Environ Monit Assess (2019) 191: 210
https://doi.org/10.1007/s10661-019-7351-1

Quantitative assessment of enterprise environmental risk mitigation in the context of Na-tech disasters

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Received: 24 October 2018 / Accepted: 25 February 2019 / Published online: 8 March 2019

Abstract As an important causative factor of environmental accidents, natural disasters have recently received much attention for environmental risk assessment. Typhoons are one of the most frequent natural disasters in the northern Pacific Ocean and South China Sea and cause enormous damage to agriculture, daily livelihood, and industry. In this study, an environmental risk assessment for industrial enterprises is conducted when considering typhoon disasters. First, a Na-tech (natural hazard triggering technological disasters) environmental risk assessment index system with the aid of an analytic hierarchy process and fuzzy evaluation model (ERA-FAM) is developed to explore the major determinants related to risk level. The impact of typhoon disasters on environmental risk from chemical enterprises is discussed using a comparative analysis of risk levels with and without typhoon disaster scenarios. A chemical plant located in Zhejiang, China, is selected as a case study using this methodology. Three hypothetical scenarios are assumed, based on actual situations, to explore the impact of various factors on environmental risk. The results demonstrate that production factors and surrounding environmental conditions are the most sensitive factors for typhoon disasters, while emergency preparation is most important for reducing environmental risk. The influence of typhoons on environmental risk values is much higher for enterprises with imperfect management and vulnerable water risk receptors. Incorporating disaster management into environmental risk management will aid in developing strategies and policies for environmental risk mitigation and risk reduction practices.

Keywords Environmental risk assessment · Na-tech disaster · Fuzzy evaluation model · Industrial enterprises

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Introduction

Over the past decade, economic losses resulting from natural disasters have reached nearly 1.4 trillion dollars

(United Nations 2017). The effects wrought by disasters include not only direct impacts, such as deaths or injuries and damages to property, infrastructure, and residential dwellings, but also associated impacts such as pollution from floods and earthquakes, namely Na-tech disasters (natural hazard triggering technological disasters) (Tierney et al. 2001; Steinberg and Cruz 2004). Industrial factories are the most important pollution sources associated with impacts from natural disasters (Yu 2015; The State Oceanic Administration 2013). When a natural hazard strikes, hazardous industrial installations are always at risk and can potentially cause severe damage to the environment and to the human population (Vallée 2003).

Emphasizing and reinforcing the centrality of environmental concerns in disaster management has become a critical priority, given the recent increases in population density and accelerating industrial development in areas subject to natural disasters (Cruz et al. 2015; Wessberg et al. 2008; Yu and Zhang 2009). Studies of Na-tech disaster management mainly focus on qualitative analysis, but more studies using quantitative analysis are needed. In a longer term, action is needed to fill major gaps in knowledge about the environmental impacts of disasters (Srinivas and Nakagawa 2008). Meng et al. (2014) constructed a simulation approach to analyze the regional life loss risk caused by airborne chemicals released after devastating earthquakes. It has been demonstrated that the life loss risk was not prominent but would be dependent on unfavorable meteorological conditions. Balluz et al. (2001) studied environmental pesticide exposures in Honduras following hurricane Mitch. Peng (2018) constructed a flood-risk environmental index and conducted a correlation analysis of flooding factors for the quantitative evaluation of degrees of hazard to assist with disaster prevention management. He noted that typhoons are one of the main causes of flooding disasters in Taiwan.

Typhoon, always exhibiting fierce winds and torrential rain, are one of the most destructive and frequently occurring natural disasters in the northern Pacific Ocean and South China Sea (Zhou et al. 2018). The secondary environmental events triggered by typhoons are some of the most dangerous disasters in these areas. For example, in 2010, the Tingjiang River pollution event led to the death of millions of tons of fish due to leakage of toxic wastewater from the Zijin Mining Corporation, which was mainly caused by heavy rain associated with the Typhoon Fanapi. However, few studies exist addressing the impact of typhoons on environmental risks. With the increasing incidence of environmental accidents, environmental risk assessment is considered an effective measure globally for incidents prevention and control by authorities (U. S. Environmental Protection Agency 1992; World Health Organization 1999). Therefore, it is essential to develop a scientific and feasible indicator system to determine the risk level of industrial enterprises when impacted by natural disasters.

In this study, a Na-tech environmental assessment index system and an assessment method based on an analytic hierarchy process and fuzzy evaluation model (ERA-FEM) was developed to explore the major impact factors related to risk level. The influence of natural disasters on industrial environmental risk is studied through a comparative analysis to determine if typhoons should be considered. A chemical plant located in Zhejiang, one of the areas most affected by typhoons in China, was selected as a case study. Three hypothetical scenarios were constructed to analyze the major influence of various factors on environmental risk in the context of a typhoon disaster.

