Zoning Abrupt Environmental Pollution Risk in a Mega-city

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Abstract

Major abrupt environmental pollution accidents can cause huge socio-economic losses and seriously damage the environment. Zoning of abrupt environmental pollution risk can greatly aid decision-making and governance, with a view to preventing and mitigating such pollution accidents in a typical mega-city. The present paper proposes a risk system for environmental pollution accidents, which comprises an index system and a quantitative risk assessment model of environmental risk zonation. The system is based on data on past abrupt environmental pollution accidents, regional environmental risk theories, and natural disaster risk theories. An Abrupt Environmental Pollution Risk Zonation (AEPRZ) approach, applicable to a large area, is proposed, which involves the selection of appropriate zonation principles, units, and indexes for the measurement and classification of environmental risk, amending the zonation, and then mapping risk zonation with GIS tools. The AEPRZ approach is applied to the risk zonation of environmental pollution accidents in Minhang District, Shanghai, China, which was divided into four zones according to high, medium, low, and very low degrees of risk. In each zone, each of the socio-economic, hazard, vulnerability, and overall risk factors is assigned a specific degree of risk, thus providing a basis for the implementation of control measures as part of environmental risk prevention management.

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1. Introduction

Accidents leading to environmental pollution are often an indirect consequence of rapid industrial development. In China, of the reported 23,316 environmental pollution accidents that occurred in the period 1993-2008, over 900 major accidents, such as the Tuojiang River pollution accident in 2004, Songhuajiang River pollution accident in 2005, and the Huaiian liquid chlorine leak in 2005, have caused huge socio-economic losses and serious damage to the environment. A risk zonation map of abrupt environmental pollution accidents can provide important information for preventing and mitigating such pollution accidents. However, few approaches have been developed for regional environmental risk zonation. To date, the approaches suggested include the risk map overlapping method [1], the experience-judgment method [2], and the comprehensive zoning method [3]. Although these zonation methods may have considered the spatial variation of risk, they did not produce accurate and widely-used risk zonation maps because the index system was incomplete, and the model over-simplified and over-dependent on

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expert opinions. Several environmental risk assessment methods have been applied to particular sites or over small areas such as reservoirs, oilfields, towns, and industrial parks. These techniques include integrated fuzzy-stochastic risk assessment [4], comprehensive assessment of environmental risk [5], information diffusion [6], algorithmic and qualitative approaches [7], non-linear modeling [8], and the analytic hierarchy process [9]. By nature, these techniques are relatively subjective and so less accurate, and not readily extendible to applications involving large areas. With this in mind, the present paper proposes an Abrupt Environmental Pollution Risk Zonation (AEPRZ) approach designed for application to large areas. AEPRZ provides a complete risk index system and appropriate measurement models for regional risk zonation using GIS tools, mechanism analysis and case-by-case analyses of abrupt environmental pollution accidents, based on previous regional environmental risk studies. AEPRZ is demonstrated to be applicable to a large area, through the case study of abrupt environmental pollution risk in the Minhang District of Shanghai, China.

2. Methodology

2.1. Environmental pollution risk system

Using selected data on major abrupt environmental pollution accidents, this paper categorizes the accidents, analyzes the mechanisms involved, and identifies the primary causative factors. Previous regional environmental risk theories [10] and natural disaster risk theories [11, 12] are considered. A regional environmental pollution risk system is determined, which involves both risk source and risk receptor. The risk source, which may arise from chemical storage, plant or transportation, is that which is likely to cause an environmental pollution hazard (and so its consideration is a prerequisite in an environmental pollution risk system). The environmental pollution hazard due to a risk source is one of the causative risk factors, and is determined by the particular characteristics of the chemical involved, precautionary control of the risk source, and incident process control. Source control includes daily monitoring, maintenance, and management of the risk sources. Process control involves the pro-active prevention and reduction of a hazard before chemicals are able to come into contact with risk receptors. Risk receptors comprise human beings and the ecosystem, which are vulnerable to the hazard (i.e. exposure to toxic chemicals). Environmental pollution vulnerability of risk receptors is another important causative risk factor, which is affected by exposure and adaptation of risk receptors.

2.2. Zonation principle and zonation unit

Environmental pollution risk zonation generally follows principles of system, consistency, dominance, dynamicity and combination of qualification and quantification [3]. An administrative unit is selected as the zonation unit for environmental pollution risk, for convenience of database preparation and zonal risk governance. However, it should be noted that rectangular grids, industrial parks, and industrial development zones have been used as units in previous environmental pollution risk zonation studies [6, 10].

