The Development and Application of the “DALY”-Based Environmental Risk Assessment Methods with a Case Study on the Impact of PM2.5 in Beijing

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Abstract. The “Four-step” method is the well accepted procedure for risk assessment, which is also adopted in China. This method regards the human body as a benchmark and takes the effects on human health to characterize the risk. On the basis of the regular “Four-Step” method, the present study proposes a quantitative evaluation on the scenario that risk already occurred with the relevant impact represented by the indicator of “disability-adjusted life year” (hereinafter referred to as “DALY”). Based on the proposed methods, this study assessed the impact of “haze”, namely, PM2.5, on the residents in Beijing in 2013. According to the assessment, the PM2.5-related death and Cardiovascular Disease are the most significant contributors in terms of health time losses of the residents. The total DALY caused by PM2.5 in 2013 is calculated to be 1557806 year, which is further converted to economic loss of RMB 15.58 Billion Yuan. This study also put forward the assessment procedure of environmental risk which can be used as the guideline for relevant research and works.

1. Introduction
Risk exists in all the human activities, while the activities in different sectors can cause the risks of variable natures. The relatively common risks include the disaster risk, investment risk, engineering risk, decision-making risk, health risk, environmental risk, and etc. Meanwhile, the risk assessment refers to the quantitative or qualitative assessment process that characterizes the risk resulted from the potential hazards related to a certain process or condition. Normally, risk assessment requires the analysis of the impacts upon human (such as residents, workers and tourists) health and ecological receptor (such as birds, fishes, and wild animals), e.g. chemical compounds leak and the hazardous substances are exposed to the environment and human beings. The risk managers need such information to facilitate their decision-making over how to protect human beings and environment from being harmed by the toxic substances or pollutants.

According to Hu Erbang, the environmental risk assessment is the evaluation of the hazard degree of the destruction, damage and other serious adverse events occurring to human society and environment due to the spontaneous natural causes or resulted from human activities and spread via the environmental media. However, Lu Yongsen [1] views the environmental risk assessment from both broad sense and narrow sense separately. The environmental risk assessment in the broad sense refers to the assessment of possible losses resulted from the risks regarding human health, social and economic development, ecological system and others caused by all sorts of human behaviors or the encountered hazards, as well as the management and decision-making process based on this. Whereas,
the environmental risk assessment in the narrow sense refers to carrying out the probability estimation over the impact degree of toxic chemical substance’s harm over human health, and also proposing the plans and countermeasures of reducing the environmental risks. As shown in these definitions, the environmental risk assessment in the broad sense includes two parts, namely, human health risk assessment and ecological risk evaluation.

Environmental risk control, also known as environmental risk management, requires effective control means and corresponding cost and efficiency analysis consistent with the environmental risk assessment results and the relevant laws and regulations. The policy and social analyses are also needed to determine the social willingness to pay for the reduction of risk. Nevertheless the ultimate goal of risk control is to protect the population health and safety of ecological system.

The study on environmental risk assessment began in 1970s. At the beginning, it was mainly conducted in developed countries, especially USA, where the relevant study and application were relatively prominent. In 1976, US Environmental Protection Agency specified the concept of risk assessment for the first time in Carcinogen Risk Assessment Criteria. Until now, the development of environmental risk assessment generally has gone through three phases. At phase 1, namely, from 1930s to 1960s, the risk assessment study was in its infancy. At that time, the connotation of risk assessment was still indefinite. The toxicological identification method was mainly applied to the human health risk analysis. The risk assessment model was not fully established yet, and the results were mainly in the form of qualitative description. Until 1960s, toxicologist proposed some quantitative methods to evaluate the health risk of being exposed to the low concentration toxic substances [2]. At phase 2 (from 1970s to 1980s), the risk assessment study was at the peak. At this phase, the risk assessment system was fully developed. US National Academy of Sciences issued the Risk Assessment in the Federal Government: Managing the Process in 1983, which proposed the “Four-Step Method” of risk assessment, namely, risk identification, dose-response assessment, exposure assessment and risk characterization [3]. This document has been viewed as a milestone in the development of risk assessment, and well accepted by France, Holland, Japan, China and many other countries and international organizations. The Phase 3 started from 1990s, In which the ecological risk assessment gradually draws more attentions. In 1990, US Environmental Protection Agency formally proposed the concept of ecological risk assessment. At first, it discussed the inclusion of the human health risk assessment into the ecological risk assessment. After going through the continuous exploration and studies, US Environmental Protection Agency officially enacted the Guidelines for Ecological Risk Assessment in 1998, proposing the framework of ecological risk assessment “Three-Step Method”, including the development of problems, analysis and risk characterization. The framework has been extensively accepted and applied by researchers worldwide.

