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A two-scale system to identify environmental risk of chemical industry clusters

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ABSTRACT

Recent reform policies in China have spurred rapid industrial development. This has led to a large increase in chemical accidents, which may have catastrophic impacts on the local population and environment. As industrial facilities become more complex, it becomes more difficult to control and mitigate the risks associated with chemical accidents. In this study, we propose a two-scale system for assessing the environmental risk level of chemical industry clusters. A series of risk early warning indices for both the plant-specific level and regional clusters level are used in this system. Firstly, at the enterprise scale, a risk early warning index is constructed using inputs such as the presence of hazardous materials, the operation of critical plant equipment and the efficiency of extant management techniques. Secondly, an index for quantifying risks on regional scales depends on environmental, economic, and social conditions as well as the specific enterprises' components. As an illustration, the system is applied to a case study involving a five-plant chemical industry cluster in Jiangsu province, China. A geographical information system-based methodology is used to obtain a composite index score for each mesh of the five plants. The results prove that the proposed two-scale early warning system can efficiently identify environmental risk and help guide emergency responses at both the enterprise and cluster level.

1. Introduction

Early warning theory was first applied in macroeconomics, and the origins of the study of economic monitoring and early-warning systems can be traced back to the end of 19th century [1]. At present, early warning theory has been applied to a broader field of environmental risk prevention and preliminary warning in long-term monitoring without accidents already happened. The three principles of early warning are the existence of harmful threats (risks), the uncertainty associated with these risks and the preventive action required to deal with such threats [2]. The greatest contribution of these principles is that once some activities are suspected as risks, preventive actions would be taken before the accidents really happened which could effectively decrease the frequency of risks [3]. An early warning system is a key approach for preventing risks. Requirements for the ideal early warning system are as follows [4–6]:

- Provides warning in sufficient time for action.
- Cost is affordable.
- Requires low skill and training.
- Covers all potential threats.
- Is able to identify the source of risk.
- Is sensitive to quality at regulatory levels.
- Gives minimal false positive or negative responses.
- Is robust.
- Is reproducible and verifiable.
- Functions year-round.

Several countries and regions have established early warning systems to identify accidental environmental risks. As early as 1978, a Global Environment Monitoring System (GEMS) was established to provide global-scale environmental quality monitoring, comparing, sorting and early warning in a global scope. The United Nations Environment Programme (UNEP) established a 'Regional Early Warning and Assessment' system aimed at evaluating the status of global environmental conditions and assessing the trends of evolution of the global environment and at providing advice for disseminating early warning signals and guidelines for decision-making [7]. In recent years, significant progress has been made in early warning systems due to advances in large-scale techniques and information. The EU began a web-based early warning system for air quality (APNEE) in 2000. The UNEP proposed the Global Environmental Alert Service (GEAS) to harness the power of the Internet

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to enhance and accelerate the flow of information from scientific research and earth observation systems to environmental decision makers and the general public [8].

For a single unit or process, Contini proposed an integrated process of quantitative risk analysis that contained analysis, estimation of accident frequency and consequences, risk calculation and risk mitigation [9]. Seveso II [10] put forward ARAMIS (Accidental Risk Assessment Methodology for Industries) to characterize potential hazards and to control the corresponding risks [11,12]. Achoura outlined a global environmental risk assessment (GERA) index to assess the environmental risks from chemical processes [13]. Nevertheless, compared with large scale environmental risks, small regional environmental risks or risks associated with independent entities are inadequately addressed by current early warning processes aimed at hazard mitigation.

Industry has developed rapidly since the industrial revolution. Long-term structural changes have occurred in industry, in particular through the concentration of companies in certain areas [14]. Chemical industries are often forced to 'cluster' due to a combination of the economics of scale, environmental factors, social motives, and legal requirements. Therefore, chemical plants are most often physically located in groups and are rarely located separately [15,16]. This leads to the continuous emergence of various industrial parks, economic and technological development zones, and circular economy zones. At the same time, the complexity of industrial systems has also considerably increased in the last decades [14], accompanied by environmental degradation and resource shortage, and this has placed local environments and nature under considerable strain. Clusters of chemical plants can consist of atmospheric, cryogenic, and pressurized storage tanks, large numbers of production installation equipment, and numerous pipelines for the transportation of hazardous chemicals [15]. Plant clusters are usually situated near rivers or lakes, posing significant risks to the local water supply and surrounding ecosystems. For instance, an accidental explosion at the Jilin Petrochemical Group in November 2005 polluted the Songhua River with nitrobenzene and caused not only basin-wide environmental pollution but also an international dispute with Russia. Due to the rapid development of chemical technology, there has been continuous growth of ever more complex installations with more extreme and critical processing conditions. The incidence and the severity of accidents have also tended to increase [17].

