F., Bi, X., Tan, H., Deng, X., 2008. Visibility variations in the Pearl River Delta of China during the Period of 1954–2004. Journal of Applied Meteorological Science 19, 61–70 (in Chinese).

Jia, J., Kan, H., Chen, B., Xu, W., Xia, D., 2004. Association of air pollution with daily mortality in Zhabei District of Shanghai: a case-crossover analysis. Journal of Environment and Health 21, 279–282 (in Chinese).

Kan, H., Chen, B., 2002. Analysis of exposure–response relationships of air particulate matter and adverse health outcomes in China. Journal of Environment and Health 19, 422–424 (in Chinese).

Kan, H., Chen, B., 2004. Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment. Science of Total Environment 322, 71–79.

Kan, H., Chen, B., Chen, C., Fu, Q., Chen, M., 2004. An evaluation of public health impact of ambient air pollution under various energy scenarios in Shanghai, China. Atmospheric Environment 38, 95–102.

Kan, H., Chen, B., Chen, C., Wang, B., Fu, Q., 2005. Establishment of exposure–response functions of air particulate matter and adverse health outcomes in China and worldwide. Biomedical and Environmental Sciences 18, 159–163.

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L., Chen, B., 2007. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. Environment International 33, 376–384.

Li, Y., Yuan, D., Kan, H., Lu, W., Ruan, S., 2003. Progress in epidemiological study on urban particulate air pollution and mortality. Journal of Environmental and Occupational Medicine 20, 47–49 (in Chinese).

Morgan, G., Lincoln, D., Sheppeard, V., Jalaludn, B., Beard, J.F., Simpson, R., Petroeschevsky, A., O'Farrell, T., Corbett, S., 2003. The effects of low level air pollution on daily mortality and hospital admissions in Sydney, Australia 1994 to 2000. Epidemiology 14 (Supplement 5), S111–S112.

National Bureau of Statistics of China, 2007. China Statistical Yearbook 2007. China Statistics Press, Beijing.

Ostro, B., 2004. Outdoor air pollution: assessing the environmental burden of disease at national and local levels. Environmental Burden of Disease Series 5.

Pope III, C.A., Bates, D.V., Raizenne, M.E., 1995. Health effects of particulate air pollution: time for reassessment? Environmental Health Perspectives 103 (5), 472–480.

Pope III, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Journal of the American Medicine Association 287 (9), 1132–1141.

Pope III, C.A., 2000. Invited commentary: particulate matter-mortality exposure-response relations and threshold. American Journal of Epidemiology 152 (5), 407–412.

Population Census Office of Guangdong Province, 2002. Tabulation on the 2000 Population Census of Guangdong Province. China Statistics Press, Beijing.

Schwartz, J., Dockery, D.W., Neas, L.M., 1996. Is daily mortality associated specifically with fine particles? Journal of the Air & Waste Management Association 46 (10), 927–939.

SEPA, 2008. China Environmental Year Book 2007. China Environmental Sciences Press, Beijing.

Statistics Bureau of Guangdong Province, 2006. Guangdong Statistical Yearbook 2006. China Statistics Press, Beijing.

Statistics Bureau of Guangdong Province, 2007. Guangdong Statistical Yearbook 2007. China Statistics Press, Beijing.

Tang, T., Ding, Y., Zheng, J., Wang, X., Ma, Q., Liang, B., Chen, S., Cai, D., 2000. Epidemiological survey and analysis on bronchial asthma in Guangdong province. Chinese Journal of Tuberculosis and Respiratory Diseases 12 (in Chinese).

Tietenberg, T.H., 2005. Environmental and Natural Resource Economics, sixth ed. Tsinghua University Press, Beijing, p. 35.

Venkatachalam, L., 2004. The contingent valuation method: a review. Environmental Impact Assessment Review 24 (1), 89–124.

Viscusi, W.K., Magat, W.A., Huber, J., 1991. Pricing environmental health risks: survey assessments of risk-risk and risk-dollar trade-offs for chronic bronchitis. Journal of Environmental Economics and Management 21, 32–51.

Wan, J., Lin, M., Chan, C., Zhang, Z., Engling, G., Wang, X., Chan, I., Li., S., 2011. Change of air quality and its impact on atmospheric visibility in central-western Pearl River Delta. Environmental Monitoring and Assessment 172, 339–351.

Wang, H., Mullahy, J., 2006. Willingness to pay for reducing fatal risk by improving air quality: a contingent valuation study in Chongqing, China. Science of Total Environment 367, 50–57.

World Bank and China SEPA, 2007. Cost of pollution in China. Economic estimates of physical damages, Available online: www.worldbank.org/epaenvironment.

World Health Organization (WHO), 2000. Air Quality Guidelines for Europe, second ed. World Health Organization Regional Office for Europe, 2000, Copenhagen (WHO Regional Publications, European Series, No. 91).

World Health Organization (WHO), 2006. WHO air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide. EURO Nonserial Publication. http://www.euro.who.int/_data/assets/pdf_file/0005/78638/E90038.pdf (accessed 08.05.11).

Wu, D., Deng, X., Bi, X., Li, F., Tan, H., Liao, G., 2007a. Study on the visibility reduction caused by atmospheric haze in Guangzhou area. Journal of Tropical Meteorology 23 (1), 1–6 (in Chinese).

Wu, D., Bi, X., Deng, X., Li, F., Tan, H.B., Liao, G.L., Huang, J., 2007b. Effect of atmospheric haze on the deterioration of visibility over the Pearl River Delta. Acta Meteorologica Sinica-English Edition- 21 (2), 215–223.

Xie, P., Liu, X., Liu, Z., Li, T., Bai, Y., 2009. Exposure–response functions for health effects of ambient particulate matter pollution applicable for China. China Environmental Science 10 (29), 861–866 (in Chinese).

Xie, P., Liu, X., Liu, Z., Li, T., Zhong, L., Xiang, Y., 2011. Human health impact of exposure to airborne particulate matter in Pearl River Delta, China. Water Air & Soil Pollution 215–363.

Yu, F., Guo, X., Zhang, Y., Pan, X., Zhao, Y., Wang, J., Cao, D., Cropper, M.L., Aunan, K., 2007. Assessment on economic loss of health effect from air pollution in China in 2004. Journal of Environment and Health 24 (12), 999–1003 (in Chinese).

Zhang, M., Song, Y., Cai, X., 2007. A health-based assessment of particulate air pollution in urban areas of Beijing in 2000–2004. Science of Total Environment 376, 100–108.

Zhang, Y., Hu, M., Zhong, L., Wiedensohler, A., Liu, S., Andreae, M.O., Wang, W., Fan, S., 2008. Regional integrated experiments on air quality over Pearl River Delta 2004 (PRIDE-PRD2004): overview. Atmospheric Environment 42, 6157–6173.

Zou, W., Zhang, S., 2010. Economic valuation of health impact of PM10 pollution in Beijing from 2001 to 2006. Chinese Journal of Population, Resources and Environment 8 (2), 68–74.