China’s studies on environmental risk assessment began in 1980s, which mainly tried to follow up with the foreign progress at that time. With the fast economic and social growth, risk management and control became a pressing concern for China government. As a result, the environmental risk assessment system was gradually established. Generally, the development of China’s study on environmental risk assessment went through three phases. At phase 1 (from mid-late 1980s to early 1990s), the relevant studies on environmental risk assessment were mainly about the establishment of the emergency countermeasure procedure in nuclear power plant, which took effect in the Qinshan Nuclear Power Plant leakage accident [3]. At phase 2 (from early 1990s to late 1990s), the environmental risk assessment was extensively carried out. In 1993, the former National Environmental Protection Agency enacted the Technical Guideline for Environmental Impact Assessment, which specified that the environmental impact assessment or environmental risk analysis must be carried out for the construction projects. Meanwhile, the risk assessment requirements are also put forward in the regulations and administrative system established by the relevant departments. At phase 3 starting from the 21st century, great progress was made for both the environmental risk assessment and relevant administration. In 2004, Technical Guidelines for Environmental Risk Assessment on Projects was issued, in which the purpose, principle, procedure, methods, compulsory contents and other requirements for the compilation of environmental risk assessment for the project were given. However, the following problems still exist in China’s present environmental risk assessment system.
1) Obstacles still hindered the practice of risk assessment. Although China has recognized the importance of environmental risk assessment and carried out the compulsory environmental risk assessment via laws and regulations, there are still many shortcomings exist in the practice of risk assessment. For instance, the health risk and ecological risk are scarcely involved. Meanwhile, at present, the only available standards and criteria of environmental risk assessment are almost all about construction, whereas none have been developed for other subjects like industrial products.

2) Uncertainty problem is significant. One of the basic features of environmental risk assessment is uncertainty. The main reason is due to the complexity of objective world and limited knowledge about it. In China, because of the relatively short history of environmental risk study, there are very limited information and data accumulation in this field, resulting in a more non-negligible uncertainty issue in the risk assessment results in China.

3) The assessment cannot fully support the decision-making. On one hand, the environmental risk decision making need to consider not only the risk assessment results, but also other factors such as social and economic conditions, ethics ideology, public awareness, and even the ethnic group and other interest groups. On the other hand, the environmental risk assessment results are normally non-quantitative. Therefore, it is inadequate or difficult to direct the decision-making.

Furthermore, both the environmental risk assessment and control are end control approach, which is inconsistent with the current trend of process control, e.g. cleaning production[5]. The ultimate goal of environmental risk control is to protect the living environment so to guarantee the human health and ecological security. This study takes Beijing’s PM2.5 as the subject, and evaluated its environmental risk by applying a standard environmental risk assessment procedure. The DALY indicator proposed by the UN was also adopted to manifest the risk impact. For relevant studies, the present research may provide some insights for environmental risk assessment method and interpretation.

2. Study Method

2.1. Human Health Impact Assessment Method

Human health impact assessment has been relatively well developed by relevant studies. To accurately describe the adverse health effects when the human beings are exposed to the environmental harmful factors, the standard procedure can be carried out as shown in Figure 1. Four basic steps, i.e. Four-step, are included as the sources analysis, hazard identification, dose-response assessment and exposure assessment, last but not least, risk characterization. Risk control strategy can only be made and conducted on the basis of the assessment results hereafter.

![Figure 1. The “Four-step” procedure for human health impact assessment](image-url)
Source analysis refers to the procedures that locate and determine the origin of the potential environmental risk. Though different countries and organizations may apply various methods for source analysis, the result must at least include the nature of risks, occurrence reason and occurrence frequency of risk.

For hazard identification, it associates the risk with human health and ecological safety. The conclusions obtained from DMPK test, short-term animal experimentation, long-term animal experimentation, and human epidemiology study provide useful information for this process. Based on the aforementioned researches and other surveillance means, the hazardous factors and their impacts can be unveiled. To facilitate the hazard identification, USA established the Integrated Risk Information System (hereinafter referred to as “IRIS”), which incorporated the pathological research data involving more than 500 common toxic elements and chemical compounds. Meanwhile, EU and other developed countries and regions also established the similar information database [6].