2.3. Zonation index system

Regional environmental pollution risk indexes should be scientific, complete, independent, operative, and causative. Furthermore, the zonation indexes should discriminate the similarity or dissimilarity of the regional environmental pollution risk for each unit. Table 1 shows the resulting four-layer complete zonation index system constructed for regional environmental pollution risk.

Table 1 Zonation index system for regional environmental pollution risk
| Objective | Medium 1 | Medium 2 | Primary |
|-----------|---------|---------|---------|
| risk source ($H_1$) | deleterious properties of hazardous substance ($H_{11}$) | ratio of stock quantity to threshold quantity of hazardous substance ($H_{12}$) | 
|        | condition of production equipment ($H_{13}$) | operation time of production and storage equipment ($H_{14}$) | clumping of risk sources ($H_{15}$) |
| hazard ($H$) | online electronic surveillance ($H_{21}$) | equipment maintenance ($H_{22}$) | exposure to natural disasters ($H_{26}$) |
| risk source control ($H_2$) | operational state of control system ($H_{23}$) | environmental management system ($H_{24}$) | safety measures ($H_{25}$) |
| process control ($H_3$) | local emergency plan ($H_{31}$) | local emergency input ($H_{32}$) | 
| exposure control ($V_1$) | population density ($V_{11}$) | proximity of mixed residential and industrial areas ($V_{12}$) | level of drinking water protection area ($V_{13}$) |
| Adaptation ($V_2$) | GDP per-capita ($V_{21}$) | local emergency rescue capabilities of medical and health institutions ($V_{22}$) | 

The regional environmental pollution risk ($R$) in the objective layer comprises two sub-indexes; namely, hazard of risk source ($H$) and vulnerability of risk receptor ($V$) in the medium 1 layer. Hazard is determined by characteristics of risk source ($H_1$), precautionary control on risk source ($H_2$), and precautionary control of the incident process ($H_3$) in the medium 2 layer. Vulnerability is determined by control of the risk receptor’s exposure to hazardous substance ($V_1$) and adaptation of risk receptor ($V_2$) in the medium 2 layer.

In the primary layer, six sub-indexes are selected to describe the state of the risk source, including the deleterious properties of the hazardous substance ($H_{11}$), ratio of stock quantity to threshold quantity of hazardous substance ($H_{12}$), condition of production equipment ($H_{13}$), operation time of production and storage equipment ($H_{14}$), clumping of risk sources ($H_{15}$), and exposure to natural disasters ($H_{26}$). Precautionary source control includes online electronic surveillance ($H_{21}$), equipment maintenance ($H_{22}$), operational state of control system ($H_{23}$), environmental management system ($H_{24}$), safety measures ($H_{25}$) and emergency response of employees ($H_{26}$). Precautionary progress control is represented through the local emergency plan ($H_{31}$) and local emergency input ($H_{32}$). Population density ($V_{11}$), proximity of mixed residential and industrial areas ($V_{12}$), and level of drinking water protection area ($V_{13}$) are selected as sub-indexes of exposure control. Adaptation is denoted by GDP per-capita ($V_{21}$) and local emergency rescue capabilities of medical and health institutions ($V_{22}$).

2.4. Risk measurement

It is difficult to determine exactly the influence of all the causative factors in the environmental pollution risk system and to measure quantitatively these factors because of their inherent complexity and uncertainty. Therefore, several qualitative risk indexes and empirical models are used in risk measurement based on understanding the environmental pollution risk system, especially the interaction between the causative factors and their sub-factors.

2.4.1. Preparation of primary layer indexes

(1) Sub indexes of $H_1$, $H_2$ and $H_3$
According to China’s code of practice relating to dangerous goods [13], the property of hazardous substance \((H_{11})\) is classified according to toxicity, explosiveness, combustibility, and corrosiveness, and ranked using the number of hazardous types involved. The ratio of stock quantity to threshold quantity of hazardous substance \((H_{12})\) is calculated according to the relevant standard [14] by using the threshold quantity. Condition of production equipment \((H_{13})\) and operation time of production and storage equipment \((H_{14})\) are ranked according to data from actual situations. Clustered risk sources can increase the environmental risk by either a chain effect or a group effect. Hence, clustering of risk sources \((H_{15})\) is determined and ranked according to the number of sources within unit area, bearing in mind the intensity of each risk source. Exposure to natural disasters \((H_{16})\) is evaluated using buffer analysis of natural disasters (e.g. high magnitude earthquakes or large-scale floods may trigger an abrupt environmental pollution accident).

