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Highlights

>Accidental releases of pollution can have severe consequences. >We present an Environmental Pollution Accident Risk Mapping (EPARM) model for a city. >It involves risk index system identifying, risk measurements, and zonal risk mapping. >It is efficient and applicable to large urban areas. >Also an operational risk prevention framework is presented for zonal risk areas.

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Environmental Risk Mapping of Accidental Pollution and its Zonal Prevention in a city

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Abstract

Accidental releases of pollution can have severe environmental, societal, economic, and institutional consequences. This paper considers the use of risk mapping of accidental pollution events, and zonal prevention measures for alleviating the impact on large urban areas. An Environmental Pollution Accident Risk Mapping (EPARM) model is constructed according to a mapping index system supported by quantitative sub-models dedicated to evaluating the risk arising from different sources of accidental pollution. The EPARM approach consists of identifying suitable indexes, assessment of environmental risk at regional and national scales based on information on previous pollution accidents, and use of GIS to map the overall risk. A case study of pollution accidents in Minghang District, Shanghai, China is used to demonstrate the effectiveness of the model.

Keywords: Risk Mapping, Environmental Pollution, Accident, Zonal Governance, Prevention, Shanghai

1. Introdcution

Countries undergoing rapid industrial and urban development are especially prone to environmental pollution accidents. Taking P. R. China as an example, the number of pollution accidents reported to and acted upon by the Ministry of Environmental Protection rose from 64 in 2003 to 171 in 2009 (Ministry of Environmental Protection, 2004-2010). A total of 784 environmental pollution accidents were responded to from 2003 to 2009. Of these, several caused major environmental and socio-economic damage. Examples include pollution incidents in the Tuojiang River in 2004 and the Songhuajiang River in 2005, cadmium pollution of Xiangjiang River in 2006, arsenic pollution of the Liujiang River in 2007, and arsenic pollution of

Yangzonghai Lake in 2008. As a consequence, the 12th State Environmental Protection Plan for China emphasizes the importance of risk prevention, targets reductions in the total quantities of different pollutants released, and encourages measures aimed at improving the environment. Environmental pollution risk maps can therefore provide useful information to decision-makers charged with environmental management.

To date, the approaches used for environmental risk assessment and mapping can be classified as deterministic assessment, probabilistic assessment, and combined deterministic-probabilistic assessment. Deterministic assessment methods include multi-criteria comprehensive assessment (Giupponi et al., 1999; Yang et al., 2006; Huang et al., 2011), risk categorization and mapping method (Gupta et al., 2002), experience and expert-judgment (Merad et al., 2004; Uricchio et al., 2004; Irene et al., 2010), fuzzy aggregative risk assessment (Sadiq & Husain, 2005), global environmental risk assessment (GERA, Achour et al., 2005), and a pan-European approach (Zwahlen, 2004). Examples of probabilistic assessment approaches include five-step regional ecological risk assessment (Xu et al., 2004), fuzzy-stochastic risk assessment (Li et al., 2007), non-linear joint probability algorithm modeling (Wang & Zhang, 2007) and the information diffusion method (Xu et al., 2009). Combined deterministic-probabilistic assessment is exemplified by ARAMIS, the Accidental Risk Assessment Methodology for IndustrieS (Kirchsteiger, 2002; Salvi & Debray, 2006). Most of these approaches follow the chain of events that occur after chemicals are released, ranging from exposure and hazard assessment to risk characterization, and utilize various different indicators, scales, underlying data, and spatial operations (Lahr & Kooistra, 2010). However, the majority of these approaches are limited to specific sites or small areas such as plant clusters, reservoirs, oilfields, towns, and industrial parks.

Some are further restricted to a single unit or process (e.g. GERA and ARAMIS). And they may not produce accurate and widely used risk mappings because of incompleteness of the index system, over-simplification of the model, and an over-dependence on expert opinions.

