Journal of Hazardous Materials 179 (2010) 500–506

Contents lists available at ScienceDirect

Journal of Hazardous Materials

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

Mapping human vulnerability to chemical accidents in the vicinity of chemical industry parks

Fengying Li[a,b], Jun Bi[a,*], Lei Huang[a], Changsheng Qu[a], Jie Yang[c], Quanmin Bu[a]

[a] State Key Laboratory of Pollution Control & Resource Reuse, School of the Environment, Nanjing University, Nanjing210093, China
[b] School of Environment Science and Engineering, Nanjing University of Information Science & Technology, Nanjing210044, China
[c] School of Environment Science and Engineering, Suzhou University of Science and Technology, Suzhou215011, China

ARTICLE INFO

Article history:
Received 1 November 2009
Received in revised form 5 March 2010
Accepted 6 March 2010
Available online 12 March 2010

Keywords:
Vulnerability
Risk assessment
Chemical industry park
Geographical information system (GIS)

ABSTRACT

China is suffering from severe pollution accidents which may have catastrophic impacts on the local population and environment. Some questions are unclear to local governments and industry operators like "who are vulnerable to the chemical risks?" and "what is the magnitude of vulnerability?". This paper concentrates on exploring the concepts of human vulnerability and the methodology of analyzing human vulnerability to chemical accidents in the vicinity of chemical industry parks. A conceptual model of human vulnerability to chemical accidents is developed, revealing the roots of human vulnerability and emphasizing its role in risk management. A geographical information system (GIS)-based methodology for mapping vulnerability is proposed and applied to the Nanjing Chemical Industry Park in China. By combining physical vulnerability and social vulnerability spatially, the total vulnerability is revealed to better respond to accidents. It is proposed to improve traffic lines and allocation of medical services, and include vulnerability assessment in land-use planning to reduce future risks. In other words, it seems feasible and effective to reveal physical, social and total vulnerability of residents in the vicinity of chemical risk sources.

1. Introduction

Accidents such as the Bhopal tragedy in 1984 and the Jilin chemical plant explosions in China in 2005 have clearly demonstrated how the impact of industrial accidents can be severely amplified in adjacent areas with hazardous installations and high-density populations. Severe damage to human life and health caused by industrial accidents prompts reorienting emergency management from simple post-event response to preventive preparedness. Risk analysis is an activity to deal with available information to aid the decision making process in risk management. However, Kasperson et al. pointed out that, "...the practice of characterizing risk by probability and magnitude of harm has drawn fire for neglecting equity issues in relation to time (future generations), space (the so-called LULU or NIMBY issue), or social groups (the proletariat, the highly vulnerable, the export of hazard to developing countries), ..." [1]. Fortunately, some researchers started digging into environmental justice in terms of potential acute health risks by examining the distribution of serious chemical accidents across diverse sub-populations since the 21st century [2–4]. Another group of researchers tried to reveal the vulnerability of people and the environment to acute health risks posed by chemical materials [5–9], providing guidance for land-use planning and emergency response, with the objective to limit the potential consequences. In member states of the European Union, the vulnerability of the hazardous installations was conventionally described and quantified. A practical method was developed in the ARAMIS project, which was funded by the European Commission [8].

In industrializing China, lots of chemical industry parks are set up in coastal or riverside urban areas. Health and safety of people in and around the chemical industrial parks has attracted great attention of national and local authorities, as well as the public. However, the heterogeneity of different targets is seldom taken into account in risk assessment. As a result, risk management activities cannot be targeted and prioritized to mitigate the losses of major pollution accidents in an efficient way as early as possible. This paper provides an approach to assess and quantify human vulnerability to chemical risks in the vicinity of chemical industries clusters, for the sake of mitigating risks either by limiting the number of targets exposed to the risk or by blocking the targets from the risk source.

Nevertheless, the theory and application of vulnerability analysis give short measure for risk management by timely designing affordable and effective strategies for reducing the negative effects of chemical accidents, especially in the vicinity of chemical industry parks in China. It is essential to stress that we can only talk meaningfully about the vulnerability of a specified system to a specified

* Corresponding author at: No. 22 Hankou Road, Room 806, School of Environment, Nanjing University, Jiangsu 210093, China. Tel.: +86 25 83592976; fax: +86 25 83597357.
E-mail address: jbi@nju.edu.cn (J. Bi).

