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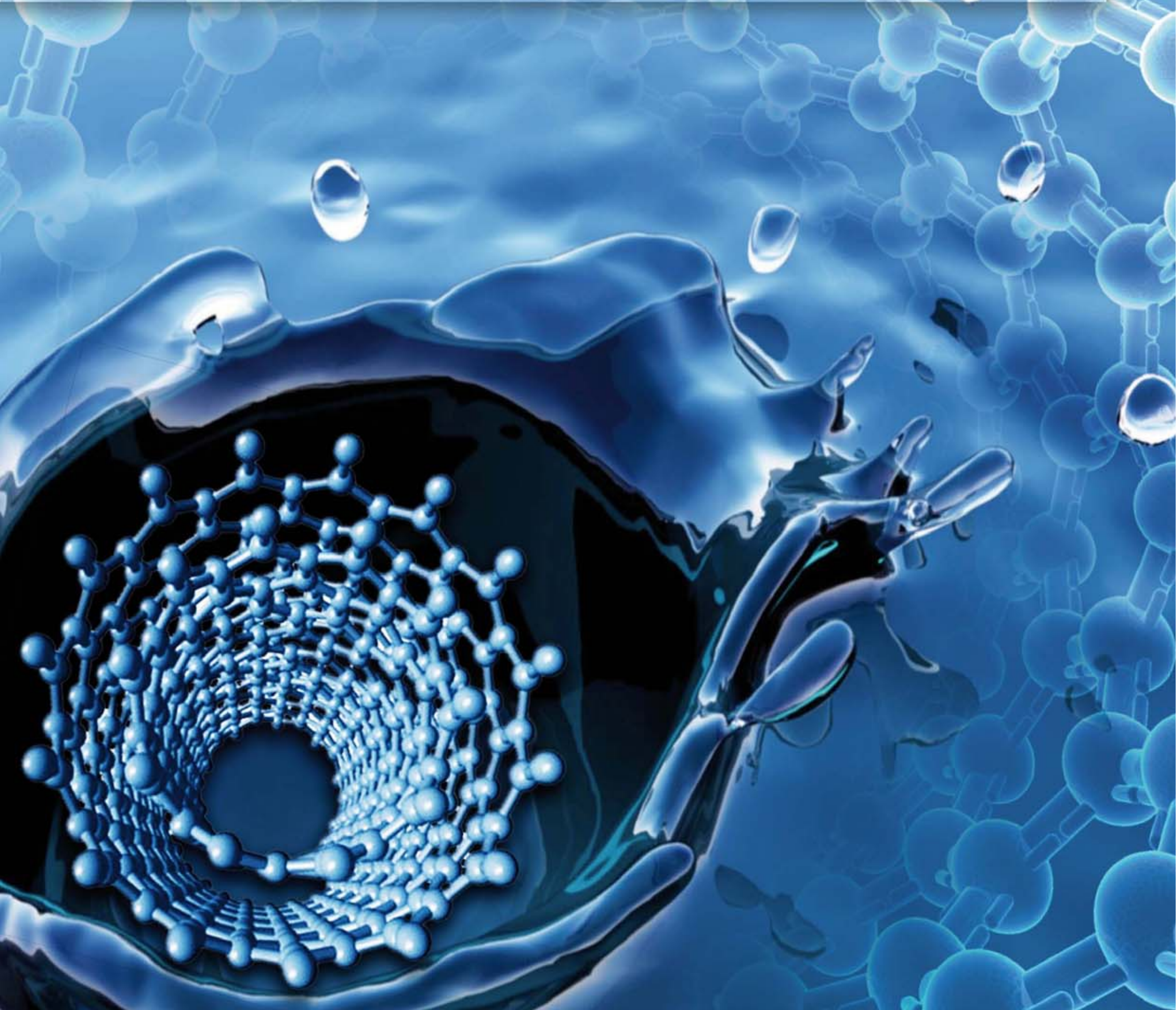

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An novel identification method of the environmental risk sources for surface water pollution accidents in chemical industrial parks

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Abstract

The chemical industry is a major source of various pollution accidents. Improving the management level of risk sources for pollution accidents has become an urgent demand for most industrialized countries. In pollution accidents, the released chemicals harm the receptors to some extent depending on their sensitivity or susceptibility. Therefore, identifying the potential risk sources from such a large number of chemical enterprises has become pressingly urgent. Based on the simulation of the whole accident process, a novel and expandable identification method for risk sources causing water pollution accidents is presented. The newly developed approach, by analyzing and stimulating the whole process of a pollution accident between sources and receptors, can be applied to identify risk sources, especially on the nationwide scale. Three major types of losses, such as social, economic and ecological losses, were normalized, analyzed and used for overall consequence modeling. A specific case study area, located in a chemical industry park (CIP) along the Yangtze River in Jiangsu Province, China, was selected to test the potential of the identification method. The results showed that there were four risk sources for pollution accidents in this CIP. Aniline leakage in the HS Chemical Plant would lead to the most serious impact on the surrounding water environment. This potential accident would severely damage the ecosystem up to 3.8 km downstream of Yangtze River, and lead to pollution over a distance stretching to 73.7 km downstream. The proposed method is easily extended to the nationwide identification of potential risk sources.