For an industrial cluster, it is imperative to construct an environmental risk early warning system that provides risk analysis and assessment to both single enterprises and to the cluster as a whole. The following critical problems are addressed in this article:

- How to construct an efficient environmental risk warning system that could rapidly identify, prevent, or provide alerts for environmental risks?
- How to merge enterprise and regional risk warning systems into a unified approach for easier management, operation, and monitoring?

This paper introduces a warning system of environmental risk for the chemical industry. We define two-scale early warning indices for both the enterprise and cluster levels as well as propose a method for identifying environmental risks of chemical plants. There are two key features that distinguish our approach from previous works. First, at the enterprise scale, we include multiple indices that are identified and valued by stakeholders and are based on such quantities as the nature of hazardous materials being used, the operation of critical equipment and the efficiency of enterprise management strategies. Second, a series of enterprise scale indices are used to quantify regional scale risks that link the social, environmental and economic information for a region. We illustrate our approach using a case study involving a five-plant cluster.

The outline of our paper is as follows. We begin by reviewing the definition of an early warning system and its key components. Section 2 explains our methods and models, and Section 3 applies our approach to a five-enterprise cluster. Finally, discussion on the case study and overall conclusions are presented in the last section.

2. Description of the proposed procedure

2.1. Framework of the early warning system

A hazard event depends on the process scale and its complexity [9]. In relation to chemical plant clusters, the level of environmental risk depends on many factors including the hazardous materials used, the equipment in operation, and the risk management strategies. One key point of our proposed system is that it quantifies and provides alerts for such risks with a focus on both the individual plant and the entire cluster. The flow chart (Fig. 1) delineates five guiding principles in early warning systems, which we expand upon below.

- *Identify*—analyze and screen hazardous chemicals and critical equipment that may be involved in accidents at the plant or at the regional level, and identify the preventative measures or management strategies in place to avoid such risks.
- *Plant*—for each plant, quantify the extent of the danger by taking into account the hazardous chemicals, equipment and risk management strategy in place. Each element has its own specific index that characterizes its contribution to the overall danger.
- *Region*—look at the ensemble of plants in the region and recognize the risks for each plant, the society, the local environment, and the local economy to monitor the status of regional risk.
- *Evaluate*—present an early warning analysis at both the plant and regional level, and estimate the risk level according to the criteria discussed below.
- *Alert*—alert the plants and cluster according to specified risk level, and providing the relevant measures of prevention, mitigation and management is recommended for managers [18].

The early warning system for a chemical cluster is constructed following the five principles as illustrated in Fig. 1.

2.2. Plant early warning system evaluation

Generally, environmental risk of a chemical plant is based on the amount of hazardous materials present, the mode of operation for dangerous equipment, and the efficiency of risk management. If such factors are not maintained safely and optimally, they may trigger accidents and cause adverse effects and damages to the local environment, economy, or human health. To quantify such risks and to help avoid and alleviate losses and damages, our proposed method takes into account contributions from several factors that interact with the external environment. The early warning index for a plant is given as:

$$E_e = \frac{\sum W_i \times \left(\sum P_j/j\right)}{M} \qquad (1)$$

where E_e is the early warning index for the specific plant, W_i is the environmental hazard index for substance i at the plant, P_j is the danger index for equipment j at the plant, and M is the environmental risk management index at the plant.

Eq. (1) indicates that the amount of hazardous chemicals and the prevalence of dangerous equipment have positive effects on E_e. That is, the more hazardous chemicals and dangerous equipment used in operation or in storage at the plant, the larger index