0304-3894/$ – see front matter
doi:10.1016/j.jhazmat.2010.03.031

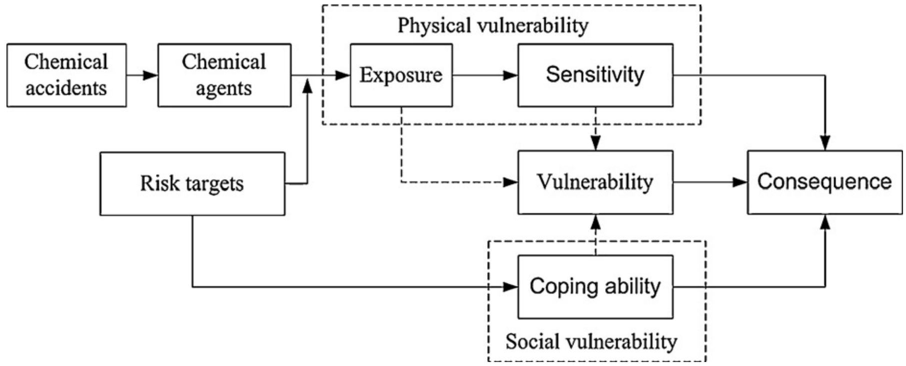

Fig. 1. Conceptual model of human vulnerability to chemical agents.

hazard or range of hazards. Vulnerability of a human community to chemical accidents, including their ability to adapt to the risk, is discussed in this paper. We regard chemical accidents as the cause of people's vulnerability, which fluctuates according to the intensity and magnitude of chemical accidents and the distribution of the population. It is a relatively new field of research in China that brings together experts from a wide range of fields, including environmental assessment and modeling, risk assessment, risk management, land-use planning, social science, policy development and economics. It will be carried out by applying the geographical information system (GIS) and statistical analysis to integrate potential exposures to chemical accidents and socioeconomic inabilities to respond to and recover from them.

The objective of this paper is to discuss the vulnerability of human communities adjacent to chemical industries, clarify necessary concepts, and outline a framework for vulnerability analysis. The vulnerability concept is discussed in more details in the next section of this paper, as well as a number of internal and external risk factors influencing human vulnerability. Section 3 presents a conceptual model of vulnerability and a general approach to vulnerability analysis of chemical industry parks. A case study in Nanjing Chemical Industry Park is put forward in Section 4. Finally, some concluding remarks are given in Section 5.

2. Literature review on vulnerability

Researches on vulnerability can be traced back to the 1970s in natural hazard studies. There are many papers on vulnerability assessment from different perspectives. There are some attempts to quantify environmental vulnerability referring to specific systems and particular stressors or classes of stressors, including risks posed by chemical industries to the surrounding environment. In these papers, vulnerability has been defined in various ways such as the threat of exposure, the capacity to suffer harm, and the degree to which different social groups are at risk [10].

Generally, there are three broad conceptual approaches to understanding vulnerability, which view vulnerability as risk of exposure, a socially constructed phenomenon, and a combination of exposure and socially constructed phenomenon respectively [11]. Based on these three types of definitions, there are three different points of views that result in three different strategies to address vulnerability.

The first one blames natural hazard as the cause of people's vulnerability and seeks for technological, scientific solutions. It corresponds to biophysical vulnerability, which examines the distribution of hazardous conditions arising from a variety of initiating events such as natural hazards, chemical contaminants, or industrial accidents. Studies based on this concept concentrate on exposure and/or sensitivity, which were underscored in an archetypal reduced-form model: the risk-hazard (RH) model [12,13].

The second point of view focuses on economic and institutional solutions to reduce vulnerability caused by costs and societal structures, which shapes social vulnerability and suggests that people have created their own vulnerability, largely through their own decisions and actions [14]. Social vulnerability describes the socio-demographic characteristics of social groups that make them more or less susceptible to the adverse impacts of hazards. Souza Porto and Freitas [15,16] explored vulnerability to major chemical accidents in industrializing countries only from perspectives of socio-political structures, proposing a deep transformation of social and environmental inequalities and a more intensive participation of the involved actors to reduce prevailing differences in standards of prevention and in the severity of major chemical accidents. In some sense, population density is often used to reflect relative human vulnerability in urban areas [9]. And the distribution of sensitive targets such as schools and trade markets are used to characterize the variability of vulnerability and to prioritize hazardous wastes transportation routes [17].

Last but not the least, the third point of view deals with the problems in a combined manner, on which this study is based. A representative diagram is a standard two-dimensional classification of post-normal science, which emphasizes axes of "social and institutional vulnerabilities" and "complexity of technological hazards". It implies that major social policies and a comprehension of the limits of the normal scientific and economic approaches to such problems are required in reducing the vulnerability of industrializing countries [15]. Perhaps equally important is the notion that vulnerability varies by location (or space) and over time—it has both temporal and spatial dimensions. Several studies investigated the vulnerability in spatial terms adopting GIS [8,9].

However, the integrative, temporal and spatial dimensions are too complicated and uncertain to be taken into account in vulnerability analysis simultaneously. Most researchers dealing with vulnerability of risk targets to chemical accidents emphasized exposure to risk or socially adaptation, instead of assessing vulnerability in synthetic approaches. Though there are a few studies revealing integrative vulnerability to chemical accidents in spatial terms, most of them defined hazardous zones using proposed safety distances [4] or other recommended protective action distances [9].