Dose-response assessment is the quantitative estimation process conducted over the relationship between the exposure level of harmful factors and occurrence rate of the adverse effects among the exposed population and ecological system. It provides a solid basis for the risk assessment afterwards. The present experimental data are mainly the dose-response of human health.

Exposure assessment involves survey, estimation, and sometimes, prediction of the amount, frequency, duration and nature (direct or indirect, airborne or waterborne, etc.) of the exposure. When it’s about human exposure, the assessment also needs to describe the number, distribution, activity status, contact means and other factors of the exposed population (or biology). The assessment results generally include the information of the discharge amount, concentration, migration and transformation rules and other parameters of the hazardous substance on the basis of the given model.

Risk characterization is the last step of risk assessment. It combines the data and analysis results obtained from the abovementioned procedures, determines the occurrence probability of harmful effects, puts forward the acceptable risk level, and specifies the uncertainty of the assessment results. Meanwhile, risk characterization also works as the bridge connecting the risk assessment and risk management. In some models, the assessment need to classify the risk subjects into carcinogenic and non-carcinogenic (or lethal & non-lethal), and then get the risk results. However, two major problems exist for such model: firstly, although some pollutants do not have the carcinogenic or lethal effect, their impacts are also very severe, for example, the disability-caused substances; secondly, the assessment results of such method normally only have the statistic meaning, because the risk predicted from such assessment is based on the hypothesis that the human body is only exposed to a single risk factor, which is obviously not the typical case in reality.

2.2. Method of Risk Characterization

In order to better solve the risk characterization problem, Harvard University and WHO carried out the global burden of disease study, and put forward the “disability-adjusted life year” (hereinafter referred to as “DALY”) indicator to quantify the health damage [7]. DALY stands for the health time loss due to sickness and early death (average loss compared to the life expectancy). It includes the “years of life lost” (hereinafter referred to as “YLL”) resulted from early death and “years lived with disability” (hereinafter referred to as “YLD”) resulted from the disability caused by the disease, as shown in eq.1.

\[
\text{DALY} = \text{YLL} + \text{YLD}
\]  

(DALY)

DALY demonstrates the health problems of variable individuals in the form of years, which can be calculated and compared. For instance, the 1 year lived in the condition of total disability (including death) resulted from sickness equals to 10 years lived with 90% of full action competence.

As the definition of DALY shows, its calculation need to determine both the YLL and the YLD. The YLL can be calculated as per eq.2, while YLD is calculated as per eq.3.

\[
\text{YLL} = N \times L
\]  

(YLL)

\[
\text{YLD} = N_i \times W_i \times L
\]  

(YLD)

Where, \(N\) refers to the acute death number due to such pollutant; \(L\) refers to the current average life...
expectancy (life expectancy-current mean age); In case that the pollutant may cause multiple diseases, \( N_i \) refers to the occurrence number of disease \( i \) due to the specific pollutant; \( W_i \) refers to the health influence weight (or disability weight) of disease number \( i \) and \( L_i \) refers to the impact duration of disease number \( i \). Therefore, the DALY is measured as below.

\[
\text{DALY} = N \times L + \sum (N_i \times W_i \times L_i) \tag{4}
\]

3. Case Study

In this research, the case study is carried out to verify the proposed method. In this case study, the Beijing’s air pollution of PM2.5 was selected as the assessment subject, due to its high concern and the availability of the relevant data.

With the rapid economic development, the urban population has been growing continuously in Beijing. Both the possession of automobiles as well as the total energy consumption have hit the record high in the recent years. As a result, the environmental quality and ecological conditions, specially the air condition in Beijing are deteriorating significantly. The suspended particles PM 2.5, which is commonly known as “haze”, drawn widely concern. PM2.5 refers to the particles in the ambient air with the diameter less than or equal to 2.5 micron. They suspend in the air for a much longer time. The higher its concentration in the air is, the more serious the air pollution becomes. Although PM2.5 is only the minor element in the composition of the earth’s atmosphere, it poses significant impact upon the air quality and visibility. Compared with the coarse atmospheric particulates, PM2.5 is small in grain size, but with large area coverage. More importantly, they easily bound with the toxic and harmful substances (for instance, heavy metal, microorganism, and etc), and have the long residence time in the air and long conveying distance. As a result, PM2.5 have much greater impact upon human health and atmospheric environment quality.