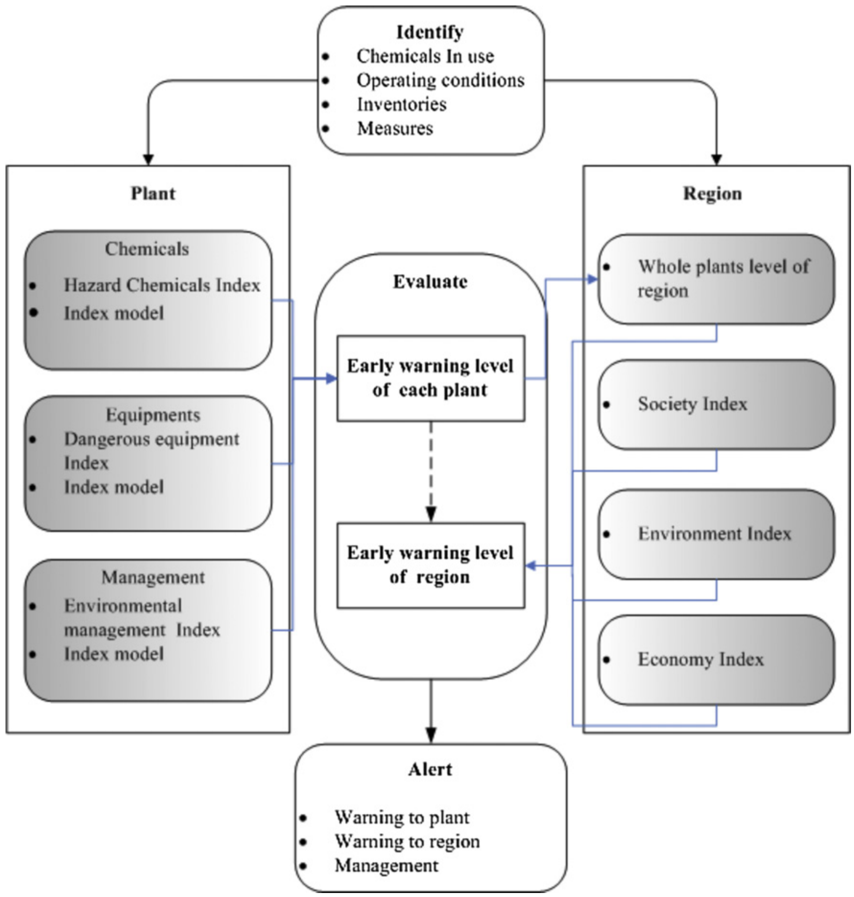

Fig. 1. Framework of the early warning system.

E_e becomes, and the need for appropriate action becomes more imperative. On the other hand, index E_e can be lowered by efficient implementation of risk management.

2.2.1. The environmental hazard index (W_i)

In chemical plants, accidents might be triggered by hazardous substances that have the potential for fire and explosion once a certain level of external conditions is reached (e.g., high temperature, high pressure, or leakage). Therefore, the root cause of accidents is the use of hazardous materials. An environmental risk warning index of hazardous materials is defined as:

$$W_i = \left[\frac{\sum I_j}{n} \right] \times \alpha_i \quad (2)$$

where W_i is the environmental hazard index for substance i, n is the total number of indices characterizing the substance's hazardous state, I_j is the substance index value corresponding to the list in Table 1, and a_i is the mole/mass fraction of substance i at the plant.

In Table 1 we present the indices used to evaluate the level of hazard that a given chemical component holds for the environment and human beings. Table 1 also presents the component definitions and provides sources for values. For the various materials, index I_t represents a chemical's health hazards. I_f represents flammability to identify the probability of fire. I_r (now in the hazardous materials identification system HMIS III) stands for the index of physical hazard to recognize water reactivity, organic peroxides and explosives, etc., and I_d is the index of environmental durability. The values are in conformity with HMIS hazard codes and range between 0 and 4. Larger values indicate more serious risk introduced by the component to the environment [9] and a corresponding higher level of warning required for the plant and region (see Tables 2 and 3).

Table 1
List of warning indices for hazardous materials.

Component risk warning index	Description	Source
I_t	Health index	HMIS
I_f	Flammability index	HMIS
I_r	Reactivity index	HMIS
I_d	Index of durability in environment	–

2.2.2. The dangerous equipment index (P_j)

According to Eq. (2), use of different equipment when handling hazardous materials can pose unique dangers for the external environment. For instance, some equipment types (e.g., a reactor) have the possibility of leakage or explosion when certain chemical substances are involved, which can then pollute the surrounding water and atmosphere. To evaluate the level of equipment hazard, values

Table 2
Example list of I_t index.

Attribute value	Description
0	No significant risk to health
1	Irritation or minor reversible injury possible
2	Temporary or minor injury may occur
3	Major injury likely unless prompt action is taken and medical treatment is given
4	Life-threatening, major or permanent damage may result from single or repeated overexposures

Table 3
Rating value of hazardous materials.

Hazard level	No hazard	Slight hazard	Moderate hazard	Serious hazard	Severe hazard
Attribute value	0	1	2	3	4

Table 4
List of warning indices for danger of equipment.

Component risk warning index	Description
I_m	Maintenance
I_a	Accidental history
I_i	Insulation
I_e	Exploration
I_x	Explosion
I_l	Leakage

for all relevant equipment at a particular plant are combined as follows:

$$P_j = \left[\frac{\sum I_i}{n}\right] \times S_j \quad (3)$$

where P_j is the danger value for equipment j, I_i is the index for the jth equipment warning, n refers to the number of equipment pieces at the plant, S_j is the scale factor of the jth piece of equipment during the chemical process (range from 0 to 1), i is the index listed in Table 4, and j is the analyzed equipment number.