Key words: water pollution accident; risk source; identification; grading; chemical industry parks

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Introduction

China is a major country producing and using chemicals. Especially in the past two decades, the chemical and petrochemical industries have become a major driving force for the development of the Chinese economy. China possesses a great majority of the chemical industry parks (CIPs) in the world, and over 1200 CIPs had been built as of 2010. Along with their great contributions to the Chinese economy, the CIPs have become the most dangerous sources of various environmental pollution accidents (He et al., 2011). According to nationwide statistics in 2006, there were 7555 chemical and petrochemical plants in China, 80% of them located near rivers, lakes or in densely populated areas, and 45% of them could result in severe environmental contamination if abnormal discharge of wastewater or accidental chemical leakage occurs. It has been reported that environmental contamination accidents had occurred as often as once every two days since 2006, 70% of which were water pollution accidents (Xue and Zeng, 2010). For example, in November of 2005, 100 tons of toxic chemicals including benzene, nitrobenzene, etc, were released into the Songhua River due to an unexpected explosion of a chemical plant in northeastern China, thus poisoning the drinking water sources for 10 million inhabitants (Xin Hua News Agency, 2006). In 2008, the accidental spill of wastewater containing arsenic into Yangzonghai Lake in Yunnan Province poisoned the drinking water source for 260,000 inhabitants and caused severe agricultural and fishery losses (Xin Hua News Agency, 2009). Such water pollution accidents from chemical release are very common in most chemical-producing countries.

All these water pollution accidents not only harmed the downstream water resource and ecosystem, but also caused serious economical losses (Zhang et al., 2012). To prevent pollution accidents and lower environmental risk to an acceptable rational level, some efforts have been made in the past decades worldwide. A series of laws, regulations and standards for environmental pollution accident

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management have been promulgated and implemented recently (US EPA, 1985; European Commission, 2006; He et al., 2011). Furthermore, to strengthen environmental risk management, some national surveys have been carried out on chemical plants. In China, 67,000 typical chemical plants have been surveyed since 2010 by the Ministry of Environmental Protection, and an environmental risk information database of more than 46,000 chemical plants was established. Therefore, to normalize, classify and identify the major risk sources from such a large number of chemical plants has been an urgent demand for most industrialized countries.

In the wake of tragic accidents in Italy, the US, Mexico and elsewhere, the Council of European Communities, the US Environmental Protection Agency, and the World Bank have each issued guidelines for identifying, assessing, and managing risks from major hazards of industrial facilities (US EPA, 1985; World Bank, 1985; Morris et al., 1987; Wood, 2009; Versluis et al., 2010). The Seveso I and the Seveso II (96/82/CE) Directives, named due to an uncontrolled release of dioxin from a chemical plant near the town of Seveso in Italy in 1976, were designed by the European Union for major accident hazard control. The Seveso II Directive set the framework for emergency management of industrial accidents involving hazardous substances in Europe (Wood, 2009; Versluis et al., 2010). Moreover, through listing the hazardous substances with their threshold quantities, the plants that store or produce these hazardous substances can be divided into two classes. Guidelines also provided methods for identifying very toxic, toxic, flammable, and explosive substances for this purpose. The World Bank guidelines, mainly based on the European Economic Community and UK guidelines, were supplemented by a technical manual and microcomputer software (World Bank, 1985; Morris et al., 1987). With US EPA guidelines, the threshold values of hazardous substances, such as Threshold Planning Quantity have also been adopted as an important tool for risk control, and a high-risk plant must notify local authorities regularly (US EPA, 1985). All these guidelines for identifying the risk sources operate in similar ways. Namely, if the storage quantity of a specific compound exceeds its threshold value, it would be considered a potential hazard to public health and needs to be more strictly managed. However, the above guidelines have different threshold values even for the same substance due to different interpretations of toxicity and dispersive potential. A problem common to all guidelines is that they cannot quantitatively analyze the probability of accidents (Morris et al., 1987; Stam et al., 1998). Additionally, most guidelines have not brought together environmental factors and inherent chemical properties, but focused mainly on the chemical itself (Gorsky et al., 2000). Therefore, the different vulnerabilities of the surrounding situations of chemical plants have not been reflected. On the other hand, although risk management is on the agenda of most companies, its implementation is 'patchy and unmonitored'. Only some worldwide powerful companies such as the DOW Chemical Company and Badische Anilinund Soda-Fabrik have their own risk identification methods, and these methods usually require a lot of information about production processes and the surrounding environment. However, for the identification of the risk sources at a national level, especially in most industrialized countries, it is difficult to obtain such detailed information (Hertwich et al., 1997). Therefore, the existing methods are not sufficient for identifying sudden water pollution sources in most countries. An effective identification method should meet three requirements: (1) The method should be simple, cheap and only need a few data. (2) With only some basic information about the production process and the surrounding environment, the risk level should be able to be determined precisely (Zabeo et al., 2011). (3) The direct losses caused by explosion or fire should not be included in the potential consequences evaluation because this identification method is only used for sudden pollution accident control (US EPA, 1985).