Method

Framework of environmental risk assessment triggered by a typhoon disaster

The framework of environmental risk assessment under the impact of a typhoon disaster is established based on the four-step risk assessment procedure described in "Risk Assessment in the Federal Government: Managing the Process" by the USA in 1983 (Fig. 1). The first step is the identification of risk factors. Risk index methods, such as Inherent Environmental Toxicity Hazard (IETH) (Warnasooriya and Gunasekera 2016) and the environmental consequence index (ECI) (Koller et al. 2000; Arunraj and Maiti 2009), are some of the most widely used methods. A systematic and effective risk indicator system is conducive to the comprehensive identification of environmental risks. Second, these factors are quantified based on relevant actual data using the established criteria. The risk assessment method is then established, and comparative analysis is performed between the two scenarios: The typhoon disaster is considered (scenario-T) or the typhoon is not considered (scenario-NT). Na-tech risk assessment for enterprises is a systematic assessment that involves multiple risk factors with uncertainty and vagueness. The fuzzy evaluation method and analytic hierarchy process (AHP) are widely applied in the processing of fuzzy problems and the determination of weights in various areas (Dağdeviren and Yüksel 2008; Wang et al. 2014; Akay et al. 2018). Finally, suggestions for preventing and migration measures are discussed.

Identification of risk factors

"Risk = Hazard × Vulnerability" is a generally accepted and applied theory of risk assessment applied to natural disasters and environmental accidents (Wisner 2004). Based on the theory, the accidental environmental risks for enterprises in China are evaluated and graded based on factors of quantity of hazardous substances, production processes, risk receptors, and risk management and control systems (Ministry of Ecology and Environment of the People's Republic of China 2018). Meanwhile, the accidental risk assessment methodology for industries (ARAMIS), developed to answer the specific requirements of the SEVESO II directive, mainly focused on the factors of hazards, safety barriers, and vulnerability of the plant surroundings (Salvi 2002). López and Vazquez-Brust built the evaluation framework for a firm's environmental risk, in which risk was defined as the result of combining hazards, vulnerability, exposure, uncertainty, and governability (López and Vazquez-Brust 2012; Vazquez-Brust et al. 2012; Wisner 2004; Salvi 2002). Literature reviews and statistical analysis indicate that factors related to risk prevention and control measures, such as environmental management and emergencies, are also crucial to Na-tech risk (Dokas et al. 2009; Hosseinnia et al. 2018; Hahn 1997). Therefore, based on the environmental risk assessment method in China, ARAMIS, and literature reviews, the most relevant factors contributing to Na-tech risk are considered to be production factors, emission factors, the surrounding environment, safety and environmental management, and emergency preparedness (Fig. 2). Production and emission factors are the inherent determinants of environmental risk, while the vulnerability of the surrounding environment is an external factor. Safety and environmental management, as well as emergency preparedness, reflect the capacity to control and reduce the environmental risk of the industrial enterprises.

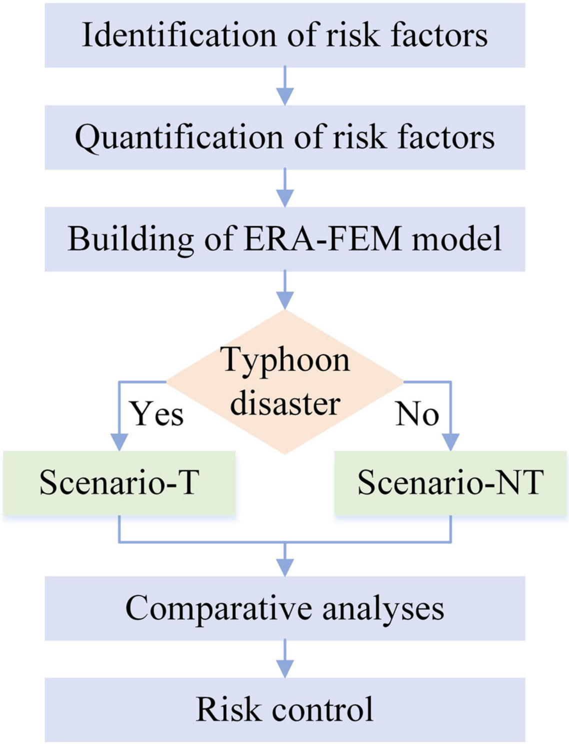

Fig. 1 Framework of the Na-tech environmental risk assessment triggered by a typhoon disaster

Production factors (B_1)

Production and storage units pose the highest risks in an industrial plant (Valencia-Barragán et al. 2016). These relevant production factors can be described as (1) quantity and hazard of chemicals (C_{11}), (2) hazards of production processes (C_{12}), and (3) reliability of equipment (C_{13}). Hazards from chemicals refer to the flammability properties, explosive properties, corrosive properties, reactivity properties, and polluting or toxicity capabilities. Hazards of production processes can be evaluated through their reaction characteristics, such as temperature, pressure, and redox properties. The reliability of equipment was evaluated according to its service life and rationality of design.

Emission factors (B_2)

The "tri-wastes"—waste gas, waste water, and waste residues—could cause harm to the environment, ecological balance, and human health if discharges into the environment took place without effective treatment. Factories must ensure their "tri-wastes" emissions meet relevant emissions standards. Moreover, the management of hazardous waste has drawn increasing attention. Emission