The danger index for each piece of equipment is evaluated for each process at the plant. Table 4 summarizes the indices of dangerous equipment. Categories are defined as follows: *maintenance* (I_m) depicts the frequency of overhaul for each piece, *accidental history* (I_a) indicates the number of accidents that have occurred, *insulation* (I_i) is the density of equipment layout, *exploration* (I_e) depicts the really ascertained number of device failures, and *explosion* (I_x) and *leakage* (I_l) represent the danger grade of the chosen equipment. Each index for dangerous pieces of equipment is evaluated according to Table 5. Higher indices indicate more dangerous equipment.

2.2.3. The environmental risk management indices (M)

Some hazardous materials and dangerous equipment are necessary when operating chemical plants. While such material and equipment are integral for the plant, they may contribute to environmental pollution and health damage and thus, an efficient and effective management strategy is required. More effective management strategies will produce a lower likelihood of risk. To evaluate the level of risk management, values for environmental management are combined according to the following equation:

$$M = \frac{\sum I_i \times w_i}{n} \quad (4)$$

where M is the effect of environmental management at the plant, I_i is the index i for management as shown in Table 6, w_i is an appropriate weighting factor for index i, and n is the number of indices.

The indices shown in Table 6 are valued from 1 to 4, with value 1 corresponding to the worst-case scenario and value 4 to the best-case scenario. For instance, I_{em} stands for the complete extent of a plant's environmental management strategy, where 1 refers to the total non-management of an environmental accident and 4 represents a plant having passed ISO14000 certification and perfected an environmental management system aimed at avoiding and alleviating risks.

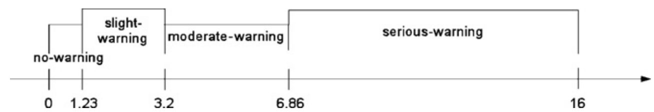

Fig. 2. Intervals of the plant-level early warning system.

2.2.4. Early warning thresholds and corresponding index intervals for a plant

According to Eqs. (1)–(4), a risk early warning index for each plant can be calculated using the warning indices of hazardous materials, dangerous equipment, and environmental management. The E_e index, as defined above, could then be used to warn of potential disasters with sufficient warning time to avoid and mitigate serious effects.

A majority of early warning systems are divided into the four following categories: no-warning, slight-warning, moderate-warning and serious-warning. As mentioned earlier, the value of W is between 0 and 4, P is between 0 and 4, and M is between 1 and 4. Hence, we divide M (Eq. (1) denominator) into four intervals on average, that is 1–1.75, 1.75–2.5, 2.5–3.25 and 3.25–4; and we also divide the molecular results of Eq. (1) into four average intervals, that is 0–4, 4–8, 8–12 and 12–16. In this way, the value of E_e is divided into four intervals, that is $E_{e(1)} = E_{e(\min)} = 0$, if $W = 0$ or $P = 0$ and $M = 4$; $E_{e(2)} = 1.23$, if $W \times P = 4$ and $M = 3.25$; $E_{e(3)} = 3.25$, if $W \times P = 8$ and $M = 2.5$; $E_{e(4)} = 6.86$, if $W \times P = 12$ and $M = 1.75$; $E_{e(5)} = E_{e(\max)} = 16$, only if $W = 4$, $P = 4$ and $M = 1$. The five warning thresholds are then given by the intervals shown in Fig. 2.

2.3. Regional early warning system evaluation

At the regional scale, we define the regional warning indices just as the plant indices. For a geographical plant cluster, there is not only a single plant but also a regional society, economy and ecology. In a small region, the interaction and interdependency between these features characterizes the scale of the environmental risk. Taking into account all of these features would instruct managers on how to avoid and reduce environmental risks by providing proper warnings to regional stakeholders. Therefore, plants,

Table 6
List of warning indices for environmental management.

Component risk warning index	Description	Value range
I_{em}	Degree of environmental management system	1–4
I_{mp}	Emergency preparedness	1–4
I_{rt}	Reaction time	1–4
I_{tr}	Training	1–4
I_{es}	Emergency support	1–4

Table 5
Rating value of danger of equipment.

Dangerous level	No danger	Slight danger	Moderate danger	Serious danger	Severe danger
Attribute value	0	1	2	3	4

Table 7
List of regional risk warning indices.