To effectively manage environmental risk sources, the objective of this work is to establish a novel five-step method for identifying risk sources of sudden surface water pollution accidents. The method has taken into account the properties and quantity of the chemicals, the potential accidental influence range and the surrounding sensitive objectives.

1 Methods

1.1 Framework of the risk source identification

The environmental risk source of sudden water pollution (WPRS) refers to the facilities for chemical production, storage, transportation, utilization and disposal, from which the accidental release of the hazardous chemicals would severely pollute surface water-bodies and threaten drinking water safety. The risk level of a WPRS is defined by the potential adverse consequences of the maximum credible accident. Through systemic study of the accidental pollution cases of water-bodies in recent years, three key aspects for the evaluation of WPRS risk level have been determined:

(1) Risk source: This plays the most important role in the risk assessment of sources. Its property and quantity not only determines the accidental release intensity, but also affects the accident types, and the accident consequences. Additionally, the preventative measures or management strategies of risk source are directly related to the accidental probability (Rhomberg et al., 2010).

(2) Influence ranges: This refers to the zone polluted by the released hazardous chemicals, and it is site-specific, such as the width, depth and flow rate of the threatened river (Thomas and Jones, 2010). The influence range is

usually calculated by one- or two-dimensional pollution diffusion models. Sometimes, to simplify the simulation process, some empirical models can also be adopted.

(3) Sensitive receptor: In a water pollution accident, the sensitive receptors are inhabitants, drinking water sources, fish, or other water organisms being sensitive to chemical pollution. In fact, most losses from a pollution accident are attributed to the poisoning effect of the chemicals to sensitive receptors. Namely, if the sensitive receptors live in the influence range, severe losses would be inevitable (Pizzol et al., 2011; Andersson et al., 2007).

All three aspects play important roles in risk assessment. Therefore, a reasonable identification method for WPRS could only be established by taking all the above three aspects as a whole. In this study, a five-step procedure for identifying risk sources is proposed as shown in **Fig. 1**.

1.2 Preliminary source screening

It is very difficult and time-consuming to identify the risk sources from thousands of chemical plants and to cope with a large amount of information related to risk sources, so preliminary source screening is essential. By avoiding too much time spent on minor risk sources, preliminary source screening has been proved very effective in hazardous waste management (US EPA, 1985; Huang et al., 2011). In this research, approximately 200 very acutely toxic chemicals were preliminarily selected and listed, and most reactive, explosive and flammable substances with relatively lower environmental pollution effects were ruled out. The threshold values of the listed chemicals were calculated by a modified method based on the Threshold Planning Quantity calculation of the US EPA (2003) (**Table 1**).

Taking one production facility with different chemicals as a risk source, the ratio of the storage quantity of one type of chemical to its threshold value can be calculated, then the total ratio in the production facilities can be obtained. If the total ratio is higher than 1.0, the risk source must be further assessed, otherwise it would be ignored. Namely,

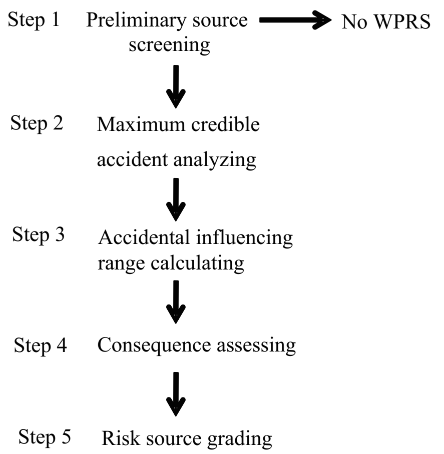

Fig. 1 Overall structure of the methodology.