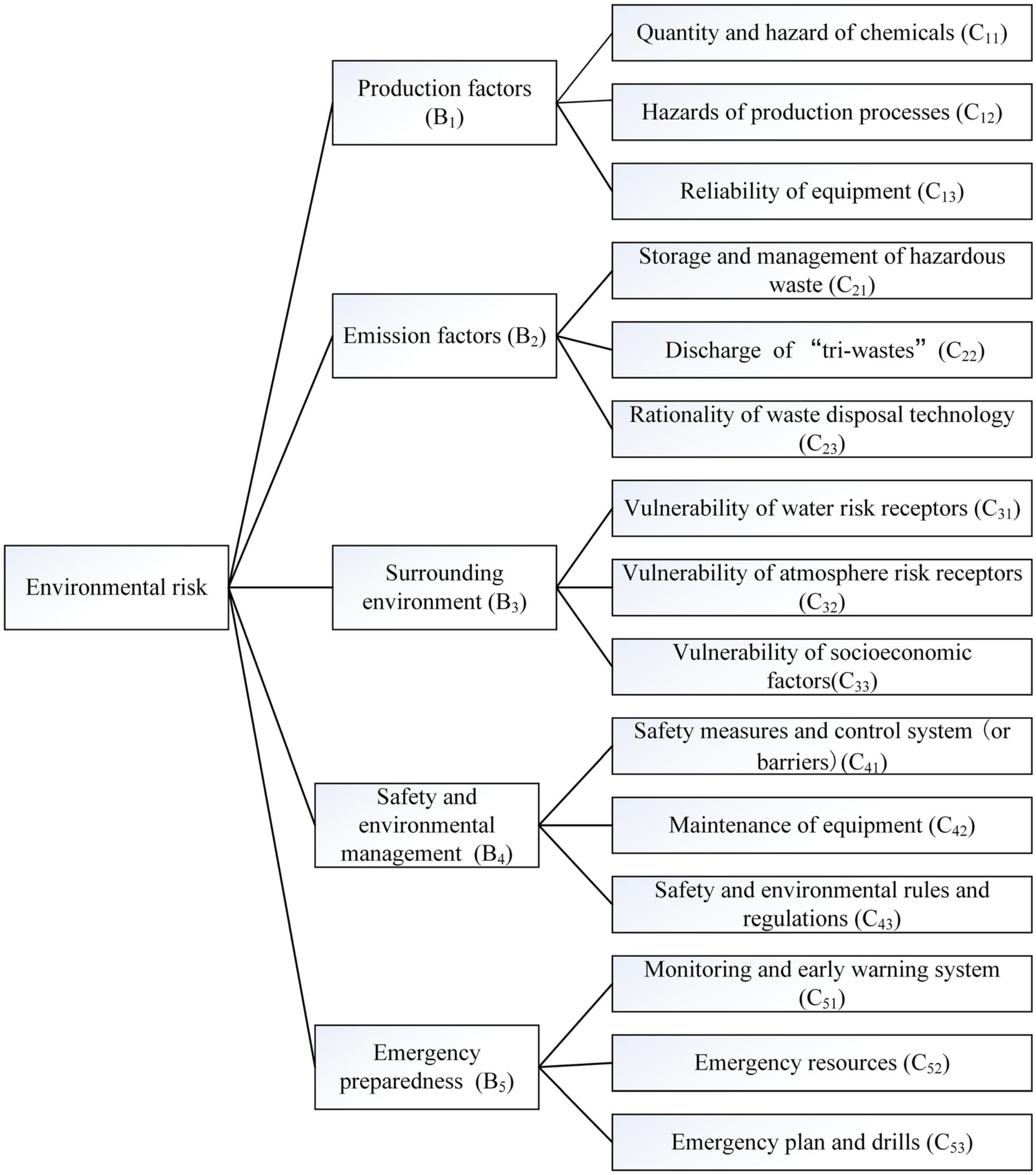

Fig. 2 Index system of Na-tech environmental risk of industrial enterprises

factors can be divided into three subfactors, namely (1) storage and management of hazardous waste (C_{21}), (2) discharge of "tri-wastes" (C_{22}), and (3) the rationality and efficiency of waste disposal technology (C_{23}).

Surrounding environment (B_3)

Vulnerability of biophysical and social environments in the vicinity of industrial sites has gained attention since the 1970s (Li et al. 2010). The effects of typhoons on environmental risks and great damage to the national economy are mainly caused by fierce winds and associated flooding (Elliott et al. 2015). Statistics for emergency environmental incidents in China from 2006 to 2013 showed that incidents of water pollution and air pollution accounted for 50.6% and 43.2% of the total environmental accidents, respectively (Ministry of Environment of the People's Republic of China 2016). The vulnerability of the surrounding environment is divided into three aspects: (1) vulnerability of water risk receptors (C_{31}), (2) vulnerability of atmosphere risk receptors (C_{32}), and (3) vulnerability of socioeconomic factors (C_{33}). Drinking water sources, natural water reserves, and aquaculture areas are sensitive risk receptors to water pollution, while populated regions are extraordinarily sensitive to atmospheric risk.

Safety and environmental management (B_4)

Safety and environmental management means "a systematic control of worker performance, machine performance, and the physical environment" (Heinrich et al. 1980). This is considered to be an effective way to reduce safety risks and pollutant levels in industrial processes (Tan et al. 2016). Safety defenses, especially the safety equipment and many activities, are used to prevent accidents and protect against damages (Guldenmund and Li 2017). In-depth analysis of major pollution accidents in China from 2002 to 2006 shows that more production accidents are caused by technical failures (42%) than by human failures (mainly due to operating errors) (12%) (Yu and Zhang 2009). Furthermore, strict regulations and rules are proven to be effective in accident prevention (Guldenmund and Li 2017; Ambituuni et al. 2014). The relevant factors can be summarized as follows: (1) safety measures and control systems (or barriers) (C_{41}), (2) maintenance of equipment (C_{42}), and (3) safety and environmental rules and regulations (C_{43}).