Guidelines and principles for countermeasures are provided by Awareness and Preparedness for Emergencies at Local Level, APELL (UNEP, 1988), Guiding Principles for Chemical Accident Prevention, Preparedness and Response (OECD, 1992), and Accidental Release Prevention Requirements (EPA, 1996). In China, guidelines have been proposed for the prevention of and response to environmental pollution accidents (see Guo et al., 2006; Bi et al., 2006), and national and local emergency response plans to environmental pollution accidents have been successively issued. At the time of writing, there appears still to be some way to go, as there remain certain weaknesses in the systemic framework and operational details, especially for different risk zones. And more attention is presently being paid to response rather than prevention.

We propose an Environmental Pollution Accident Risk Mapping (EPARM) approach that utilizes a fully populated risk index system supported by assessments of risk at regional and national scales. The approach is based on case histories, with Geographical Information Systems used to aid the data analysis and interpretation. We consider the demonstration example of the risk of environmental pollution due to accidents in Minghai District, Shanghai, China. A systemic framework is also provided for the prevention of accidental pollution events, along with a description of detailed countermeasures applicable to specific risk zones.

2. Methodology and materials

2.1 Risk system and mapping index system

Part A in Fig. 1 provides a conceptual illustration of the environmental pollution risk system. Risk sources and receptors have to be identified. The risk system encapsulates the main causes of accidents. An environmental pollution accident is deemed to have occurred when an environmental pollution hazard is triggered and its residual impacts on a vulnerable risk receptor are sufficient to cause damage. The risk source is defined as anything that might cause an environmental pollution hazard, and often derives from the production, transport, and storage of toxic or reactive chemicals. In such cases, the hazard depends on the specific chemical under consideration, and the source and process controls applied. The risk receptor is anything that is vulnerable to damage by the hazard. And vulnerability is itself affected by exposure and adaptation of risk receptors.

Risk indexes should have several desirable characteristics. They should be determined using a scientifically acceptable methodology. They should be based on complete data as far as possible, and be statistically independent. They should be operative, causative, and act to discriminate the degree of environmental risk for each unit considered. A four-layer risk mapping index system (see Liu et al., 2010) is used in the present study, derived from the conceptual model indicated in Fig. 1. Risk depends on hazard and vulnerability. And hazard is determined by risk source state, risk source control, and incident process control. Vulnerability is determined by the exposure and adaptation of the risk receptor. Here, 19 primary sub-indexes are used to provide the information required to evaluate the above indexes.

Fig.1 Conceptual system (A) and prevention framework (B) of environmental pollution accident risk

2.2 Risk measurement

Liu et al. (2010) discuss the empirical models presently used in risk measurement. In the present study, the risk measurement procedure involves the following steps. Firstly, primary data or information is provided for 19 sub-indexes in each basic mapping unit (which could be an administrative unit according to database preparation and zonal risk governance requirements). Secondly, sub-indexes of hazard and vulnerability are measured using specific models (see Liu et al., 2010) with normalized quantitative values of primary indexes. Thirdly, values of hazard and vulnerability are estimated using simple positive/negative relation models based on their sub-indexes. Finally, the risk value for each unit is obtained from the hazard and vulnerability by multiplication (see Varnes, 1984).

2.3 Mapping and risk prevention

Three maps of hazard, vulnerability, and risk are constructed using GIS tools, according to the measured results in each mapping unit. Three ranks are assigned to the degrees of hazard (H) and vulnerability (V). The risk map is then divided into four zones with degrees of high, medium, low, and very low.

In practice, risk prevention measures should be determined for each zone according to its local hazard, vulnerability, and risk characteristics. Here, a framework for risk prevention has been constructed in order to deal with causative factors in the risk system (see part B in Fig.1). For risk prevention, the two essential strategies are hazard mitigation and vulnerability reduction. The precautionary principle is applied to mitigate the degree of hazard. For example, hazardous substances should be stored in containers away from receptors. The precautionary principle includes lowering the hazardous level of risk sources, strengthening source control, and enforcing preparation for incident process control. Exposure reduction and adaptation promotion can help avoid or minimize damage by reducing the vulnerability of risk receptors in the presence of hazardous substances. In a given city, different combinations of the foregoing strategies are required in order to reduce the local risk of accidental environmental pollution for different zones which share different degrees of hazard, vulnerability, or risk. More detailed measures will be illustrated for these basic strategies in the case study discussed in Sections 3 and 4.