A robust, accurate, effective environmental management system comprising equipment, technology and human resources is very important for an enterprise to reduce its exposure to environmental pollution risk. Online electronic surveillance \((H_{21})\), equipment maintenance \((H_{22})\), operational state of control system \((H_{23})\), environmental management system \((H_{24})\), safety measures \((H_{25})\) and emergency response of employees \((H_{26})\) are classified by the judgment of a panel of experts considering the relevant enterprises located in each zonation unit. The regional emergency response system also plays an important role in precautionary control regarding environmental pollution risk. The local emergency plan \((H_{31})\) and local emergency input \((H_{32})\) are ranked according to the actual levels.

(2) Sub indexes of \(V_1\) and \(V_2\)

Population density \((V_{11})\) is ranked using actual density data weighted according to residential suitability. The proximity between mixed residential and industrial areas \((V_{12})\) is estimated according to the relative distance between residents and the industrial areas, and is ranked with four degrees. The level of drinking water protection area \((V_{13})\) is ranked according to the importance of each zonation unit in supplying drinking water, and where buffer analysis may be used.

GDP per capita \((V_{21})\) is derived from economic statistics provided by local government agencies, and ranked according to criteria related to the degree of development. The index concerned with the local emergency rescue capabilities of medical and health institutions \((V_{22})\) is estimated from the numbers of sickbeds available, the data collected from local government statistics.

2.4.2. Measuring models

(1) Measuring risk

With reference to natural disaster risk [15], the regional environmental pollution risk is given by

\[
R = H \cdot V
\]

where \(H\) and \(V\) are respectively the hazard and vulnerability of environmental pollution in a zonation unit.

(2) Measuring hazard and vulnerability

Hazard is determined by risk source, source control and process control as follows

\[
H = H_1 \cdot (H_2 \cdot H_3)
\]

where \(H_1\) is state of risk source, \(H_2\) is level of source control, and \(H_3\) is level of process control.

Vulnerability is determined by exposure control and adaptation, formulated as

\[
V = V_1 / V_2
\]

where \(V_1\) is level of exposure control and \(V_2\) is adaptation for environmental pollution accidents.

(3) Measuring sub indexes of hazard and vulnerability

State of risk source is determined by characteristics of hazardous substance (i.e. \(H_{11}\) and \(H_{12}\)), plant equipment condition (i.e. \(H_{13}\) and \(H_{14}\)), and triggering factors (i.e. \(H_{15}\) and \(H_{16}\)). However, characteristics of hazardous substances...
substance and safety level of equipments have a higher weighting as causative factors. In the present application, the state of risk source is represented by

\[
H_1 = 0.6 \sqrt[3]{0.5(H_{11} + H_{15})^2 \times 0.5(H_{11} + H_{16}) + 0.4 \times 0.5(H_{15} + H_{16})}
\]  

(4)

State of source control depends on the device control system and the institutional control system. The control device system is influenced by \(H_{21}, H_{22},\) and \(H_{23},\) where 0.4, 0.4, 0.2 are assigned as weights respectively according to their relative importance. \(H_{24}, H_{25},\) and \(H_{26}\) in institutional control system are equally weighted. The state of source control is formulated herein as

\[
H_2 = \sqrt[3]{(0.4H_{21} + 0.2H_{22} + 0.4H_{23})^2 \times (H_{24} + H_{25} + H_{26})}
\]

(5)

Process control is denoted as

\[
H_3 = 0.5(H_{31} + H_{32})
\]

(6)

Exposure control mainly considers exposure of human beings (i.e. \(V_{11}\) and \(V_{12}\)) and exposure of the ecosystem (represented by the drinking water protection area), and is measured using

\[
V_i = \sqrt[3]{0.5(V_{11} + V_{12})}
\]

(7)

Adaptation is estimated from

\[
V_2 = \sqrt[3]{V_{21} \times V_{22}}
\]

(8)

2.5. Mapping and amendment of risk zonation

After estimating the primary layer indexes, the medium layer indexes and final objective index are evaluated using the above formulae. The resulting values of risk, hazard, and vulnerability are mapped using GIS tools. According to the degree of risk, a regional environmental risk zonation is carried out, merging units with the same degree of risk. Several scattered but small units are incorporated in the neighboring zonal area for convenience regarding zonal environmental risk administration.