Emergency preparedness (B_5)

Emergency response planning for major accidents in industrial enterprises is essential to minimizing the impact of accidents on the public and on worker health and to reducing the environmental impacts (Hosseinnia et al. 2018). Leakage detection and alert systems should detect failures promptly, providing an opportunity to control accidents in a timely manner (Rebelo et al. 2014). The fundamental causes of social vulnerability include a lack of resources, information and knowledge, limited access to political power and representation, certain beliefs and customs, and infrastructure and lifelines (Wisner 2004; Cutter et al. 2015). For emergency response, it is critical to enhance the resilience of targets inside and outside to reduce risk levels (Li et al. 2010). Emergency planning and emergency drills, used as mitigation measures, play a key role in reducing the effect of accidents (Lin et al. 2009; Zhong et al. 2010). Relevant factors for emergencies are summarized as (1) monitoring and early warning systems (C_{51}), (2) emergency resources, including emergency facilities and supplies (C_{52}), and (3) emergency plans and drills (C_{53}).

Quantification of risk factors

Indices, which are positively correlated with risk level (production and emission factors), are evaluated and graded into minor hazards, general hazards, and major hazards, while surrounding environment factors are graded into general low vulnerability, middle vulnerability, and high vulnerability. Indices of safety and environmental management are graded into loose, moderate, and strict. The emergency factors are graded into imperfect, moderate, and perfect. The stricter and more nearly perfect management and emergency are, the lower the risk level.

The *Classification method for environmental accident risk of enterprise (HJ 941-2018)*, *Technical guidelines for environmental risk assessment on projects (HJ/T 169-2004)*, and *Standard for pollution control on hazardous waste storage (GB 18597-2001)* are used to quantify these factors. For example, the index of quantity and hazards of chemicals (C_{11}) is evaluated according to the ratio of a hazardous substance and its critical quantity, as displayed in Eq. 1.

$$Q = \sum_{i=1}^{n} m_i / M_i \qquad (1)$$

where m_i represents the maximum storage of hazardous substance i in the plant and M_i represents the critical mass of the hazardous substance i stipulated in *HJ 941-2018*. When $Q < 1$, a minor hazard is present; when $1 \leq Q < 10$, a general hazard exists; $Q \geq 10$ represents a major hazard.

Risk assessment method based on AHP and the fuzzy evaluation method

Many risk factors cannot be quantified accurately using classical mathematical methods due to their uncertainty but can be described using linguistic variables that can be quantified through a fuzzy logic approach (Li et al. 2007). Fuzzy set theory, proposed by Zadeh in 1965, has been developed to mathematically represent uncertainty and vagueness and to provide formalized tools for dealing with the uncertainty inherent in decision-making problems (Ji et al. 2000; Zhou et al. 2017). In this study, a Na-tech environmental risk assessment methodology based on an analytic hierarchy process and fuzzy evaluation model (ERA-FEM) was proposed to analyze the impact of a typhoon disaster on risk levels of industrial enterprises (Fig. 3). The ERA-FEM procedures include four steps: (1) establishment of the finite set of risk factors, (2) construction of a comment set for the evaluation object, (3) determination of the weight vector, and (4) evaluation of environmental risk using fuzzy operators.

The finite set of risk factors and comments set

The finite set of risk factors is a 5-tuple:

$$\mathrm{U} = \{U_1, \ldots, U_i, \ldots, U_5\} \quad (i = 1, 2, 3, 4, 5) \tag{2}$$

$$U_i = \{U_{i1}, \ldots, U_{ij}, \ldots, U_{im}\} \quad (j = 1, 2, 3, \ldots, m) \tag{3}$$

where U_{i} represents the finite set of *i* indices.

The comment set is a collection of the evaluation results that the evaluator made of the evaluation object. Generally, the evaluation interval or degree language is used as the evaluation target, which can be usually expressed as

$$\mathrm{V} = \{V_1, \ldots, V_i, \ldots, V_n\} \qquad (i = 1, 2, \ldots, n) \tag{4}$$

The conversion scale figures proposed by Chen et al. (2003) were used to systematically transform linguistic terms to their corresponding fuzzy sets. These scale figures cover the linguistic expressions of "major risk" (major hazard, high-vulnerable, loose management, and imperfect emergency), "general risk" (general hazard, mid-vulnerable, moderate management, and moderate emergency), and "minor risk" (minor hazard, low-vulnerable, strict management, and perfect emergency) with the risk scores of 90, 70, and 50 respectively.

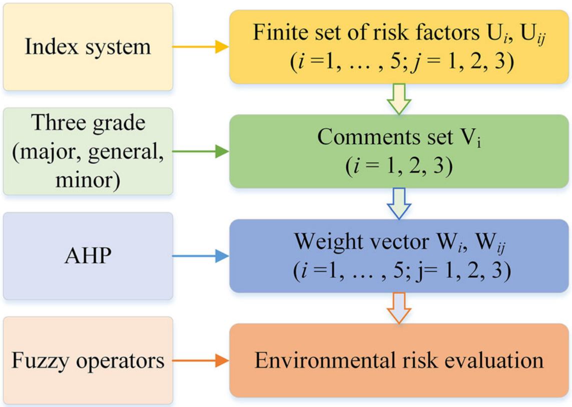

Fig. 3 Four-step procedure of the ERA-FEM method

Determinant of the weight vector

The fuzzy weight distribution vector, which is mainly influenced by the importance of factors, is shown in Eq. 5.

$$\begin{aligned} &\mathrm{W} = (w_1, w_2, \cdots, w_i, \cdots, w_m) \\ &0 \le w_{\mathrm{i}} \le 1, \text{and} \textstyle\sum_{(i=1)}^{m} w_i = 1 \end{aligned} \tag{5}$$

where w_i represents the weight of i factor.