Table 1 List and threshold values of environmental risk substances (selection)

Name	CAS number	Threshold value (ton)	Reference source
Chlorine	7782-50-5	1	IDLH
Phosgene	75-44-5	0.25	IDLH
Hydrogen sulfide	7783-06-4	2.5	IDLH
Hydrogen chloride (gas only)	7647-01-0	2.5	IDLH
Arsine	7784-42-1	0.5	IDLH
Phosphine	7803-51-2	2.5	IDLH
Formaldehyde	50-00-0	0.5	IDLH
Chloromethane	74–87–3	10	IDLH
Methyl Bromide	74-83-9	7.5	IDLH
Ethylene oxide	75-21-8	7.5	IDLH
Nitrogen dioxide	1010-44-0	1	IDLH
Methanethiol	74-93-1	5	IDLH
Natural gas	NA	7.5	IDLH
Arsenic trichloride	7784-34-1	7.5	US EPA
Propylene oxide	75-56-9	10	IDLH
Ammonia	7664-41-7	7.5	IDLH
Toluene 2,4-diisocyanate	584-84-9	5	IDLH
Methyl isocyanate	624-83-9	5	IDLH
Toluene diisocyanate	26471-62-5	2.5	IDLH
Acrylonitrile	107-13-1	10	IDLH
Acetonitrile	75-05-8	10	IDLH

IDLH: immediately dangerous to life or health concentration.

(1) if $\sum_{i=0}^{n} \frac{q_i}{Q_i} > 1$, the risk source needs further assessment
(2) if $\sum_{i=0}^{n} \frac{q_i}{Q_i} < 1$, the risk source is not a WPRS
where, n is the amount of the hazardous chemicals in one potential risk source, q_i (ton) is the maximum storage quantity of the chemical, and Q_i (ton) is the threshold value.

1.3 Maximum credible accident analysis

Even for one type of dangerous chemical, the accident scenarios might be fire, explosion, and toxic release, or a combination of these events, due to different situations at different plants. Correspondingly, each accident scenario would produce a special consequence (Jenkins, 1999; Sharratt and Choong, 2002). To simplify the risk assessment procedure, the maximum credible accident scenario was used. The maximum credible scenario is the possibly worst accidental situation that puts people and the environment at risk. Therefore, the most critical step is to predict the worst accident scenario among various potential accidental scenarios.

In many countries, such as the US and China, the environmental protection agencies are mainly responsible for the management of health and environmental impacts caused by environmental pollution accidents (EEC, 1982; Park and Park, 2011). Therefore, in this study, only the release and dispersion scenarios of toxic substances are considered in the risk source identification. Through an analysis of more than 400 environmental pollution accidents occurring in the past thirty years, the accident scenarios could be divided into four categories, namely abnormal discharge of wastewater, secondary leakage of chemicals from fire or explosion, direct leakage of chemicals, and others (Guarnaccia and Hoppe, 2008).

The release intensity is crucial for calculating the influence range and the accident consequence. Considering the characteristics of the accidental release processes, the release intensity can be calculated by two kinds of mathematical models. For a direct leakage accident of liquid chemicals, the modified Bernoulli Equation can be adopted as expressed in Eq. (1):

$$Q = \alpha \times k \times S \times \rho \sqrt{\frac{2\,(P_a - P_0)}{\rho} + 2gh} \quad (1)$$

where, Q (kg/sec) is the release intensity of chemicals, α is the proportion of chemicals flowing into the water bodies, k is the release coefficient, S (m^2) is the split area, ρ (kg/m^3) is the liquid density, P_a (Pa) and P_0 (Pa) are the container pressure and atmospheric pressure respectively, g (9.81 m/sec^2) is the acceleration due to gravity , and h (m) is the water level above the spill point.

For a secondary leakage accident caused by fire or explosion, or abnormal discharge accident of wastewater, an empirical model can be used:

$$Q = \alpha \times G_{max} \times k_2/t \quad (2)$$

where, G_{max} (kg) is the maximum storage of hazardous chemicals, k_2 is the leakage coefficient; and t (sec) is the leaking time.

1.4 Accidental influence range calculation

In a water pollution accident, the influence range refers to the contaminated watercourses with so many hazardous chemicals that the sensitive receptors are put in danger. The influence range is the most common and effective index to quantify risk level (Yu et al., 2009). In addition, even in one pollution accident, different sensitive objectives have different influence ranges due to their respective vulnerabilities (Pizzol et al., 2011; Jiang et al., 2012).

A pollution accident usually damages the environment through different forms, such as acute toxicity effects, chronic toxicity effects, water-mediated effects, and direct or indirect economic losses (EEC, 1982). However, though the immediate danger to life or health has been widely used to quantify the accidental risk level of dispersing toxic chemicals in water pollution accidents, direct health impact caused by sudden water pollution is rather rare, based on case analysis. In almost all sudden water pollution accidents, if the drinking water sources are polluted by the dispersed toxic chemicals, they will be abandoned at least temporarily. In fact, most sudden water pollution accidents with hazardous chemical dispersion usually cause three kinds of losses: social and economic losses due to the temporary suspension of water supply, and ecological losses owing to the destruction of the ecological system (Lei et al., 2008).