3. Conceptual model and procedure of assessing vulnerability

3.1. Conceptual model of vulnerability

In this paper, vulnerability is considered a multidimensional concept involving exposure—the degree to which a human group contacts with chemical accidents; sensitivity—the degree to which a risk target is affected by exposure to any set of chemical agents; and coping ability—the ability of the target to resist or recover from

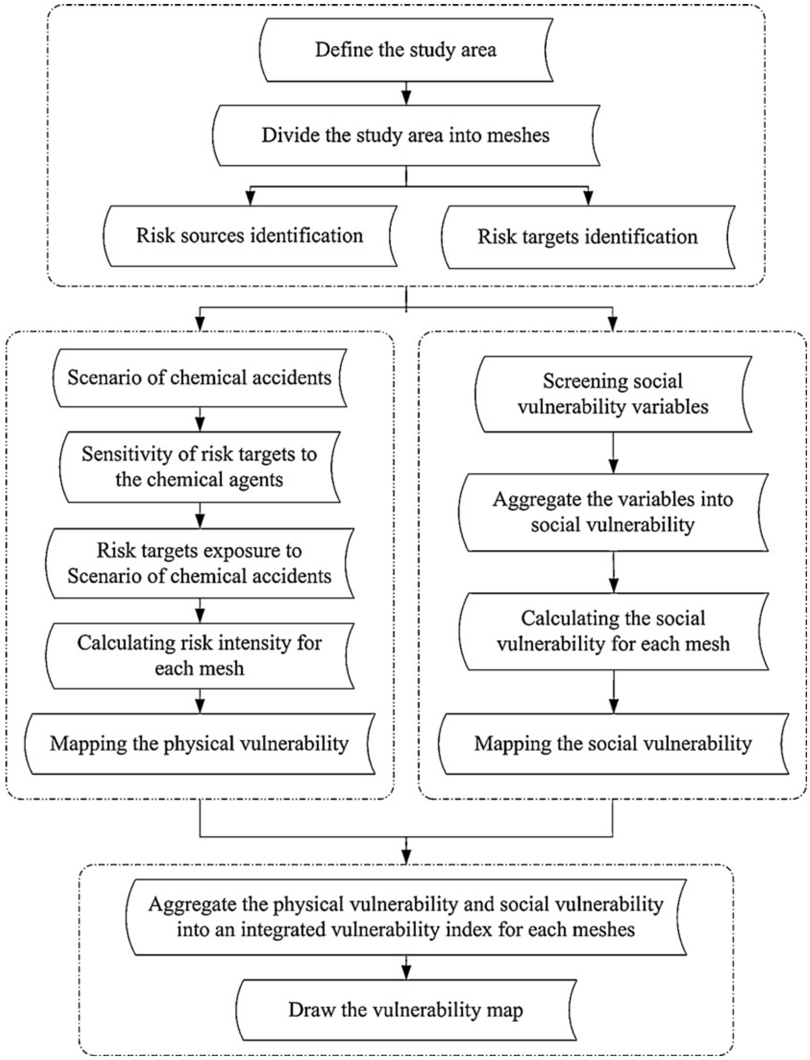

Fig. 2. General overview of vulnerability assessment.

the damage associated with exposure to the chemical agents. The exposure and sensitivity constitute physical vulnerability, and the lack of coping ability reflects social vulnerability which indicates social roots for targets being vulnerable to hazards. In this manner, a conceptual model of vulnerability is developed as Fig. 1 shows. Compared with the risk-hazard model, coping ability is an additional dimension in this model, which is of great significance in this research.

According to the conceptual model of vulnerability mentioned above, it reflects both potential hazard levels and resistibility of targets. In other words, potential hazard levels of targets reflect physical vulnerability, determined by exposure and sensitivity, while resistibility of targets indicates social roots for vulnerability. Mitigating potential hazard levels of targets can be achieved by removing or relocating chemical industry activities or human targets, or by introducing obstacles between them. In emergency response, it is critical to focus on the targets with a relatively higher vulnerability. Enhancing resistibility of targets has been another major approach in risk reduction. Usually, risk targets with high vulnerability, like school age populations, should be given special and prioritized protection. For example, special channels of communication are opened up for sensitive targets, and a higher level of earthquake-resistance is demanded for school buildings. In emergency situations, it will be necessary to identify who needs resistibility enhancement and how to allocate limited resources among risk targets effectively based on vulnerability assessment. The above key nodes are identified for avoiding risks to targets in risk management.

3.2. Procedure of vulnerability assessment

As vulnerability is composed of physical and social vulnerability, it is not solely dependent on the proximity to the potential risk source and the magnitude of the source, but also on social-economic properties of the risk targets. Analyzing vulnerability in this manner requires identifying potential risk sources which might threaten human targets and how the human targets are capable of resisting accidents. In other words, the proposed procedure reveals vulnerability in a synthetic manner, considering both physical and social factors. And GIS technology provides a practicable tool for demonstrating vulnerability in spatial terms. Compared with the above-mentioned studies [4,8,9], the proposed procedure delineates explicitly the footprint of hazardous accidents, instead of relying on proximity-based measures with some proposed distances. Thus it focuses on vulnerability of sensitive targets to specific hazardous accidents, which provides a significant reference for emergency responders. The vulnerability analysis process is illustrated in Fig. 2. In principle, it is comprised of four major steps, explained in more details as follows.