General index/w	Subsidiary index	Description
Environment index ($E_N I$)	I_{ew}	Wastewater emissions
	I_{ec}	Complexity of wastewater
	I_{ee}	Emissions
	I_{ed}	Dust
	I_{ef}	Environmental function zoning
Economy index ($E_C I$)	I_{cg}	GDP
	I_{ce}	Environmental inputs
Society index ($S_O I$)	I_{sf}	Fire engines
	I_{sh}	Fire hydrant
	I_{sd}	Population density
	I_{ss}	Emergency support
	I_{sp}	Emergency preparedness
Plant index	I_{ei}	Each plant warning level

the society, the economy and the local environment are integrated to provide a multiple environmental risk warning indices system to quantify the regional risk warnings.

In general, risk warning is based on the warning limits defined by decision-makers and it provides warning information for managers. For the purpose of giving risk warning to regional managers, according to the evaluation of plants' risk warning values and regional warning indices, we chose to use interval numbers rather than a single concrete number, which can help represent a more realistic situation. Additionally, it is more rational to perform early warnings by numerical ranges for the warning grading standards due to the fuzzy state of risks.

2.3.1. Interval level numbers

An interval number $x = [x^S, x^E]$ is described by four features, which are left and right bounds x^S and x^E, the interval length $\pi = x^S - x^E$, and the interval mid-point $\varphi = x^S + x^E/2$. To combine the original information carried by an interval number, Zhang et al. [19] proposed the following equation:

$$L(x,y) = \frac{\left|x^S - y^S\right| + \left|x^E - y^E\right| + \left|\pi_x - \pi_y\right| + \left|\varphi_x - \varphi_y\right|}{3} \quad (5)$$

where $L(x, y)$ is the distance between two interval numbers x and y. The distance also satisfies the following properties:

- $L(x, y) \geq 0$;
- $L(x, y) = L(y, x)$;
- $L(x, y) = 0$, if and only if $x = y$.

2.3.2. The regional scale early warning indices

According to the interval numbers, the regional risk warning is constructed with an evaluation function by using the indices shown in Table 7. The regional risk warning indices consist of four general indices, with each index composed of subsidiary indices. These four general indices are the Environment index ($E_N I$), Economy index ($E_C I$), Society index ($S_O I$) and plant index (I_{ei}).

For the plant early warning indices (I_{ei}), the plant scale in regional indices as a partition could be calculated as:

$$I_{ei} = \prod_{i=1}^{n} Ee_i^{w_i} \quad (6)$$

where Ee_i is calculated by Eq. (1), w_i refers to the weight of plant i in the entire cluster, and n is the number of plants.

Due to the different corresponding levels for plant warning indices, we also use four different corresponding levels to provide for a continuous and convenient set of calculations. There are four corresponding levels for each index, as shown in Table 8. Each level could be either an interval number or a single number. Therefore, according to Eq. (7), each value of the corresponding linear weights of different levels can be calculated as:

Table 8
Rating value of regional warning.

Response level	No warning	Slight warning	Moderate warning	Serious warning
Attribute value	1	2	3	4

$$e_{ij} = \frac{L(x, x_j)}{L_j} \quad (7)$$

where x_j is the standard value of the early warning indices for the corresponding level, j refers to the early warning level of 1–4, $L(x, x_j)$ is the distance between the evaluated elements x and x_j, L_j is the distance between the no warning and serious warning levels for index i, and both $L(x, x_j)$ and L_j can be calculated according to Eq. (5).

$$E_i = \sum_{i=1}^{n} w_i e_{ij} \quad (8)$$

The linear weights are evaluated using Eq. (8), where n is the number of indices used, and w_i is the weight of the evaluated index i and should satisfy that normalization condition $\sum_{i=1}^{n} \omega_i = 1$.

An integrated distance measure is constructed using the linear weight function. The smaller the distance value, the closer between warning elements and the corresponding level. For our final results of the regional early warnings, the level corresponding to the smallest distance is the regional warning level.

3. Application

To illustrate our warning system method, we selected a typical scenario for industrial processes. In this case, there is a plant cluster of pesticide companies located along the Yangtze River and to the north of Jiangsu province, China. There are five plants in this geographical area, as shown in Fig. 3. The plants congregate in a chemical industry cluster to obtain more efficient production. According to Section 2 above, we will provide risk warnings on an enterprise scale for each of these five plants and on regional scales for the entire area.

3.1. Display of enterprise-scale

According to the hazardous materials used in each plant, we can obtain the index values of these materials from Eq. (2). Taking plant 3 as an example, the relevant hazardous materials are listed in Table 9. The 15 critical pieces of equipment for plant 3 are calculated according to Eq. (3) and yield the results listed in Table 10. The last component of Eq. (1), the index value of risk management, is

Table 9
List of used materials in plant 3.