In 2013, the atmospheric environment quality in Beijing was overall poor. There were 25 haze days in January, while the average visibility was only 9.2km. The highest PM 2.5 concentration exceeded 800 ug/m³, and the total haze days were 2.2 times of the same period of the other years (11.4 days). The statistic data of PM 2.5 in 2013 taken from weather record was shown in Table 1.

| Air Grade          | Range of PM2.5 concentration ug/m³ | Computational parameter of PM2.5 ug/m³ | Days |
|--------------------|------------------------------------|---------------------------------------|------|
| Excellent          | 0~35                               | 17.5                                  | 41   |
| Good               | 35~75                              | 55                                    | 135  |
| Mild               | 75~115                             | 95                                    | 84   |
| Contamination      |                                    |                                       |      |
| Medium             | 115~150                            | 132.5                                 | 47   |
| Heavy Contamination| 150~250                            | 200                                   | 45   |
| Severe Contamination|                                 | 250                                    | 13   |

PM2.5 and other small particles can enter into human body through inhalation. To measure the exposure, exposure concentration, exposure duration and inhalation rate must be considered. The exposed dose is calculated following the equation as in below.

\[
D_{exp} = \int_{t_1}^{t_2} c(t) \times IR(t) dt \tag{5}
\]

Where, \( D_{exp} \) refers to particle inhalation exposure amount (mg); \( t_1 \) & \( t_2 \) stand for the start and final time of the exposure duration, respectively; \( c(t) \) refers to the mass concentration of particle matter which varies with the exposure time (mg/m³); \( IR(t) \) refers to the human inhalation rate which changes
with the exposure time \( (m^3/h) \); and \( t \) refers to exposure time (h). This exposure assessment model can be applied to the cases with much smaller scope, fewer population and shorter time. However, it is obviously not applicable to the whole-year resident health impact assessment in Beijing. Therefore, this study assumes the exposure process of PM 2.5 over all urban citizens in Beijing as a black-box process, and then conducted the dose-response assessment.

In previous study, Xie et al. has found that for every increase of the PM2.5 concentration by 10ug/m^3, the corresponding resident death number in China will increased by 0.38%[8, 9]. Meanwhile, PM 2.5 may also cause many diseases. Four diseases are considered herein, namely, chronic obstructively pulmonary disease (hereinafter referred to as “COPD”), cardiovascular disease, cerebrovascular disease and acute respiratory infection. If the concentration of PM 2.5 is increased by 10ug/m^3, the occurrence rates of COPD, cardiovascular disease, cerebrovascular disease and acute respiratory infection will be increased by 6%, 6%, 8% and 13.5% (\( \gamma \)), respectively.

It is assumed that when the air quality grade is good, the residents will not be affected by PM2.5, so the death rate and prevalence rate at that condition are regarded as control. The \( R_{\text{total}} \) of the annual death rate, and the incidence rate of COPD, cardiovascular disease, cerebrovascular disease and acute respiratory infection of Beijing’s residents at present are 4.52%, 1.55%, 1.43%, 0.66%, 4.41% (China Health Statistical Yearbook), respectively. \( R_{\text{total}} \) includes both the cause of PM2.5 and other causes. If the regional variation and individual difference are ignored, the death and prevalence rates due to PM2.5 can be obtained by the following equations.

\[
R_{\text{total}} = \left( \frac{C_{PM2.5} - C_0}{10} \cdot \gamma + 1 \right) \cdot R_{\text{other}} 
\]

\[
R_{PM2.5} = R_{\text{total}} - R_{\text{other}}
\]

Where, \( C_{PM2.5} \) is the PM2.5 concentration in 2013; \( C_0 \) is the concentration when the concentration condition of PM2.5 is considered good, namely, 17.5 ug/m^3. \( \gamma \) refers to the enhancement of Death rate or pathogenicity rate caused by the higher concentration of PM2.5. The death and disease due to higher PM2.5 (>55ug/m^3) of residents in Beijing were calculated and are shown in Table 2.

| PM2.5-Related Disease          | Population Affected (Person. Year) | Health Weight | Duration Time |
|-------------------------------|------------------------------------|---------------|---------------|
| Death Rate                    | 0.06%                              | 12000         | 1             | —              |
| COPD                          | 0.32%                              | 64000         | 0.15          | 10a            |
| Cardiovascular Disease        | 0.30%                              | 60000         | 0.24          | Lifetime       |
| Cerebrovascular Disease       | 0.17%                              | 34000         | 0.2           | Lifetime       |
| Acute Respiratory Infection   | 1.64%                              | 328000        | 0.08          | 14d            |