3.2.1. Systematic definition

The procedure begins with defining the features of the study area, as well as the scope and boundary of the vulnerability analysis. Specifically, the size of the study area should be large enough to cover the impacted area of the reference accident scenarios from the industrial site. The mesh size should be determined appropriately to keep homogeneity in a mesh and reflect heterogeneity among different meshes. Generally, a 500 m × 500 m mesh size is suggested for a 20 km × 20 km size study area [8]. Identification of risk sources is carried out in accordance with the national standard [18]. Moreover, to obtain information about the various targets, it requires a survey of each target category in each mesh of the study area.

3.2.2. Mapping physical vulnerability

The second part of the vulnerability assessment procedure is the estimation of potential hazard zones using a simulation model and GIS spatial analysis, which measures the exposure of sensitive targets to the chemical agents. The sensitivity of the targets to the chemical agents represents a dose–effect relationship between a specific chemical agent and a specific target. There are several databases providing scientific information on toxicology, recommending toxicity thresholds for demarcating hazard zones.

Airborne risks posed by chemical accidents include explosions, fires and toxic gas releases from both fixed facilities and mobile risk sources. As far as mobile risk sources are concerned, a buffer of half a mile is created around each railroad and arterial highway segment, which is recommended by the US Department of Transportation for a fire involving hazardous chemicals [19]. On the subject of fixed facilities, either a Gaussian spread function or other numerical models, with some proposed toxicity thresholds, can be used to predict the hazard zone where the toxic gas concentration is too high to harm people. As commonly recommended in risk assessment studies, the Aerial Location of Hazardous Atmospheres (ALOHA) program is employed to delineate the plume footprint of the maximum threat zone for accidental release. It is beyond the scope of this paper to describe this program, and any further information can be found in the user's guide [20].

3.2.3. Social vulnerability mapping

Since social vulnerability is derived from the activities and circumstances of everyday life or its transformation [21], it is a sticking point to elaborate and integrate social indicators for vulnerability. Social indicators are playing a vital role in vulnerability of humans to chemical risk, besides the hazard levels of potential risks. Former studies and examples from recent disasters illustrate how certain categories of people, such as the poor, the elderly and recent residents, are at greater risk throughout the emergency response process [22]. Some relevant factors are identified to be pivotal for vulnerability in industrializing countries to major chemical accidents at national level, for example the location of such plants near residential communities for marginalized workers and their families, the role of these countries in the global production system, the enforcement of safety and planning laws, quality of housing, and lifestyle of residents [15]. Some factors that influence the fundamental causes of social vulnerability include lack of resources (including information and knowledge), limited access to political power and representation, certain beliefs and customs, weak buildings and/or weak individuals, as well as infrastructure and lifelines [9,17,23].

As far as the chemical accidents are concerned, population and structure, and their access to emergency resources determine the social vulnerability of people. Generally, social vulnerability of a highly populated area is higher than that of sparsely populated ones. Pollutants always pose more risks to females, young children and old people, who might be weaker. Moreover, access to social resources is critical for resisting chemical risk, like communities close to evacuating routes and hospitals. Safety education can help people increase the possibility of survival during and after pollution accidents. The characteristics and variables listed in Table 1 are recommended to characterize social vulnerability based on literature [9,24]. The data is mainly obtained via official statistics and fieldwork.

Table 1
Measure of social vulnerability of populations.

	Characteristics	Variables
Infrastructure	Settlement	Housing units
	Infrastructure	Utility networks
	Critical facilities	Hospitals; police stations; fire stations; life line; accessibility of drinking water and safe food
Social environment	Demographics	Age; health; gender; race and ethnicity; education
	Social relations	Class; family; structure; social support
Economic environment	Micro-economy	Income; debt; assets
	Macro-economy	Community wealth; market dependency
Political environment	Institutions	Level of democracy; stakeholder involvement; resource distribution and redistribution; scope of institution activities; accessibility of institutions
	Individual perceptions	Experience; education; socioeconomic status

3.2.4. Integrating physical and social vulnerability

Finally, total vulnerability mapping is carried out by overlapping physical vulnerability and social vulnerability in GIS. As the conceptual model suggests, the overlapping of physical and social vulnerability produces the spatial variation in total vulnerability for the study area. Weight allocation between the individual layers should be flexible according to local conditions. The vulnerability assessment represents the first scientific basis for the decision support system and should be followed by the development of potential pollution risk maps. The results not only lay out each individual layer of vulnerability independently, but also produce a broad view of the spatial distribution of total vulnerability within a study area, which provides a new and comprehensive perspective for the emergency management community.