Hazardous materials	Index value
Chlorhydric acid	0.37681
Dimethyl phosphonate	0.23550
Chlorine	0.22043
Phosphorus trichloride	0.21195
Methyl alcohol	0.18464
Phosphorous acid	0.07065
Chloromethane	0.07065
Yellow phosphorus	0.05613
Concentrated sulfuric acid	0.01472
Sum	1.44148

Fig. 3. Location map of case study.

Table 10
Example of critical equipment in plant 3.

Esterification reactor	Value	*S*	*P*
Maintenance	3	0.9	2.54
Insulation	4		
Exploration	2		
Explosion	1		
Leakage	2		

calculated using Eq. (4) with results listed in Table 11. Values for the four other plants in the chemical industry cluster can also be calculated in this manner.

The method of mapping risk warning level is applied for this chemical industry cluster. The study area is divided into hundreds of meshes with a size of 0.00005 × 0.00005° (a unit of latitude and longitude) (see Fig. 4). The ArcGIS system is an integrated geographic information system (GIS) that provides a framework for implementing GIS for users. The version of ArcGIS 9.2 is used to build a geodatabase and carry out spatial analysis, including buffer analysis and union analysis [20]. To isolate the hazardous materials and dangerous equipment profile of impacted areas, the values of the indicators are calculated according to Eqs. (2) and (3) for each mesh. The value of environmental management index is assigned uniformly for each plant in the map due to the same management system of each plant. Then the index values of hazardous materials, dangerous equipment, and environmental management are integrated to obtain a composite index score for each mesh, which represents an aggregate risk early warning level for each mesh of the five plants in the chemical industry cluster (see Fig. 4). Each mesh in the research area can be examined independently and can immediately and directly alert the environmental risk to the emergency response agencies and personnel.

On the basis of Eq. (1) and the values for each variable, we can obtain the mean values of risk early warning for each plant in the chemical industry cluster as listed in Table 12. According to the interval of warning levels at enterprise scales (see Fig. 2), we can recognize that the risk warning level of plant 5 is at the minimum

Table 11
Index value of risk management of plant 3.

Management	Value	*w*	*M*
Degree of environmental management system	2	0.2	2
Emergency preparedness	2	0.3	
Reaction time	3	0.2	
Training	1	0.2	
Emergency support	2	0.1	

Table 12
Warning level of each plant and the aggregate results.

Plant	E_e	Warning level	Plant assets (billion yuan)	*w*
1	4.53777	Moderate warning	3.5	0.175
2	1.37435	Slight-warning	5.4	0.270
3	1.83069	Slight-warning	3.0	0.150
4	7.15187	Serious warning	6.3	0.315
5	0.98159	No-warning	1.8	0.090
Aggregation of five plants				
I_{ei}	2.88	Slight-warning	20.0	1.000

Table 13
Standard intervals for regional warning indices.

Index	1	2	3	4
Wastewater emissions/*t*	<1000	(1000, 5000]	(5000, 10,000]	>10,000
Complexity of wastewater	None	Simple	Mid	Complex
Emissions/m^3	<1	(1, 100]	(100, 1000]	>1000
Dust/*t*	<0.001	(0.001, 0.01]	(0.01, 0.1]	>0.1
Environment function zone	Key protection zone	Common protection zone	Common control zone	Key control zone
GDP/dollar	Poor	Developing	Mid developed	Developed
Environmental inputs/%	>8%	(3%, 8%]	(1%, 3%]	<1%
Fire engines	>4	[3, 4]	[1, 2]	0
Space between fire hydrants/m	<20	(20, 40]	(40, 60]	>60
Population density	No residents	Low	Mid	High
Emergency support	Abundant	Basic	Scarcity	None
Emergency preparedness	Complete system	Basic system	Initial system	None
Each plant warning level	[0, 1.23)	[1.23, 3.2)	[3.2, 6.86)	[6.86, 16]