The calculation results demonstrate that the PM2.5-related acute death number in Beijing in 2013 was 12000 persons, compared with Kan’s study on the relationship between air pollution in 2000 and Shanghai’s resident health problem which unveiled 8220 cases of resident death in that year were due to air pollution. Besides, there were also 16870 cases of newly infected chronic bronchitis, 5240 cases of respiratory hospitalization, 2,690 cases of cardiovascular disease hospitalization, 386,600 times of internal medicine department, 40,040 times of pediatric outpatient department, 540,300 cases of acute bronchitis and 9,990 cases of asthmatic attack [10]. For the Great Smog in 1952, more than12000 death cases occurred among the 5 million London urban citizens. As shown in the study of IEPOA and School of Public Health, Peking University, PM2.5 in 2013 caused 257000 excess number of deaths among 31 provincial capitals and municipalities nationwide. Among which, 79 excess number of deaths exist among every 100000 persons in Beijing (If the total population in Beijing is taken as 20
million, there are 15800 excess number of death due to PM2.5 [11]. Hence, the results obtained by the present study are within the reasonable scope.

Meanwhile, the health weight of all diseases related to PM2.5 is also given in Table 2, which represents the severity of the impact the specific disease pose upon the human action competence. In the global burden of disease study carried out by WHO, 22 sorts of indicative symptom and their disability weight are determined. Among which, 0 represents completely healthy, while 1 stands for death or complete loss of body function caused by serious disease (for instance paralysis, human vegetable and etc). For the recoverable disease, the duration time of the disease must be considered. For the disease that cannot be completely recovered, or sequel exists after the recovery or chronic disease, the duration time is regarded as lifetime, namely, the present life expectancy.

When the results in Table 2 were further combined with the life expectancy of Beijing residents, the PM2.5-related DALY may be calculated. As per the relevant data, it is known that the average life expectancy of Beijing residents is 81.5 years. According to the Sixth National Population Census, it is estimated that the present average age of Beijing residents is 37.5 years. Therefore, the present life expectancy of Beijing residents is 44 years. For PM 2.5, as per the DALY calculation results, it is found that cardiovascular disease is the primary threat for the overall health condition of Beijing residents, while death and cerebrovascular disease rank the second and third respectively. The corresponding economic loss were also measured with the association with the per capita GDP in Beijing (RMB 100000 (person. year) in 2013) and shown in Table 3.

| Disease                  | DALY (person. year) | Economic Loss ($\times 10^8$) |
|--------------------------|---------------------|-------------------------------|
| Death                    | 528000              | 52.8                          |
| COPD                     | 96000               | 9.6                           |
| Cardiovascular Disease   | 633600              | 63.4                          |
| Cerebrovascular Disease  | 299200              | 29.9                          |
| Acute Respiratory Infection| 1006              | 0.1                           |
| In Total                 | 1557806             | 155.8                         |

4. Conclusion
The DALY-based pollutant environmental risk assessment process flow is as shown in Figure 2. As shown in the case study, it is found that based on this method, variable pollutants may cause different impacts upon human health, including pathopoiesia, disability, carcinogenesis and Death, which can be quantified and summed up via the bridge of “time”. In this manner, the integrated assessment and analysis of environmental risk under the influence of multi-factors may be realized. Meanwhile, the risk assessment results are demonstrated in the manner of DALY, instead of possibility or statistical probability. Therefore, they may be further converted to economic loss and other easily understood manner, which also facilitates the application and comparison of environmental risk assessment results.
Figure 2. DALY-based Pollutant Environmental Risk Assessment Process Flow

As shown from such assessment process flow, the more complex the assessment object is, the larger the population base is (such as the case of health impact of Beijing haze provided in this paper), then the lower the credibility of assessment results becomes. On one hand, many required data cannot be directly obtained; they shall be calculated via the indirect data or take the average value. On the other hand, large gap may exist between the model adopted by the calculation and the reality. For instance, the aforesaid case does not consider the age impact and weight when calculating the death rate and life loss, which is obviously inappropriate. When the assessment is conducted over the object with a smaller range, the national average level may be directly taken for reference. For instance, when the study is conducted over certain occupational disease (such as the mining worker’s silicosis resulted from dust), the relevant health data of patients may be compared with the national average level. Thus, the lethal and pathogenic data of a given pollution factor may be directly obtained. The DALY data obtained in this manner will be more precise, while the assessment results may also be more credible.

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