The analytic hierarchy process (AHP) is a multicriteria hierarchical method that is widely used in the process of decision-making and assessment of priorities (Tixier et al. 2006). This method is based on four steps: (1) description of the studied system, (2) construction of hierarchies, (3) assessment of priorities based on expert judgments, and (4) validation of coherence. Risk factors were identified and organized in a hierarchical structure as discussed in the previous section. Binary comparisons were conducted among all elements at a given level according to the element of the upper level. The elements were ranked according to their relative importance. As shown in Table 1, a scale based on classic numerical variables or more qualitative variables was used in the binary comparisons.

The square root method was applied to calculate the weight of elements based on judgments by experts. Through normalization processing, the weight vector was obtained, as shown in Eq. 6.

$$w^{k \to k-2} = w_{i,j}^{k} \times w_i^{k-1} \tag{6}$$

where $w_{i,j}^{k}$ is the weight of *j* index in *k* layer to the *i* index in *k*-1 layer, w_i^{k-1} is the weight of *i* index in *k*-1 layer to index in *k*-2 layer, and $w^{k \to k-2}$ is the weight of indices in *k* layer to indices in *k*-2 layer.

Finally, the validation of coherence was conducted per Eq. 7.

$$\mathrm{CR} = \sum_{i=1}^{m} a_i(\mathrm{CI})_i / \sum_{i=1}^{m} a_i(\mathrm{RI})_i \tag{7}$$

where CI is the consistency index, RI is the random index, which is a randomly generated consistency index

Table 1 Scale of binary comparison

Degree of importance	Definition
1	Equal importance of two elements
3	Weak importance of an element in comparison to the other one
5	Strong importance of an element in comparison to the other one
7	Certified importance of an element in comparison to the other one
9	Absolute importance of an element in comparison to the other one
2, 4, 6, 8	Intermediate values between two appreciations
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reciprocal values of the previous appreciation

of the risk matrix and is related to the rank of the matrix, and CR is the consistency ratio. This index is considered to be acceptable when CR ≤ 0.1. Otherwise, it is considered inconsistent and requires a reevaluation.

Environmental risk evaluation applied fuzzy operators

Many operators used as performance functions are included in the fuzzy evaluation method and are represented d as "o." The operator M (·, ⊕), which multiplies the elements of the matrix and then sums the results, is a weighted average function. This operator was selected and applied in the calculation of environmental risk level in this study. It is suitable for the optimization of overall index values based on the weight balance of all factors. Therefore,

$$B = W \circ R \tag{8}$$

where R represents the quantified intensity matrix of risk index in the previous section. For each factor, the intensity matrix was established, as shown in Eq. 9.

$$R_i = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ \cdots & \cdots & \cdots \\ c_{m1} & c_{m2} & c_{m3} \end{pmatrix} \tag{9}$$

where R_i represents the production hazard, emission hazard, vulnerability of the surrounding environment, level of safety and environmental management, and emergency preparedness. c_{i1} represents the intensity of major risk of i index, c_{i2} is the general risk, and c_{i3} is the minor risk.

The environmental risk score for an enterprise is in the range of 50–90. For more convenient understanding and comparative analysis, the risk score is converted to the range of 0–100 through the use of Eq. 10, with a general risk level represented by 50. When the final risk value is less than 50, the environmental risk for the enterprise is relatively low, and it is relatively high when the final risk value is larger than 50. Risk grading is not carried out due to the small number of samples.

$$V = \frac{R\text{−min}}{\text{max−min}} \times 100 \tag{10}$$

In this study, min is 50, the minor risk; max is 90, the major risk; R is the calculated risk score; and S is the final risk value in centesimal system.

Case study

A chemical plant in Zhejiang Province, located in the south of the Yangtze River Delta on the southeast coast of China, was selected as a case study to illustrate the applicability of the proposed approach in this study (Fig. 4). This plant is one of the world's largest manufacturers of hydroxybenzoic acid and neoplastic products and covers an area of more than 72,000 square meters; it has fixed assets of 262 million yuan and 300 employees. Hazardous chemicals in this plant include sulfuric acid, methanol, and phenol, and emissions of waste gas and wastewater pollutants are generated. Production processes include esterification, hydroxylation, pressure filtration, and drying. There are many petrochemical enterprises in this city, which is densely populated and has many interconnected waterways.

A total of 30 experts were invited to evaluate the risk level of this factory using the risk index system for two scenarios: one in which typhoon disasters are considered and one in which they are not considered. The experts include professors majoring in chemical engineering, scholars engaging in the investigation of environmental risk assessment (ERA), professional assessors of environmental risk, and first-line workers in chemical factories with many years of experience.