4. Case study

The method of mapping vulnerability is applied for the Nanjing Chemical Industrial Park (NJCIP) in Jiangsu Province, China. The NJCIP is located along the Yangtze River and to the north of Nanjing City. The 9 km × 9 km study area is divided into 900 meshes in size of 300 m × 300 m. The applications of chlorine are broadly known in many chemical industries, such as bleaching agents, synthetic rubbers, plastics, etc. And chlorine leakages are common industrial accidents in industrializing countries and regions, posing acute toxicity to local populations once it is released accidentally [25]. Therefore it is chosen to demonstrate the proposed methodology in this study.

The Arcgis system is an integrated GIS, which provides a framework for implementing GIS for users. The version of Arcgis 9.2 is adopted to build a geodatabase and carry out spatial analysis, including buffer analysis and union analysis. ALOHA is employed

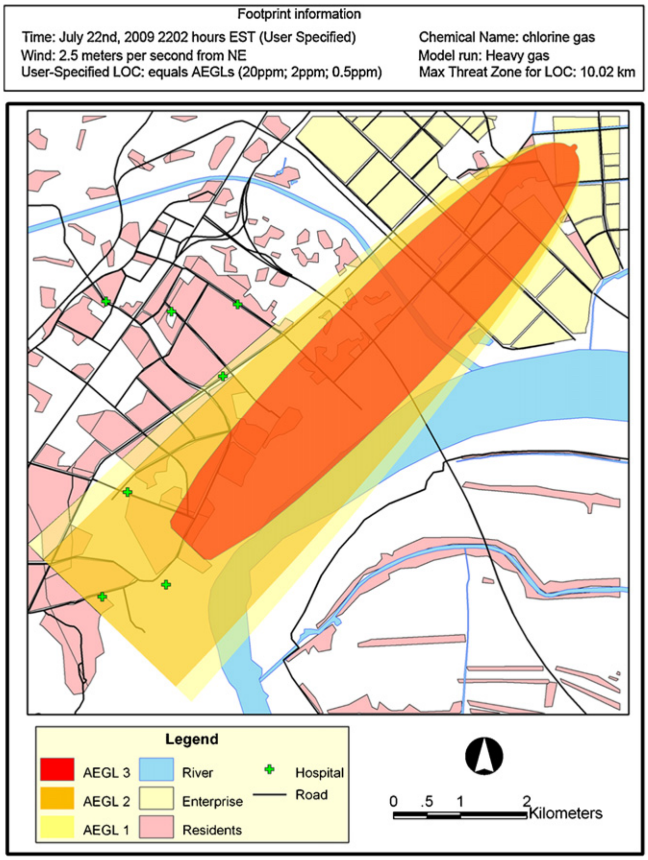

Fig. 3. Plume footprint of hazardous zone for accidental release of chlorine delineated by ALOHA.

to delineate the plume footprint of the maximum threat zone for an accidental release from a fixed facility under specified conditions, as shown in Fig. 3, providing information for residents on where and how to evacuate from the risk. The main information associated with the accidental release is listed in the box at the top of the figure. Acute exposure guideline levels (AEGLs) [26] are specified for concentration ranges of each threat zone. The AEGLs take into account sensitive individuals, and they are meant to protect nearly all people. Three categories of threat zones are identified by plotting concentration isoclines with the three-tiered AEGLs for toxicity thresholds. And the three-tiered threat zones are assigned 3, 2, 1 as the value of corresponding physical vulnerability, while the physical vulnerability of the remaining areas beyond the threat zones are treated as 0.

Based on the existing literature, indicators on the target population and their residential environment are screened to characterize the social vulnerability at the level of census blocks. As Lara-Valencia et al.'s [27] research indicated, the spatial distribution of hazards in developing countries seems to be influenced much more by the location and accessibility of the urban and transportation infrastructure than by the location of low socioeconomic status neighborhoods. Therefore, we mainly include population, distance to nearest accessible hospital, and distance to nearest passable road to characterize the social vulnerability of residents. Demographic data were taken from 2008 Census Block Statistics of local counties. Information concerning residential areas, traffic lines and hospitals were obtained and verified through field survey.

In order to isolate the demographic profile of impacted areas, the values of the indicators were calculated for each mesh. The residential density of each census block was calculated by dividing

Table 2
Grading of indicators and social vulnerability.

Indicators	Range	Assigned value
Population (v_1, inhabitants)	0	0
	[1, 9]	1
	[10, 90]	2
	More than 90	3
Distance to nearest accessible hospital (v_2, m)	500 and less	1
	(500, 1000]	2
	(1000, 3000]	3
	More than 3000	4
Distance to nearest passable road (v_3, m)	300 and less	1
	(300, 500]	2
	(500, 1000]	3
	More than 1000	4
Social vulnerability (V_{soc})	0	Not vulnerable
	[1, 4]	A bit vulnerable
	[5, 18]	Quite vulnerable
	[19, 48]	Seriously vulnerable

the population by the residential area as follows:

$$pd_i = \frac{p_i}{a_i} \quad (1)$$

where p_i is population and a_i is the residential area. In this study nine census blocks were taken into account.