2.4 Study area and data sources

Minhang is a newly-developed residential and industrial district occupying a land area of 372 km^2 situated on the floodplain of the Huangpu River close to the center of Shanghai. The region contains a river network with more than 200 waterways, and is close to the coast. It is therefore particularly susceptible to typhoon, spring tide and flood natural hazards. Minhang includes 300 km^2 of environmentally sensitive quasi-water source protection area located along the upper reach of the Huangpu River and the Matsuura Bridge water intake, the most important drinking-water intake in Shanghai. In 2009, Minhang had a population of 1.81 million residents located in 13 administrative suburbs, with an economy of US$ 19 billions GDP. Four industrial parks (including Xinzhuang) are located in Minhang District and its excellent transport system has led to it becoming the main industrial hub of Shanghai. Many of its more than 3400 industrial enterprises are traditional chemical users or producers and are located in or near parks, posing a high pollution risk.

To assess and map the risk of environmental pollution accidents for Minhang, 13 administrative suburbs were used as basic mapping units. A database was build in terms of hazard and vulnerability information related to 19 primary layer indexes concerning the 13 mapping units. A total of 254 enterprises handling hazardous substances were identified from a total of 3400 enterprises, most of which are located close to the Matsuura Bridge water intake. A survey was carried out using a simple questionnaire in late 2008, and rough information gained for the 254 enterprises on the hazardous substances involved and potential receptors. By considering the quantity and toxicity of the stored hazardous substances, 52 enterprises were identified as major environmental risk sources, including Shanghai Coking Co. Ltd, Shanghai Wujing Chemical Co. Ltd, and Shanghai NO.1 Biochemical & Pharmaceutical Co. Ltd. A comprehensive questionnaire was completed by, and an interview conducted with representatives of each of these 52 enterprises in April 2009 and July 2009. Detailed information on the major risk sources and their receptors were collected for all 13 mapping units. With the assistance of local government authorities, social and economic information, including population density and GDP per capita, was derived from the official statistics (Minhang Statistics Bureau of Shanghai, 2010). Spatial locations of enterprises, residential areas, and rivers were prepared using GIS tools. Further mapping operations were undertaken using specialized spatial analysis functions in GIS software including buffering and overlaying.

3. Results

3.1 Risk mapping

Using the EPARM approach, values of hazard, vulnerability, and risk were calculated for all 13 basic units in Minhang. The degrees of hazard were ranked in term of the following hazard values: high (≥ 0.2), medium (≥ 0.1 and < 0.2), and low (< 0.1) (see Table 1). The degrees of vulnerability were ranked as high (≥ 1.0), medium (≥ 0.75 and < 1.0), and low (< 0.75). And Minhang District was divided into zones at high risk (≥ 0.3), medium risk (≥ 0.15 and < 0.3), low risk (> 0 and < 0.15), and very low risk (= 0).

Table 1 Degrees of Hazard, Vulnerability, and Risk for Minhang District, Shanghai, China

3.2 Zonal risk prevention

According to the risk zonation map shown in Fig.2, Minhang District has been divided into four areas corresponding to high, medium, low, and very low risk of environmental pollution due to accidents. However, a single zone might require different hazard prevention measures when divided into sub-zones corresponding to specific degrees of hazard and vulnerability (see Table 1).

Fig. 2 Risk mapping of environmental pollution accidents for Minhang District, Shanghai, China

3.2.1 High risk zone

The high risk zone includes Meilong, Wujing, and Jiangchuanlu. Obviously, high risk relates both to high hazard and high vulnerability. There are clusters of old petrochemical enterprises storing large quantities of hazardous substances (with complicated chemical properties), notably in Wujing Industrial Park and the Minhang Economic Development Zone. The locally high population density and close proximity between residential and industrial areas contribute to the human exposure to danger. Moreover, most of the high risk zone is situated near the Matsuura Bridge water intake in the environmentally sensitive quasi- water source protection area.