3. Case study: Minhang District, Shanghai, China

3.1. Study area

The port city of Shanghai is the largest economic center in China. Within the Shanghai metropolis, Minhang District is a relatively new residential and industrial area through which flow the Wusong River and Huangpu River. By the end of 2008, the resident population and registered population estimates for Minhang District were 1.8 million and 0.9 million, located in 12 administrative suburbs. Minhang District has several industrial parks (including Xinzhuang) and has become the main industrial hub of Shanghai. The parks contain numerous traditional industries, which pose a high risk of heavy pollution. A river network and a 300 km² quasi-water source protection area are located at the upper reach of Huangpu River within Minhang District. The Matsuura Bridge water intake, the most important drinking-water intake in Shanghai, is located 3 km further upstream. World Expo 2010 Shanghai is located in downriver, close to Minhang District. In this area, enterprises are potentially exposed to typhoon, spring tide and flood natural hazards.

3.2. Risk zonation

For Minhang District, 13 zonation units are utilized, each based on a separate administrative suburb or street. To prepare the database of primary layer indexes for the 13 units, three field surveys were carried out in November 2008, April 2009 and July 2009. The surveys obtained data on 254 enterprises located in the quasi-water source protection area, with detailed information on risk sources and risk receptors derived for the 52 enterprises assessed.
as being the major environmental risk sources. Social and economic information was derived from statistics provided by the local government authorities. A base map of Shanghai was prepared using GIS tools.

Derived from the database, 19 primary layer indexes for each unit were normalized following the guidelines listed in Table 2 using ranks one, two, three, and four, and then graded with values of 4, 3, 2, and 1 respectively. Values for the medium layer indexes were calculated based on the primary layer indexes, using the weighted formulae given in Section 2.4. Finally, the risk values were determined for all 13 basic units.

Table 2 Normalization of the primary layer indexes

| Indexes | Rank one                          | Rank two                      | Rank three                  | Rank four                          |
|---------|----------------------------------|-------------------------------|-----------------------------|------------------------------------|
| H_{11}  | 3-4 types of hazardous properties| 2-3 types of hazardous properties| 1-2 types of hazardous properties| 0-1 types of hazardous properties |
| H_{12}  | >1                               | 0.6-1                         | 0-0.6                       | 0                                  |
| H_{13}  | below domestic average           | domestic average              | domestic advanced           | international advanced             |
| H_{14}  | >20 years                        | 10-20 years                   | 5-10 years                  | <5 years                           |
| H_{15}  | highly intensive                 | intensive                     | scattered                   | very scattered                     |
| H_{16}  | A buffer area                    | B buffer area                 | C buffer area               | outside buffer area                |
| H_{17}  | in production, storage, and release| in production, and storage | nowhere                     | ——                                 |
| H_{18}  | regular maintenance              | rare maintenance              | no maintenance              | ——                                 |
| H_{19}  | good                             | medium                        | poor                        | bad                                |
| H_{20}  | ISO certified                    | perfect                       | preliminary                 | no                                 |
| H_{21}  | safety assessment, emergency plan and team | no safety assessment, but have safety assessment, but no emergency plan and team | no | —— |
| H_{22}  | regular safety training and drills| non-scheduled safety training and drills | no | —— |
| H_{23}  | high                             | medium                        | low                         | no                                 |
| H_{24}  | perfect emergency plan           | reasonable emergency plan     | preliminary emergency plan | no emergency plan                  |
| V_{11}  | >9000 per km$^2$                 | 3000-9000 per km$^2$          | <3000 per km$^2$            | ——                                 |
| V_{12}  | high                             | medium                        | low                         | ——                                 |
| V_{13}  | water intake                     | A protection area             | B protection area           | non-protection area                |
| V_{14}  | 7000-10000 US$                   | 3000-7000 US$                 | 1000-3000 US$               | 0-1000 US$                        |
| V_{15}  | >500 sickbeds                    | 301-500 sickbeds              | 80-300 sickbeds             | <80 sickbeds                      |