The released chemicals harm the receptors to different extents depending on their sensitivity or susceptibility. Therefore, when we calculate the economic losses, social losses and ecological losses, their influence ranges are different, corresponding to each boundary limit. The water quality standard of drinking water sources can be adopted as the boundary limit for the evaluation of economic and social losses and the parameter 10% LC_{50} (lethal concentration 50) of the evaluated hazardous chemical can be used for the assessment of ecological losses, in which the aquatic organisms might experience life-threatening health effects or death (Wang et al., 2010).

The influence range can be calculated by an adjusted one-dimensional diffusion model, as shown in Eq. (3):

$$X = \frac{uQ^2}{4\pi D_X A^2 (C_X - C_0)^2} \quad (3)$$

where, X (m) is the maximum dispersal distance of chemicals at C_X concentrations, u (m/sec) is the average flow rate of the river, Q (kg/sec) is the chemical release intensity, D_X (m^2/sec) refer to the horizontal discrete coefficients, A (m^2) is the river cross-sectional area, and C_X (kg/m^3) and C_0 (kg/m^3) refer to the boundary limit and background value of chemicals, respectively.

1.5 Accidental consequence assessment

Quantifying the losses from a potential chemical pollution accident is a difficult and even controversial task (Arunraj and Maiti, 2009). Some factors, such as human perception, time scale, process effects, and release effects are all important to assess the consequences of an environmental accident; whereas most factors cannot be precisely quantified due to being unquantifiable, deficient, unknown, non-obtainable data or partial ignorance (Zhao et al., 2010). Therefore, a relatively simple assessment method might be more practical. The index system method was adopted in the calculations of these three kinds of losses. The social losses was calculated by using inhabitants' compensation costs due to the suspension of water supply, and the affected inhabitants were counted in terms of the service population of the suspended water supply. The economic losses were derived from the direct production losses of enterprises due to the suspension of water supply. The ecological losses were the potential losses from the direct destruction of the water ecosystem. Both the social and the economic losses can be expressed as Eq. (4):

$$L_{sc\ (or\ em)} = \sum_{i=1}^{n} (W_i \times T_{1i} \times M_{1i} \times \varepsilon_i) \quad (4)$$

where, L_{sc} (\$) is the social losses, L_{em} (\$) is the economic losses, W_i is the population size (or enterprise number) in the influence range; T_{1i} (sec) is the duration of water supply suspension, M_{1i} (\$ per person (or enterprises) per hour) is the loss intensity of an inhabitant (or enterprise) in the accident, and ε_i is the regional-effect impact factor, which should be calculated repeatedly when new administrative regions are crossed.

Correspondingly, the ecological losses should be calculated by using the influence distance, the duration, the vulnerability factor, the sensitivity factor and the cross-border factor according to Eq. (5):

$$L_{ec} = \sum_{i=1}^{n} (S_i \times T_{2i} \times p_i \times M_{2i} \times \alpha_i \times \beta_i \times \varepsilon_i) \quad (5)$$

where, L_{ec} (\$) is the ecological losses, S_i (m^2) is the area of surface water-bodies in influencing range, T_{2i} (sec) is the accident influence time, p_i is the mortality of the protected aquatic organisms; M_{2i} (\$/m^2) is the ecological value per area, α_i is the sensitivity factor of the aquatic ecosystem and β_i is the vulnerability factor of water quality.

The overall equivalent environmental losses are calculated by superposing the products of the weights and membership values for all losses:

$$L = \lambda \sum L_{sc} + \mu \sum L_{em} + \nu \sum L_{ec} \quad (6)$$

where, L (\$) is the overall equivalent loss, and λ, μ, ν are weight values, $\lambda + \mu + \nu = 1$.

1.6 Risk source grading

The accident probability is also an important factor in identifying risk sources. However, accurately assessing the probability of a potential accident is very difficult due to its low frequency and many affecting factors. Therefore, the modified average probability based on statistical data for the past thirty years was adopted. The average probability would be enough to show the common characters of a similar accident. For an accident caused by special toxic chemical release in a special industry, the average probability was similar. However, for a particular risk source, due to distinct management level, production process, personnel quality and so on, the practical failure rates may be higher or lower than the statistical data. In such cases, an adjustment factor should be added to modify the average probability to reflect the real situation of a particular risk source (Schweitzer, 2008). Thus, the probability of a potential accident can be calculated using the following relations:

$$P = P_{av} \times \sigma \quad (7)$$

where, P ($year^{-1}$) is the accident probability, P_{av} ($year^{-1}$) is the average probability based on the analysis of 30-year accidental cases in China, and σ is the particular adjustment factor according to the characteristics of the enterprise and surrounding conditions.