Then if a mesh covers an area with a residential density of pd_i, the population of the mesh can be measured as follows,

$$p_n = \sum a_{nj} \cdot pd_i \quad (2)$$

where n = [1,2,3,. . .,900], and a_{nj} denotes the area of the j-th residential area in the n-th mesh.

Each social variable should be normalized, rather than using simple percentages and distances. Then the index values for each variable are integrated to obtain a composite index score for each mesh, which represents an aggregate measure of social vulnerability. A map of social vulnerability reflects the social vulnerability value for each mesh. Each individual indicator of social vulnerability can be examined independently. However, only the combination of all the measures produces a broad overview of the spatial distribution of social vulnerability within the study area. This broad overview has greater functionality for the emergency management community, who need both the generalized information as well as the specifics.

As the population in each mesh is concerned, its grading is based on that of residential density. It is thought to be normal when the residential density is less than 100 inhabitants/km^2, while a residential density is considered unusually high when there are more than 1000 inhabitants/km^2. The distance to the nearest accessible hospital and the distance to the nearest passable road are both graded according to the judgments of experts on emergency management. The values of each mesh are determined according to Table 2.

The social vulnerability V_{soc} is measured as follows,

$$V_{soc} = \prod_{m=1}^{3} v_m \quad (3)$$

where v_m are the indicators which contribute to social vulnerability.

Fig. 4 clearly depicts that the spatial pattern of social vulnerability appears to be similar to that of residents. Because "0" is assigned to those meshes with no residents at all, all the meshes without residents are evaluated as "not socially vulnerable". Moreover, due to the lack of passable traffic lines and accessible hospitals, some residents located at the lower right corner and upper left corner of the study area are considered to be "seriously vulnerable". Therefore, it is considered important that critical infrastructures and lifelines

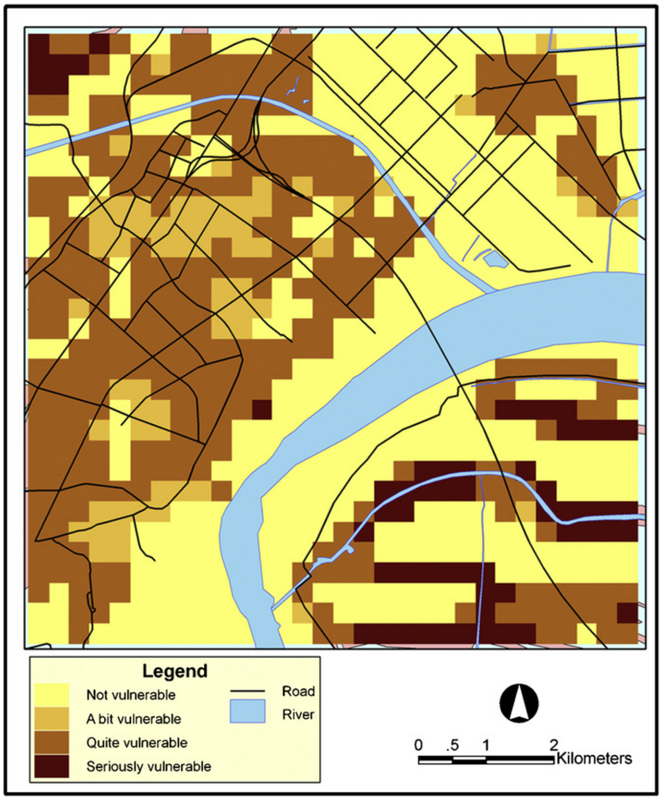

Fig. 4. Social vulnerability of residents.