Table 3 lists the values obtained for the basic units. The value ranges of the indexes $H$, $V$, and $R$ are $0 \leq H \leq 4$, $0.25 \leq V \leq 4$, and $0 \leq R \leq 16$. Fig.1 and Fig. 2 present the hazard and vulnerability maps constructed according to five degrees of severity from the orders of the $H$ and $V$ values. For risk zonation purposes, Minhang District was divided into zones according to four degrees of risk: high risk where $R \geq 0.3$; medium risk where $0.15 \leq R < 0.3$, low risk where $0 < R < 0.15$, and very low risk where $R = 0$. Fig. 3 shows the final environmental pollution risk zonation map obtained after amending the primary risk zonation according to the actual situation of Minhang District.
Table 3 Values of Hazard, Vulnerability, and Risk for Minhang District, Shanghai

| Zonation unit        | Hazard, $H$ | Vulnerability, $V$ | Risk, $R$ |
|----------------------|-------------|--------------------|-----------|
| Huacao town          | 0.22        | 0.65               | 0.14      |
| Hongqiao town        | 0.13        | 0.61               | 0.08      |
| Meilong town         | 0.28        | 1.53               | 0.43      |
| Qibao town           | 0           | 0.56               | 0         |
| Xinzhuang town       | 0.10        | 0.40               | 0.04      |
| Zhuanqiao town       | 0.11        | 0.50               | 0.06      |
| Maqiao town          | 0.17        | 1.12               | 0.18      |
| Wujing town          | 0.30        | 1.22               | 0.37      |
| Pujiang town         | 0.26        | 0.82               | 0.21      |
| Longhai St.          | 0           | 1.22               | 0         |
| Gumeilu St.          | 0           | 1.22               | 0         |
| Jiangchuanlu St.     | 0.25        | 1.62               | 0.40      |
| Xinzhuang industrial park | 0.20    | 0.79               | 0.16      |

Fig. 1 Hazard map of abrupt environmental pollution for Minhang District, Shanghai
Fig. 2 Vulnerability map of abrupt environmental pollution for Minhang District, Shanghai

Fig. 3 Risk zonation map of abrupt environmental pollution for Minhang District, Shanghai
3.3. Results

3.3.1. High risk zones

High risk zones include Meilong town, Jiangchuanlu Street, and Wujing town, and cover 93 km² (i.e. 26 % of the area of Minhang District). Obviously, high risk relates both to high hazard and high vulnerability. There are clustered petrochemical enterprises containing large quantities of hazardous substances, notably in Wujing Industrial Park and the Minhang Economic Development Zone. The high local population density and close proximity between the residential and industrial areas contribute to the human exposure to danger. Moreover, most of the high risk zones are situated in the quasi-water source protection area and near to the water intake.

3.3.2. Medium risk zones

Pujiang town, Maqiao town, and Xinzhuang industrial park occupy the medium risk zone whose area of 144 km² area is 41 % that of Minhang District. The medium risk zone has both high hazard and medium vulnerability (e.g. Pujiang town), or else medium hazard and medium vulnerability (e.g. Maqiao town and Xinzhuang industrial park). The high hazard arises from several industrial parks containing obsolete production plant and powerless source control. A small area belongs to the quasi-water source protection area, where the population density is low, but the GDP per-capita is rather high, which results in medium vulnerability.

3.3.3. Low risk zones

The low risk zone includes Huacao, Hongqiao, Xinzhuang, and Zhuanqiao towns. Its area is 81 km² corresponding to 25 % of Minhang District. Most of the units in this zone have a medium or low hazard and low vulnerability. The low vulnerability is because of low population density, non-water source protection area and high level of GDP per capita.

3.3.4. Very low risk zones

Qibao town, Longbai Street and Gumeilu Street are classified as very low risk. Their 30 km² area accounts for 13 % of Minhang District. They are commercial and residential areas either without risk sources or else located far away from risk sources. Here the hazard is negligible, and risk is very low.

4. Conclusions

An Abrupt Environmental Pollution Risk Zonation (AEPRZ) approach has been proposed for application to a typical mega-city. The approach is based on a regional environmental pollution risk system, whereby risk is determined as the product of hazard of risk source and vulnerability of risk receptor. The approach involves development of a zonation index system, risk measurements, and amendment of risk zonation. The measurement formulae observe the actual non-linear relationships between risk causative factors, avoiding inaccurate simple linear measurements. Consequently, an efficient, useful means of evaluating regional environmental pollution risk has been derived that is applicable to a mega-city. Herein, AEPRZ was applied to a demonstration case study of Minhang District, Shanghai, which was divided into four zones with risk degrees of high, medium, low, and very low. The zonation results are essentially in accordance with the actual risk distribution, and so could provide a basis for decision making in zonation risk governance, and in preventing and mitigating pollution accidents in Minhang District.

Further work is still needed on validation of the measurement formulae and improving the robustness of AEPRZ. The risk posed to areas neighboring the area of interest should also be analyzed.
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