The following prevention measures are suggested for the high risk zone:

(1) Adjust the industrial structure to limit (or even eliminate) obsolete and high risk industries.

(2) Relocate previously scattered enterprises to industrial parks.

(3) Improve the safety of old enterprises by updating their production facilities and enforcing

source controls.

(4) Relocate residents out of exposed areas, and use green buffers or partitions.

(5) Promote the adaptive capacities of local residents and the protected wetlands area in dealing with pollution accidents.

(6) Emphasize the need to improve the capability of local risk monitoring and emergency response services.

(7) Reinforce local coping abilities and resilience.

(8) Make emergency plans and perform incident response drills at enterprise, residential, and local scales.

3.2.2 Medium risk zone

Maqiao, Pujiang, and Xinzhuang Industrial Park occupy the medium risk zone. Maoqiao is subject to medium hazard and high vulnerability, which may be attributed to the presence of several enterprises involved with hazardous substances, the close proximity between residential and industrial areas, and Maoqiao's location near the water intake. Pujiang and Xinzhuang Industrial Park are prone to high hazard but medium vulnerability. The high hazard arises from a cluster of obsolete production plants with archaic technology, leading to poor source control.

The following risk prevention measures are recommended for Maoqiao:

(1) Relocation of the presently dispersed enterprises to industrial parks.

(2) Rehousing of residents away from exposed industrial areas, and, where appropriate, the use of green buffers and partitions.

(3) Promotion of adaptive capacities of local residents and the protected wetlands area in dealing with pollution accidents.

(4) Strictly limit the setting up of new risk enterprises.

For Pujiang and Xinzhuang Industrial Park, risk prevention measures could include:

(1) Limitation (or elimination) of obsolete, high risk industries.

(2) Promotion of safe production practices and improved technology in old enterprises.

(3) Use of monitoring and control systems, and the enforcement of source controls by enterprises.

(4) Avoidance of further residential exposure through better urban planning.

(5) Education of local residents in risk prevention and emergency response procedures.

(6) Improvement in local risk monitoring and emergency response procedures.

3.2.3 Low risk zone

The low risk zone includes Huacao, Hongqiao, Xinzhuang, and Zhuanqiao. Most of the units in this zone are exposed to high or medium hazard and have low vulnerability. The low vulnerability is due to low population density, a high level of GDP per capita, and the towns being away from the protected wetlands and major water intake. The high hazard in Huacao arises from Minbei Industrial Park which hosts several enterprises processing quite large quantities of hazardous substances using old equipment without source control.

Four main countermeasures are proposed.

(1) Switch high risk industries to low risk ones, while eliminating obsolete enterprises.

(2) Limit the number of new residents and reduce residential exposure before countermeasure (1) is completed, especially in Huacao.

(3) Upgrade old enterprises that cannot be located, and invest in monitoring and control systems.

(4) Educate local government officials and industrialists in the importance of monitoring risk sources in Huacao, and carry out emergency response drills.

3.2.4 Very low risk zone

Qibao, Longbai and Gumeilu are classified as very low risk. They are commercial and residential areas either without risk sources or else located far away from risk sources. Here the hazard is negligible, but Longbai and Gumeilu are vulnerable because of their large populations and low GDP per capita. The following measures are suggested for Longbai Street and Gumeilu Street.

(1) Strictly prohibit the establishment of any risk enterprises.

(2) Promote risk prevention and response capacities of local residents.

(3) Make residential evacuation plans and perform drills.

For Qibao, which is low hazard and low vulnerability, the following measures are recommended:

(1) Prohibit the establishment of risk enterprises, while encouraging no risk ones.

(2) Locate new residential areas far from risk sources.