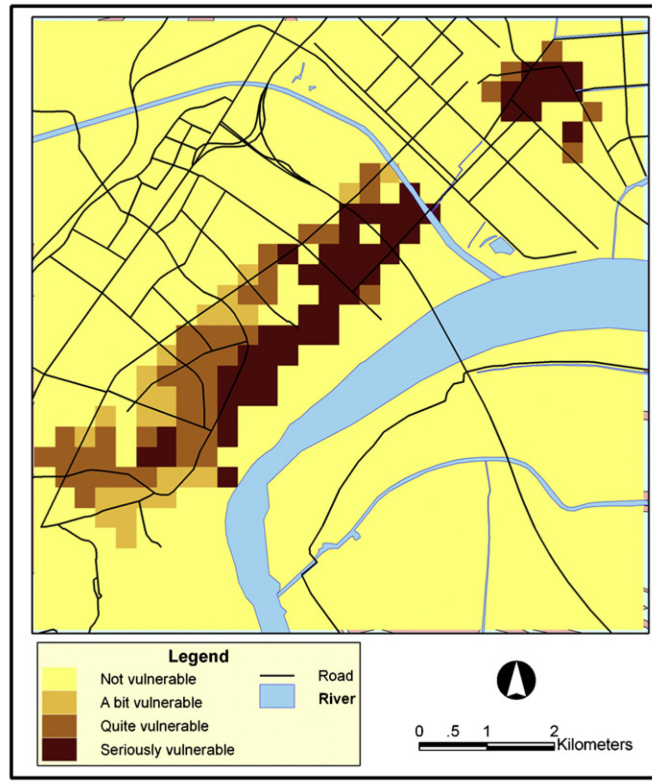

Fig. 5. Total vulnerability of residents in the vicinity of the risk site.

like roads and hospitals are urgently built up and renovated as soon as possible in those areas.

The total vulnerability of residents, by overlaying the maps of physical and social vulnerability in GIS, is critically important in emergency management once an accident happens. No priori weights were assigned to the individual layers within the GIS or in the composite social vulnerability. Instead, both social and physical vulnerabilities, as well as the indicators of social vulnerability, were treated equally and assumed to have the same relative importance in their contributions to vulnerability, The total vulnerability is calculated as,

$$V = V_{phy} \cdot V_{soc} \quad (4)$$

Fig. 5 distinctly reflects that the total vulnerability and hazardous zone for accidental release of chlorine are noticeably similar. While focusing on the hazardous zone, more about the vulnerability can be revealed for guiding emergency management. Most of the seriously vulnerable residents reside in the center due to high residential densities and/or long distances to hospitals and sparse traffic lines. Thus some risk avoidance strategies should be taken into account in land-use planning, e.g., keeping a rational safe distance between residential areas and risk sources, and allocating accessible traffic lines and medical services for residents.

Different results can be achieved while assembling vulnerabilities differently. On the one hand, while comparing Figs. 3 and 5, it is clearly demonstrated that the residents with the highest physical vulnerability are not always those with the highest total vulnerability. It is a critical finding because it reflects the likely "social costs" of the hazard on the area. That is why the same accident may exhibit different consequences in different areas. On the other hand, it is also a fact that a certain community can be harmed to a quite different extent by different accidents. It really reflects the potential "exposure" of residents to the hazard. Thus both the physical and social factors are indispensable while exploring human vulnerability to chemical risks.

5. Conclusion

This paper concentrates on exploring the concepts and methodology of analyzing human vulnerability to chemical accidents in the vicinity of chemical industry clusters. A conceptual model for human vulnerability to chemical accidents is developed, revealing the roots of human vulnerability. A geographical information system-based methodology for mapping vulnerability is proposed and implemented in the Nanjing Chemical Industry Park in China. In the case study, the plume footprint of the accidental release under specified conditions is evaluated. Population, distance to the nearest accessible hospital, and distance to the nearest passable road are mainly chosen for revealing fundamental roots of social vulnerability. The final vulnerability is determined by combining the physical and social vulnerability.

Vulnerability assessment helps screening key nodes for prioritizing risk management, especially for how to protect risk targets against environmental risks. Knowledge of the spatial distribution of physical and social vulnerability, as well as the overview of the total vulnerability can help to better prepare for accidents and to develop mitigation strategies to reduce risks for the areas under consideration. The results reflect that the residents residing in highly populated areas near the accidental site tend to be more vulnerable, as well as those with long distance to hospitals and sparse traffic lines. The physical vulnerability and social vulnerability reflects "exposure" to and "social costs" of hazards in the area respectively. Thus for mitigating risks, adjustments in land-use planning and improvement in medical services and traffic lines are recommended for relevant areas.

As the social vulnerability factors are concerned, while not fully explaining the underlying causes of the social vulnerability, they do provide an initial metric for explaining the concept. From the perspective proposed in this article, vulnerability assessment of humans and the ecosystem may involve non-routine accidental releases of hazardous materials from both fixed facilities and mobile units. The present study focuses mainly on human vulnerability to risks from fixed facilities, while vulnerability of other risk targets such as ecosystems, as well as vulnerability to accidental releases from mobile units and multi-risks in a chemical industry cluster, will be tackled in further studies. And the relative importance of social indictors and physical and social vulnerability in predicting vulnerability remains unsolved. Thus the weighting schemes are also recommended to be developed in the future.

However, such a methodology relies heavily on the quality of the data, such as the availability of the data about risk sources and targets, the reliability of the data from various stakeholders (industrial enterprises may provide false data to avoid their risk responsibility), as well as a possible homogenous distribution of risk sources and targets, which will make such an assessment of few values in providing information for decision making process in regard to cost-effective risk management. Therefore, various data mining solutions should be developed to make this methodology applicable and practical to scientists and other stakeholders.

Acknowledgement

This research was supported by China 863 R&D Project (2007AA06A402) and (2007AA06A405), and Key Projects in the National Science & Technology Pillar Program (2006BAC02A15).