Risk value, as only tool to evaluate the grade of a risk source (Houa and Zhang, 2009), is defined as the product of the probability and the consequence. In mathematical terms, the risk value (R) is calculated by:

$$R = 1000 \times P \times L \quad (8)$$

Based on the risk value, the risk sources are divided into three levels: low-level ($10 < R < 100$, WPRS-III), medium-level ($100 < R < 1000$, WPRS-II) and high-level ($R < 1000$, WPRS-I). In the worst-case accident scenario, they respectively lead to light, medium and heavy surface water pollution accidents.

2 Results and discussion

The case study was based on a CIP in Jiangsu Province of China. The chemical industry park was founded in 2001. There have been more than 30 chemical plants in this CIP and the industrial output is over 5 billion dollars per year. The CIP is centered on the development of petroleum or petrochemical industries, organic chemistry industry production, fine chemicals, new chemical materials and other industrial chemicals, almost all of which have high environmental pollution risks. The park is close to the Yangtze River. There are two towns of 12,000 people situated along the 10 km downstream from the CIP. A drinking water source serving 51,000 people and more than 10 small enterprises is located about 50 km downstream from the park. The locations of these chemical enterprises in the CIP, the drinking water sources, and the densely populated areas are shown in **Fig. 2**.

Through preliminary screening for the hazardous chemicals contained in the raw material storage areas, manufacturing workshops, product tanks and waste treatment areas among all enterprises of this CIP, five potential risk sources (namely five toxic chemicals) were found (**Table 2**). According to the toxic, flammable, explosive and corrosive characteristics of these risk materials, the maximum credible accidents were determined as the abnormal discharge of wastewater and secondary leakage accident caused by fire or explosion. Correspondingly, their accidental intensities were quantified according to the empirical model (Eq. (2)).

Table 2 suggests that the hazardous materials could be present in different forms, such as raw materials, finished products and wastes, which were stored in raw material and product tanks, workplaces, shipping docks as well as waste treatment areas. According to the physical-chemical properties of these identified chemicals, the secondary chemical leakage accident caused by fire or explosion, representing 80% of all potential accidents, was the main type of accident in this CIP. Even if 50% of the risk chemicals were released into the Yangtze River within 10 min, the accidental intensity would range from 83 to 500 kg/sec.

The parameter 10% LC_{50} was used as the boundary limit for the ecological influence range, in which the aquatic organisms might experience life-threatening health effects or death. In addition, the water quality standard of drinking-water sources was adopted as the boundary limit for the social and economic influence ranges, in which the

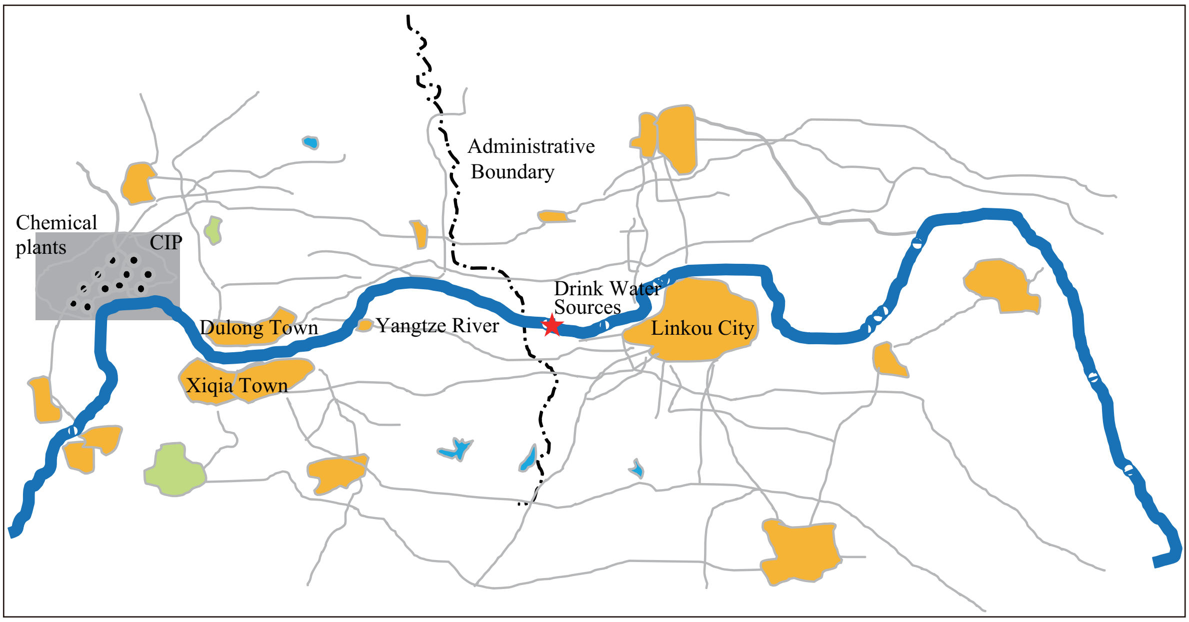

Fig. 2 Location of the risk enterprises, chemical industry park (CIP) and densely populated areas.

drinking water supply would be at least temporarily suspended. The integrated environmental impact assessment is summarized in **Table 3** and the influence ranges are shown in **Fig. 3**.