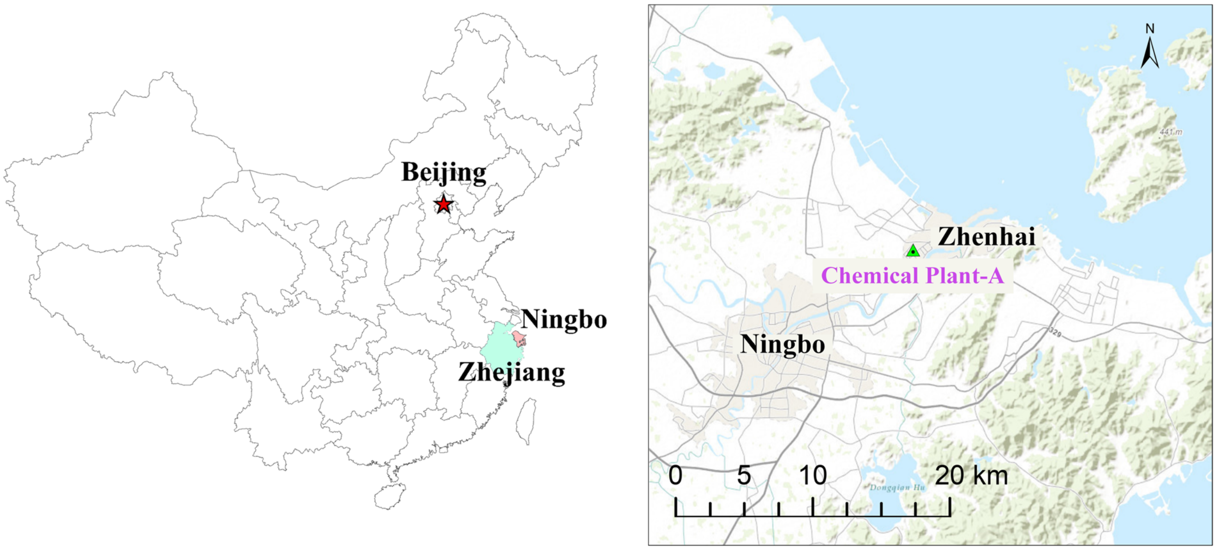

Fig. 4 Location of the case-study chemical plant

Results and discussion

Quantification of risk factors

The state vectors of indices were obtained and normalized from evaluation results obtained from 30 experts. In general, the quantity and hazards of chemicals (C_{11}) was in the high-risk level; the hazards of production processes (C_{12}), vulnerability of water risk receptors (C_{31}), and vulnerability of atmospheric risk receptors (C_{32}) were in the general risk level; and other factors were at a minor risk level. This plant was a major hazardous source with $Q = 267.22$, far surpassing the limiting value (100) of major risk due to the large amounts of sulfuric acid and dimethyl sulfate present. Most experts ranked the index of hazards of production processes (C_{12}) as a general risk, while the index of reliability of equipment (C_{13}) was graded as a minor risk. The main pollutants include flue gas, dust, SO_2, NO_X in exhaust emissions, and COD_{cr} and NH_4^+-N in effluents, as well as a small amount of hazardous waste, such as volatile phenol in water, waste activated carbon, and wastewater sludge. Environmental protection facilities at this plant normally meet the standards for the emission of production wastewater and exhaust gases.

Residents around the plant are the major atmospheric receptors. There are thousands of people living within a 2-km radius, and a river near the plant is no more than 5-km distance. The water quality of the river conforms to the class III water quality standard for surface water. Nearly 80% of experts ranked atmospheric and water receptors as a general risk, while the remaining socioeconomic receptors were graded as minor risks. The evaluation results showed that the process control system was 66% perfect and 17% imperfect. Most experts pointed out that the safety and environmental rules and regulations are strict, while 60% considered that the equipment maintenance was performed at a medium level. Approximately 90% of the experts considered the monitoring and early warning system to be perfect, and 87% considered the emergency plans to be well established and that drills were performed well. However, the emergency resources perhaps were ill-prepared or unreasonable. Therefore, the degree of membership of factors in the comment set was obtained as listed in Table 2.

Comparative analysis of weight vectors between considering a typhoon-related disaster or a non-typhoon-related disaster

The weight matrix was obtained based on judgments of the relative importance of indicators for each level by experts. The comparison analysis of weights between scenarios considering the impact of a typhoon disaster or a non-typhoon disaster is displayed in Table 3. The production factors show the highest weight, followed by factors of safety and environmental management, showing a slight increase when considering the impact of a typhoon disaster. The weight of emission factors and

Table 2 Scores of environmental risk indices as evaluated by 30 experts

Level	Production factors (R_1^T)			Emission factors (R_2^T)			Surrounding environment (R_3^T)			Safety and environmental management (R_4^T)			Emergency preparedness (R_5^T)		
	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}	C_{51}	C_{52}	C_{53}
Major risk	1	0	0.1	0.2	0	0.3	0	0.03	0	0.17	0.1	0.13	0	0.2	0
General risk	0	0.7	0.3	0.67	0.3	0.63	0.8	0.8	0.07	0.17	0.3	0.64	0.1	0.3	0.13
Minor risk	0	0.3	0.6	0.13	0.7	0.07	0.2	0.17	0.93	0.66	0.6	0.23	0.9	0.5	0.87

surrounding environment decreased considerably for the case of a typhoon-related disaster, while that of emergency factors clearly increased for this same case.