References

[1] R.E. Kasperson, O. Renn, P. Slovic, et al., The social amplification of risk: a conceptual framework, Risk Anal. 8 (1988) 177–187.
[2] D.D. Derezinski, M.G. Lacy, Chemical accidents in the United States, 1990-1996, Soc. Sci. Q. 84 (2003) 122–143.
[3] M.R. Elliott, Y. Wang, R.A. Lowe, et al., Environmental justice: frequency and severity of US chemical industry accidents and the socioeconomic status of surrounding communities, J. Epidemiol. Community Health 58 (2004) 24–30.
[4] F.L. Margai, Health risks and environmental inequity—a geographical analysis of accidental releases of hazardous materials, Prof. Geogr. 53 (2001) 422–434.
[5] M.P. Cutchin, K.R. Martin, S.V. Owen, et al., Concern about petrochemical health risk before and after a refinery explosion, Risk Anal. 28 (2008) 589–601.
[6] B. Stojanović, J.S. Milena, Chemical and radiological vulnerability assessment in urban areas, Spatium 13–14 (2006) 21–26.
[7] N. Uddin, R.W. Peters, A. Haque, Community preparedness and response model for addressing environmental risk and vulnerability, Environ. Prog. 23 (2004) 126–134.
[8] J. Tixier, A. Dandrieux, G. Dusserre, et al., Environmental vulnerability assessment in the vicinity of an industrial site in the frame of ARAMIS European project, J. Hazard. Mater. 130 (2006) 251–264.
[9] S.L. Cutter, J.T. Mitchell, M.S. Scott, Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina, Ann. Assoc. Am. Geogr. 90 (2000) 713–737.
[10] S.L. Cutter, Vulnerability to environmental hazards, Prog. Hum. Geogr. 20 (1996) 529–539.
[11] J. Ford, Vulnerability: Concepts and Issues, A Literature Review of the Concept of Vulnerability, its Definition, and Application in Studies Dealing with Human–Environment Interactions, University of Guelph, 2002, pp. 2–4.
[12] I. Burton, R.W. Kates, G.F. White, The Environment as Hazard, Oxford University Press, Oxford, 1978, pp 23-27.
[13] R.W. Kates, Climate Impact Assessment, John Wiley and Sons, New York, 1985, pp. 3–36.
[14] S.L. Cutter, B.J. Boruff, W.L. Shirley, Social vulnerability to environmental hazards, Soc. Sci. Q. 84 (2003) 242–261.
[15] M.F. Souza Porto, C.M. Freitas, Major chemical accidents in industrializing countries: the socio-political amplification of risk, Risk Anal. 16 (1996) 19–29.
[16] M.F. Souza Porto, C.M. Freitas, Vulnerability and industrial hazards in industrializing countries: an integrative approach, Futures 35 (2003) 717–736.
[17] J. Bi, J. Yang, Q.L. Li, Regional Environmental Risk Analysis and Management, Chinese Environmental Science Press, Beijing, 2006, pp. 89–100 (in Chinese).
[18] National Economy and Trade Committee, Identification of Major Hazardous Sources, GB18218-2000, http://www.linan.gov.cn/uploadfiles/im/20090518164357_110_0.doc.
[19] Unite State Department of Transportation, Emergency Response Guidebook, Government Printing Office, Washington, 1993, pp. 33–78.
[20] National Oceanic and Atmospheric Information (NOAA), United States Environmental Protection Agency (USEPA), User's manual for Areal Locations of Hazardous Atmospheres (ALOHA), National Safety Council, Washington, DC, 1995, http://www.epa.gov/emergencies/docs/cameo/ALOHAManual.pdf.
[21] K. Hewitt, Regions at Risk: A Geographical Introduction to Disasters, Longman, London, 1997, pp. 189–213.
[22] B.H. Morrow, Identifying and mapping community vulnerability, Disasters 23 (1999) 1–18.
[23] P. Blaikie, T. Cannon, I. Davis, et al., At Risk: Natural Hazards, People's Vulnerability and Disasters, Routledge, New York, 1994, pp. 195–236.
[24] HERO Network, A Protocol to Assess Regional Vulnerability to Environmental Hazards, http://hero.geog.psu.edu/products/protocol.pdf.
[25] J.J. Hornga, Y.S. Lina, C.M. Shub, et al., Using consequence analysis on some chlorine operation hazards and their possible effects on neighborhoods in central Taiwan, J. Loss Prev. Process. Ind. 18 (2005) 474–480.
[26] AEGL Committee, Unite State Environmental Protection Agency, AEGL Program, 2009, http://www.epa.gov/oppt/aegl/.
[27] F. Lara-Valencia, S.D. Harlow, M.C. Lemos, et al., Equity dimensions of hazardous waste generation in rapidly industrializing cities along the United States-Mexico border, J. Environ. Plan. Manage. 52 (2009) 195–216.