Table 3 indicates that once the accident occurred, the secondary leakage of aniline from the product tank area in HS chemical plant would pollute 73.7 km downstream of the Yangtze River. Then the water supply of more than 51,000 inhabitants and some plants would be suspended due to the pollution of the drinking water sources within

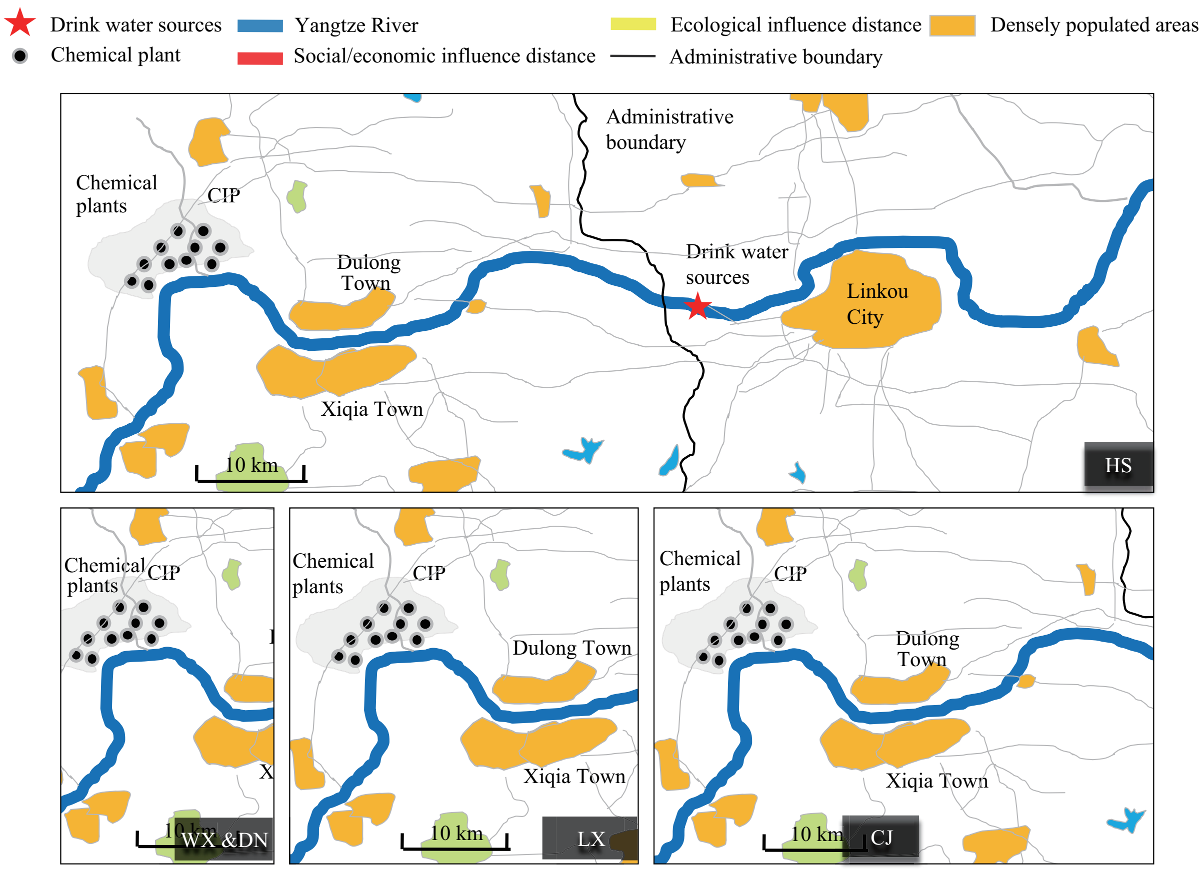

Fig. 3 Potential influence ranges of different risk sources.