4. Discussion

A complete mapping index system has been proposed for regional environmental pollution accident risk. The system composes four layers, with 14 primary layer indexes of hazard and 5 primary layer indexes of vulnerability. These mapping indexes are pertinent in the measurement or assessment of degrees of risk because they are derived from the causal risk system. The mapping index system is more complete than previous systems (see e.g. Bi, et al., 2006; Guo, et al., 2006), in that it involves not only hazardous substances and sensitive receptors, but also considers risk management at both enterprise- and local-scales. There is an obvious difference between the risk indexes for environmental pollution accidents and for natural disaster accidents. In environmental pollution accidents, hazard mitigation is most important, especially at operational level because human mistakes are mainly responsible for environmental pollution hazards. As 'acts of God' natural hazards are difficult to mitigate, and so vulnerability reduction is more important. However, more detailed questionnaire-based information is needed to improve the accuracy of vulnerability indexes. And mapping indexes need to be more representative and aimed at precise risk measurement; such improved indexes can be derived from further case studies and systematic analysis of environmental pollution accidents.

The paper proposes empirical models by which to measure risk, hazard, vulnerability, and their associated sub-indexes. These measurement models are designed according to risk causation mechanisms, including causative indicators and their correlations. Such models describe actual nonlinear correlations and are effectively white box models, which predate linear plus grey box models for risk assessment. The resulting risk maps are accurate and applicable to large areas, owing to the normalization methods used for the primary layer indexes and the ranking ranges for risk degree. The case study of Minhang District in Shanghai demonstrates the practical use of the Environmental Pollution Accident Risk Mapping (EPARM) approach. The risk map obtained for Minhang is consistent with the views of local decision makers and provides a great deal of quantitative information that is useful for risk governance purposes. However, more evidence is needed in order to validate the measurement models. It is recommended that a sensitivity analysis be undertaken to improve the robustness of the EPARM approach, once more detailed information are available, especially with regard to vulnerability.

A framework for risk prevention planning and management has been constructed for zonal risk areas. The basic principles underpinning the framework relate to causative factors of environmental pollution risk and are systemic, having been derived using a risk systems methodology. The paper outlines detailed countermeasures designed for each risk zone based on its particular hazard, vulnerability, and risk characteristics. In practice, the risk prevention countermeasures should be taken up by planners, government officials, industry, residents, and other stakeholders.

5. Conclusions

Accidental pollution of the urban environment is of considerable importance as cities grow in size and population density. This paper has outlined details of an Environmental Pollution Accident Risk Mapping (EPARM) approach for assessing and mapping such risk at the scale of a city. EPARM is constructed according to a regional risk system for environmental pollution hazards due to accidents. Here, risk is defined as the hazard multiplied by the vulnerability. The approach involves development of a mapping index system, risk measurements, and zonal risk mapping. The mapping indexes are pertinent and complete, having been derived from the causative system of accidental environmental pollution risk. Actual, non-linear dependences between the risk factors are incorporated in the measurement formulae, an improvement on methods that rely on less accurate linear measurements. The resulting model of regional pollution risk is efficient and applicable to large urban areas. A framework of risk prevention has been presented for zonal risk areas. Its systemic specific strategies and detailed countermeasures serve as effective and operational means for zonal risk governance. The present paper presents results from a demonstration case study of Minghang District in Shanghai, China. The results are zonated according to high, medium, low, and very low degrees of risk, and are found to be consistent with the views of local administrators. The proposed zonal-specific countermeasures should offer sensible ways of preventing and mitigating pollution accidents in Minhang District.

Further case studies and systematic analysis of environmental pollution accidents are needed to improve the mapping indexes. A sensitivity analysis could be undertaken to improve the robustness of the EPARM approach especially with regard to vulnerability. And to what level countermeasures should be taken to prevent or mitigate the risk is another challenge in terms of risk carrying capacity, which could be considered into the carrying capacity of the environment (Liu, et al., 2011).