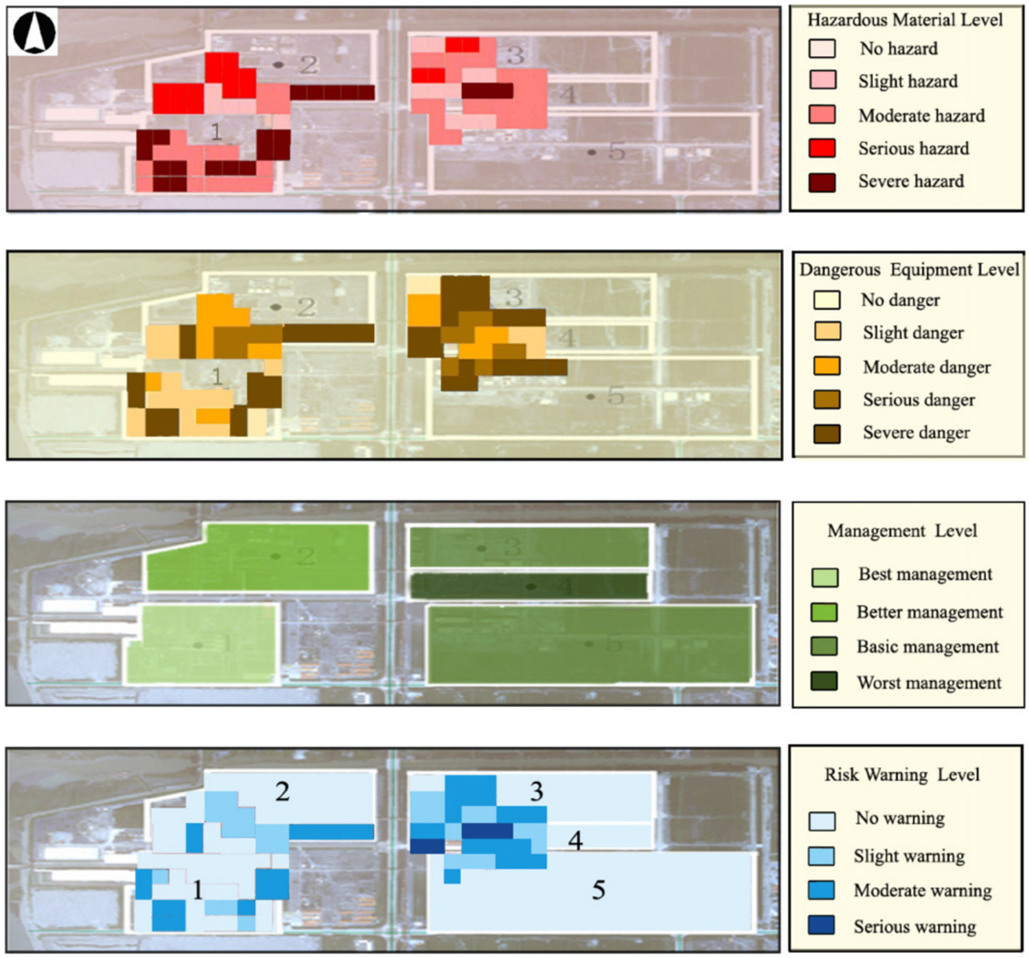

Fig. 4. Hazardous material level, dangerous equipment level, management level and the aggregate risk warning level of each plant in the chemical industry cluster.

(no-warning), while plant 4 is at the maximum risk warning level for the cluster.

3.2. Display of regional scale

Using the interval numbers method mentioned above, we can also obtain warning values on the regional scale. The intervals of standard indices are displayed in Table 13, and the weight assignments of indices are shown in Table 14, which are designed according to comprehensive consideration of ten experts' recommendations. To illustrate the calculation process of regional warning indices, we use two standard indices—*Wastewater emissions and Plant warning level*, as an example (see Table 15). There are four ranks for each index. For *Wastewater emissions*, this research area has approximately 2000–3000t. Notes the maximum of interval for open interval is 1.5 times than the left bound, so the maximum standard interval of *Wastewater emissions* should be (10,000, 15,000]. Then, $x_{max} = [x^S, x^E] = [10{,}000, 15{,}000]$, $y = [y^S, y^E] = [2000, 3000]$, and the $L(x_{max}, y)$ can be calculated with Eq. (5). Other values can be calculated with Eqs. (5), (7) and (8) as shown in Tables 15 and 16. According to Table 12 and Eq. (6), we calculate I_{ei} to be 2.88, and the w values in Eq. (6) are assigned with the scales of plants assets. The results of the *Plant warning level* also can be seen in Tables 15 and 16. E represents the distance from the target, and a smaller value for E indicates a closer distance from the target. In the results of the regional scale, the lowest value (0.0218) of the index plant warning level for all plants is in the rank of E2, which represents slight-warning. Also, the index of the environmental inputs represents the investment of environmental protection, including equipment, personal training, etc. The lowest value (0.0257) of this index is in the rank of E4, which represents a level of serious-warning. The lowest values of the other indices are mainly concentrated in the rank of E2 and E3. Therefore, as calculated using Eq. (8), the regional early warning value

Table 14
Weight assignments of regional risk warning indices.

General index/w	Subsidiary index/w'	Final weight
Environment index/(0.3)		
	Wastewater emissions/(0.33)	0.099
	Complexity of wastewater/(0.33)	0.099
	Environmental function zoning/(0.33)	0.099
Economy index (ECI)/(0.3)	Environmental inputs/(1.0)	0.3
Society index (SOI)/(0.2)		
	Fire engines/(0.2)	0.04
	Fire hydrant/(0.2)	0.04
	Population density/(0.2)	0.04
	Emergency support/(0.2)	0.04
	Emergency preparedness/(0.2)	0.04
Plant index/(0.2)	Each plant warning level/(1.0)	0.2

Table 15
Example of the step results for regional warning indices.