Table 2 Maximum credible accident for water pollution risk sources in CIP

Business name	Risk chemicals	Maximum credible accident	Risk sources' location	Maximum storage capacity (ton)	Accidental intensity (kg/sec)
DN Chemical Industry Plant	Toluene	Secondary leakage from fire and explosion	Raw materials tank area	200	167
HS Chemical Industry Plant	Aniline	Secondary leakage from fire and explosion	Product tank area	600	500
WX Chemical Industry Plant	Methanol	Secondary leakage from fire and explosion	Workplace	253	211
LX Shipping Company	Xylene	Secondary leakage from fire and explosion	Dock	400	333
CJ Paint Plant	Petroleum	Abnormal wastewater discharge	Wastewater treatment area	100	83

Table 3 Integrated environmental impact assessment of water risk sources in CIP

Business name	Boundary limits (mg/L)		Influence range (m)		Accidental consequences (1,000,000 $)			Overall equivalent losses (1,000,000 $)
	Social/economic influence	Ecological influence	Social/economic influence	Ecological influence	L_{so}	L_{em}	L_{ec}	
DN Chemical Industry Plant	0.7	1	167	82	25	0	16	15
HS Chemical Industry Plant	0.1	0.44	73720	3808	3300	1000	761	1848
WX Chemical Industry Plant	1	2.9	131	16	25	0	3	11
LX Shipping Company	0.5	1.35	1311	180	650	50	36	286
CJ Paint Plant	0.05	1	8191	20.5	800	200	4	381

50 km downstream from the plant. Additionally, this pollution would also cause severe ecological destruction of 3.8 km downstream. The social, economic and ecological losses were 3300, 1000, and 761 million dollars equivalent respectively, and the total losses could reach 1848 million dollars by weighted-overlay calculation. For the DN chemical plant and WX chemical plant, the social, economic and ecological influence distances were relatively short, less than 200 m. There were no important sensitive objects to be protected in these ranges, thus the total losses of these two plants would be only 15 and 11 million dollars equivalent, respectively.

Table 4 shows the grading results of the risk sources for sudden water pollution in this CIP. Among the five potential risk sources identified in the preliminary screening, there were one WPRS-I, one WPRS-II, two WPRS-IIIs, and one no-WPRS. Therefore, in this CIP, the secondary aniline leakage caused by fire or explosion accident in HS chemical plant might produce the most serious water pollution accident. The abnormal discharge of petroleum-containing wastewater in the CJ plant might cause the second most serious water pollution accident.

In the worst-case accident scenario, the dispersion of the methanol and xylene respectively from the workplace of the WX Chemical Plant and the dock of LX Shipping Company would only lead to light water pollution. For the DN Chemical Plant, the risk value of toluene leakage accident was only 7.2, suggesting no significant impact on the downstream water quality. Therefore, the DN Chemical Plant was excluded from the potential risk sources.

3 Conclusions

The chemical industry parks have become one of the most dangerous sources of water pollution accidents in some industrialized (or industrial) countries. All these water pollution accidents have not only harmed the downstream water resources and ecosystem, but also caused serious economic losses. To strengthen the environmental risk management, a national survey of typical chemical plants is required, thus, a means to identify and manage the risk sources from such a large amount of information becomes more urgent.

By simulating the whole process of an accident, a novel identification method for the ranking of potential water-environment risk sources nationwide has been developed. This method included four specific areas: (1) A simple and fast technique to screen preliminary sources was developed, which reduced the time spent on low risk facilities. The name and threshold values of nearly 200 toxic chemicals were selected and assessed. (2) Five assessment models were developed, which facilitate the calculation of the influencing ranges, losses, probability, and risk values. The model parameters were mostly obtained from more than 400 pollution accident cases from 1980 to 2010. (3) Three typical sudden chemical-accident scenarios, namely abnormal discharge of wastewater, secondary leakage of chemicals from fire or explosion, and direct leakage of chemicals were selected and simulated, which simplifies the determination of the maximum credible accident scenarios. (4) Three major types of losses, namely social, economic and ecological losses were used for overall

Table 4 Grading of sudden water pollution risk sources

Business name	Risk grading	Maximum credible accidental	consequence
DN Chemical Industry Plant	7.2	No WPRS	Non pollution accident
HS Chemical Industry Plant	4732.1	WPRS-I	Heavy pollution accident
WX Chemical Industry Plant	28.0	WPRS-III	Light pollution accident
LX Shipping Company	42.9	WPRS-III	Light pollution accident
CJ Paint Plant	414.8	WPRS-II	Medium pollution accident

consequence modeling.

To confirm its practical applicability, the proposed method was applied to identify the risk sources of a CIP in Jiangsu Province in China. The results showed that there were four WPRS among more than 30 enterprises of this CIP. The secondary aniline leakage caused by a fire or explosion accident in the HS Chemical Plant would lead to the most serious impact on the water environment, by the pollution of 73.7 km downstream and severe ecological destruction of 3.8 km downstream of the Yangtze River, suggesting that the local government should pay more attention to the aniline facilities in the HS Chemical Plant. The identification results showed that the proposed method could not only identify the WPRS effectively, but also provide some valuable information, such as the potential influence ranges and consequences of various loss types, so as to improve the risk management level.

Acknowledgments

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