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Figure captions:

Fig.1 Conceptual system (A) and prevention framework (B) of environmental pollution accident risk

Fig. 2 Risk mapping of environmental pollution accidents for Minhang District, Shanghai, China

Figure 1

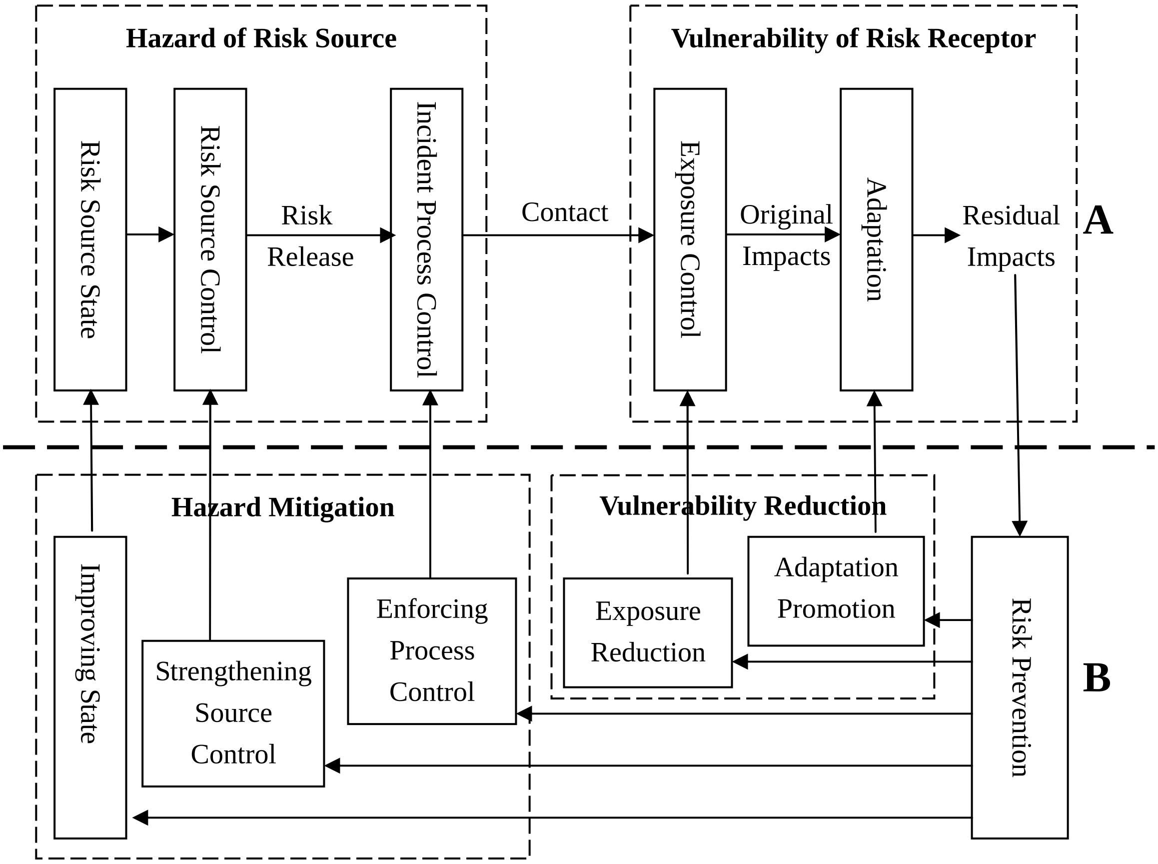

Fig.1 Conceptual system (A) and prevention framework (B) of environmental pollution accident risk