Index	Standard interval	1	2	3	4
I_{ew}	Wastewater emissions	<1000	(1000, 5000]	(5000, 10,000]	>10,000
I_{ei}	Plant warning level	[0, 1.23)	[1.23, 3.2)	[3.2, 6.86)	[6.86, 16]
Index	Regional value	e1	e2	e3	e4
I_{ew}	(2000, 3000)/*t*	0.1500	0.1625	0.4750	0.8500
I_{ei}	2.88	0.0199	0.0109	0.0249	0.0861
Index	Weight	E1	E2	E3	E4
I_{ew}	0.099	0.0149	0.0161	0.0470	0.0842
I_{ei}	0.2	0.0397	0.0218	0.0498	0.1722

Table 16
Results of regional warning values.

Index	E1	E2	E3	E4
Wastewater emissions	0.0149	0.0161	0.047	0.0842
Complexity of wastewater	0.066	0.033	0	0.033
Environmental function zoning	0.033	0	0.033	0.066
Environmental inputs	0.231	0.138	0.0766	0.0257
Fire engines	0.0133	0	0.0133	0.0267
Fire hydrant	0.0078	0.0156	0.0273	0.0400
Population density	0.0267	0.0133	0	0.0133
Emergency support	0.0133	0	0.0133	0.0267
Emergency preparedness	0.0133	0	0.0133	0.0267
Plant warning level	0.0397	0.0218	0.0498	0.1722
Total				
E	0.4590	0.2378	0.2736	0.5145

for the environmental risk of the chemical industry cluster is a slight-warning, but this value is also very close to the standard of moderate-warning (see Table 16).

4. Discussion and conclusion

In this paper, we have proposed a feasible method for quantifying and comparing risk levels for industrial plants and surrounding regions. In our specific example of a cluster of five plants, plant 5 has the lowest risk and plant 4 has the highest risk, plant 2 and plant 3 are in the slight-warning risk level and plant 1 is in the moderate-warning risk level. These results indicate that the risk levels of the five plants are significantly different. The index values for each plant could be compared to reveal any intrinsic deficiencies. For instance, chlorhydric acid, dimethyl phosphonate, and chlorine are the most notable hazardous materials for processes in plant 3, and it is critical to improve the manner and timing of staff training and reinforce the emergency preparedness for risk management. Simultaneously, the mean value of the risk warning level for plant 5 is no-warning due to its low hazardous materials level and dangerous equipment level, while the risk warning level for plant 4 is serious-warning due to it having the worst risk management level.

Although the regional early warning level is a slight-warning, this value is close to the standard of moderate-warning. The complexity of wastewater is at a moderate-warning level, indicating that governors of the region should heed notice on this issue. Also, the regional authorities should pay greater attention to safety measures and adopt specific measures such as cleaner and safer facilities and holding lectures and staff training sessions about environmental safety. Furthermore, the serious-warning level of the environmental inputs indicates that the local government should pay more attention to the investment of risk management.

The warning system outlined here provides an effective approach for assessing and quantifying environmental risk of a single enterprise and for an industrial cluster. The framework of the early warning system identifies sources of risk, estimates the likelihood of risk on both the enterprise and regional scales, analyzes the risk levels, and constructs the proper alert status. The estimated indices are then used as criteria for the environmental risk warning level due to the presence of hazardous materials, dangerous equipment, and management procedures of a given plant. Also, according to the risk value on the enterprise scale, one can construct an early warning level on the regional scale for the local society, environment, and economy and for other plants in the area. This approach could also permit us to set reference values of the indices for different processes or industrial regions, constituting a comparison method for environmental risk. Further, the application of interval numbers could display the consequences more realistically than single numbers by reference distances and comparisons between each distance could be used to identify the deficiencies of the corresponding early warning elements.

However, such a methodology relies heavily on the quality of the data, such as the availability of the data about hazardous materials and dangerous equipment of the study region and the reliability of the data from various stakeholders (industrial enterprises may provide false data to avoid their risk responsibility). Meanwhile, the method only provides a first rough scan of the risks produced by the plants based on comparatively simple calculations of hazard parameter values, but does not consider the occurrence of some complex situations, such as domino effects of one part of a plant to another or of one plant to another. Besides, some important indices related to the risk warning level may be omitted. Therefore, all of these issues must be considered to make this methodology applicable and practical to scientists and other stakeholders.

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