The index of quantity and hazards of chemicals (C_{11}) was the most important factor for environmental risk for both scenarios and exhibited a noticeable increase when considering the impacts of a typhoon-related disaster. When the disaster was not a typhoon-related disaster into account, the atmospheric risk receptors (C_{32}) were slightly more important than the water risk receptors (C_{31}). However, the weight of water risk receptors clearly increased in the typhoon disaster scenario, while that of atmospheric risk receptors decreased significantly and was much lower than that of water risk receptors. The emergency resources (C_{52}) and emergency plan and drill (C_{53}) became more important to risk levels when considering the impact of a typhoon-related disaster, while the weight of monitoring and early warning facilities (C_{51}) clearly decreased. The weight of hazards from production processes (C_{12}) and discharge of "tri-wastes" (C_{22}) decreased for the case of a typhoon-related disaster, while the weight of safety defenses and control systems (or barriers) (C_{41}) decreased considerably.

Table 3 Comparison of two weights considering the influence of a typhoon-related disaster or a disaster with no typhoon present

Index	N	Y	Label
Production factors (B1)	0.2694	0.2766	↑
Quantity and hazard of chemicals (C_{11})	0.1466	0.1798	↑↑↑
Hazards of production processes (C_{12})	0.0785	0.0627	↓↓
Reliability of equipment (C_{13})	0.0443	0.0342	↓
Emission factors (B_2)	0.1453	0.1178	↓↓↓
Storage and management of hazardous waste (C_{21})	0.039	0.0407	↑
Discharge of "tri-wastes" (C_{22})	0.0877	0.0646	↓↓
Rationality and efficiency of waste disposal technology (C_{23})	0.0186	0.0125	↓
Surrounding environment (B_3)	0.1533	0.1221	↓↓↓
Vulnerability of water risk receptors (C_{31})	0.0647	0.0830	↑↑
Vulnerability of atmosphere risk receptors (C_{32})	0.068	0.0197	↓↓↓↓
Vulnerability of socioeconomic factors (C_{33})	0.0207	0.0194	↓
Safety and environmental management (B_4)	0.2365	0.2518	↑↑
Safety measures and control system (or barriers) (C_{41})	0.121	0.1371	↑↑
Maintenance of equipment (C_{42})	0.0742	0.0709	↓
Safety and environmental rules and regulations (C_{43})	0.0412	0.0438	↑
Emergency preparedness (B_5)	0.1955	0.2316	↑↑↑↑
Monitoring and early warning system (C_{51})	0.0922	0.0579	↓↓↓
Emergency resources (C_{52})	0.0789	0.1237	↑↑↑↑
Emergency plan and drills (C_{53})	0.0244	0.050	↑↑↑

N, the scenario without the impact of typhoon disaster; Y, the scenario with the impact of typhoon disaster

The primary reason for these results is that the damage from a typhoon disaster is mainly caused by high winds and heavy rains. These impacts could cause damage to raw materials, products and semifinished products, leading to leakage of hazardous chemicals and pollutants, causing environmental events, especially for chemical enterprises (Showalter and Myers 1994; Young et al. 2004). The damage to power facilities, buildings, and infrastructures, such as workshop and warehouse collapses and waterlogged equipment, could increase the probability of failure of storage vessels, facilities, and equipment, which is likely to aggravate the leakage of hazardous chemicals (Liu et al. 2010; Yin et al. 2013). Therefore, the production factors, especially quantity and hazards of chemicals (C_{11}), were more important to the environmental risk of chemical factories. Meanwhile, if large quantities of hazardous chemicals are present, toxic and harmful substances are discharged into water bodies, and the diffusion range increases, creating an increased risk to water risk acceptors. Wind speed is one of the major factors for impacts on the atmospheric environment (Zhang et al. 2018). During high wind conditions, air pollutant disperse easily, which eliminates the importance of atmospheric receptors.

Perfect safety and environmental risk management and sufficient emergency preparedness can effectively reduce the environmental risk level from chemical factories. For example, advanced rainfall and sewage diversion systems, and a sufficient emergency pool capacity can effectively reduce pollution to the external environment by preventing pollutants from flowing outside the plant. Perfect emergency plans and drills can effectively improve the processing efficiency and shorten the response time to sudden accident, thereby reducing impacts.

The decrease of factors, such as C51, C12, and C22, does not mean that they pose insignificant environmental risk in the case of typhoon incidents, due to the decrease of determinacy compared with other factors. This phenomenon is mainly due to the strong destructive force of typhoons, which readily leads to large-scale destruction of equipment. For this scenario, monitoring and early warning systems have less impact on the level of environmental risk. The emissions of conventional "tri-wastes" and safety facilities contribute relatively little to the overall environmental risk from enterprises.

Comparative analysis comprehensive rating results

The comparative analyses of the assessment results of the case-study plant for our two scenarios are shown in Table 4. In general, this plant presents a minor-general environmental risk for both scenarios, and the total risk increases from 38.82 to 41.36 when considering the impact of a typhoon. The risk level of production factors shows a major risk increase with a significant increase from 68.73 to 76.07 when considering the impact of a typhoon-related disaster. By contrast, the risk levels of other factors are much lower, showing small changes when considering the impact of a typhoon-related disaster. Overall, this case-study plant is a typical major risk source plant with a high-risk level. The risk receptors around the plant exhibited moderate vulnerability. The emergency preparedness and safety and environmental management were adequate and in good conditions.