Figure 2

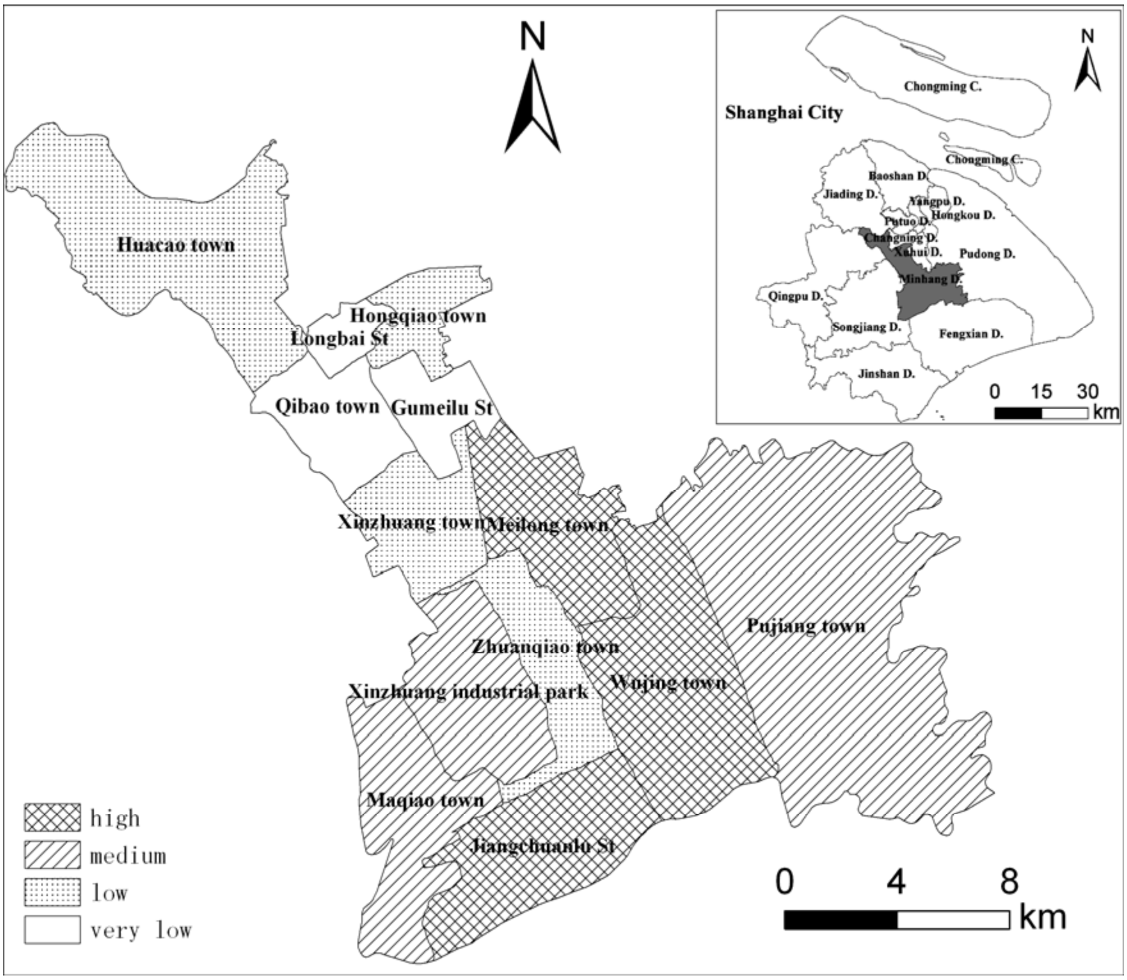

Fig. 2 Risk mapping of environmental pollution accidents for Minhang District, Shanghai, China

Table1

Table 1 Degrees of Hazard, Vulnerability, and Risk for Minhang District, Shanghai, China

Basic unit	Hazard degree	Vulnerability degree	Risk degree
Huacao	High	Low	Low
Hongqiao	Medium	Low	Low
Meilong	High	High	High
Qibao	Low	Low	Very low
Xinzhuang	Medium	Low	Low
Zhuanqiao	Medium	Low	Low
Maqiao	Medium	High	medium
Wujing	High	High	High
Pujiang	High	Medium	Medium
Longbai	Low	High	Very low
Gumeilu	Low	High	Very low
Jiangchuanlu	High	High	High
Xinzhuang Industrial Park	High	Medium	Medium