Table 4 Comparative analysis of risk level of the case-study plant for two scenarios

Risk score	N	Y
Total risk	38.82	41.36
Production factors (B_1*)	68.73	76.07
Emission factors (B_2*)	31.29	33.24
Surrounding environment (B_3*)	36.51	34.68
Safety and environmental management (B_4*)	28.68	28.75
Emergency preparedness (B_5*)	17.29	21.34

N, the scenario without the impact of typhoon disaster; Y, the scenario with the impact of typhoon disaster

Hypothetical scenario

To explore the impacts of various factors on environmental risk of enterprises in the context of a typhoon, three scenarios were assumed based on the situation of the case-study enterprise and are displayed in Table 5. The worst management scenario (S1) was assumed with the highest risk of management factors, such as C41, C42 C43, C52, and C53, based on the actual situation. Water risk receptors are the most susceptible factors. The most vulnerable of the water risk receptors scenario (S2) is assumed based on S1. Meanwhile, for the low hazard scenario (S3), it is assumed that the enterprise has a low hazard level but poor management, similar to scenario 1.

Comparative analysis of the evaluation results for the actual situation and the hypothetical scenario shows that the influence of a typhoon on environmental risk clearly increases for all hypothetical scenarios. The environmental risk value is much higher when the enterprise has imperfect management relative to the actual situation. The more sensitive the water risk receptors are, the higher the environmental risk presented. However, when the inherent hazards are low, the potential impact on the surrounding environment is relatively small, even though the management level is not perfect. Therefore, during site selection, enterprises using hazardous chemicals and processes should maintain an adequate distance from water bodies and avoid low-lying areas to reduce the impact of flooding caused by typhoons, especially for storage areas and equipment using hazardous chemicals. Perfect safety and environmental risk management and sufficient emergency preparedness can effectively reduce the environmental risk level associated with industrial plants. Plants with large quantities of hazardous chemicals and with vulnerable water environmental risk receptors should strengthen their safety and environmental management, especially those plants located in typhoon-prone areas. Emergency plans should be nearly perfect and more readily executable when a plant is vulnerable to typhoons. Therefore, emergency response supplies should be properly equipped and distributed to ensure the effectiveness of emergency facilities.

Table 5 The quantitative results of actual situation and assumed scenarios

Scenario	Factors															Results	
	C_{11}	C_{12}	C_{13}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}	C_{51}	C_{52}	C_{53}	N	Y
R	90	64	60	71.4	56	74.6	67.2	66	51.4	60.2	60	68	52	64	52.6	38.82	41.36
S1	90	64	60	71.4	56	74.6	67.2	66	51.4	90	90	90	52	90	90	63.07	72.21
S2	90	64	60	71.4	56	74.6	90	66	51.4	90	90	90	52	90	90	66.75	76.94
S3	50	50	60	50	50	74.6	67.2	66	51.4	90	90	90	52	90	90	36.69	43.57

In summary, environmental risk assessment of an industrial enterprise in the case of a typhoon disaster is a type of Na-tech risk assessment. It combines the differences and similarities between natural disaster risk assessment and environmental risk assessment and includes a process of establishing an index system. The ERA-FEM model is a resilient, feasible, and semiquantitative method that can effectively solve the problem of insufficient data and uncertainty when characterizing environmental risk effectively. Meanwhile, the quantitative methods for evaluating risk factors can be adjusted according to regulations and standards in various countries and regions.

Conclusions

In this study, the impact of typhoons on environmental risk of industrial enterprises was discussed for the first time, in an effort to provide a comprehensive description of differences and corrections between natural disaster risk and environmental risk assessment. All major impact factors were categorized into five groups: production factors, emission factors, surrounding environment, safety and environmental management, and emergency factors. Meanwhile, a resilient, feasible, and semiquantitative assessment method (ERA-FEM) was developed based on an analytic hierarchy process and a fuzzy evaluation model. The environmental risk of the case-study chemical plant was then evaluated for both scenarios (i.e., whether or not a typhoon is to be considered as part of a disaster). Furthermore, three hypothetical scenarios were defined based on the actual situation of the case-study enterprise, such as the worst management scenario, the most vulnerable of water risk receptors scenario, and the low hazard scenario. The results showed that production factors, especially quanty and hazards of chemicals, are the most important factors impacting environmental risk of chemical plants for both scenarios. Safety and environmental management are the second most important factors to environmental risk, the risk level of which rises when taking the impact of typhoons into account. Under the influence of typhoon disasters, the importance of emergency preparedness increases, while emission factors and environmental factors decrease. Moreover, the effect of a typhoon on water environmental risk receptors is significantly greater than that on atmospheric environmental risk receptors. The impact of a typhoon on environmental risks clearly increased when the enterprise exhibited imperfect management and emergency preparedness.

Perfect safety and environmental management systems, as well as adequate emergency preparedness, can effectively reduce the environmental risk level of chemical industry plants. Therefore, adequate attention should be paid to emergency preparedness and management within the enterprise, as well as allocating emergency supplies and facilities reasonably and effectively, especially in typhoon-prone areas. Meanwhile, authorities and government should strengthen the regulation of major risk source plants, while supervising, urging, and guiding them to improve management.

Funding information This work was supported by the Major Science and Technology Program for Water Pollution Control and Treatment (2012ZX07503-003-005), General Program of Science and Technology Plan of the Beijing Education Commission (KM201711232017), Project of Construction of Innovative Teams and Teacher Career Development for Universities and Colleges under Beijing Municipality (IDHT20180508), the special fund of Beijing Key Laboratory of Clean Fuels and Efficient Catalytic Emission Reduction Technology (BZ041420180003), and the Key Research and the Development Projects of Shanxi Province (201803D31003).

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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