Original Research

Research on the Spatiotemporal Evolution and Influencing Factors of Sudden Environmental Incidents in China from 2008 to 2021

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Abstract

Based on the statistical data of sudden environmental incidents in 31 provinces, municipalities, and autonomous regions in China from 2008 to 2021, the spatiotemporal evolution characteristics and influencing factors were analyzed by employing regression analysis, exploratory spatial analysis, and geographic detectors, aiming to provide references for the construction of ecological civilization. The results demonstrate as follows: (1) The quantity of sudden environmental incidents in China exhibited an inverted V-shaped structure with 2013 as the turning point, showing an overall decreasing trend, and the occurrence frequency of sudden environmental incidents significantly decreased after 2014. (2) The months with the highest occurrence frequency of sudden environmental incidents were July and August, followed by May and June, while the lowest occurrence frequency months were November and December. (3) The frequency distribution was uneven, with the highest frequency in the eastern coastal comprehensive economic zone and the lowest frequency in the northeastern comprehensive economic zone. The hotspots and coldspots of sudden environmental incidents in provinces revealed that the H-H region first increased, then decreased, the L-L region had relatively more events, the L-H region remained relatively stable, and the H-L region exhibited a fluctuating pattern of decreasing, then increasing, and then decreasing again. (4) The total population, GDP per capita, and the added value of the secondary industry were the main driving factors for sudden environmental incidents in China based on geographical detector analysis, while the level of pollution control and the legal environment played a suppressive role in the occurrence of sudden environmental incidents. The occurrence of sudden environmental incidents is the result of the comprehensive effects of multiple factors.

Keywords: Sudden environmental incidents, spatio-temporal evolution, exploratory spatial data analysis, influencing factor

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Introduction

Sudden environmental incidents refer to events that are caused by factors such as pollution discharge, natural disasters, and production safety accidents that result in toxic and harmful substances such as pollutants or radioactive materials entering the environment, such as the atmosphere, water bodies, soil, etc. They can lead to sudden environmental quality degradation, endangering public health and property safety, or causing ecological environmental damage or significant social impact, requiring emergency measures to be taken [1]. In recent decades, as China's economy and society have developed, environmental risk and hazard problems have become more prominent, with various sudden environmental pollution incidents occurring frequently. While the total number of sudden environmental incidents has decreased significantly and stabilized, the high-risk situation of frequent sudden ecological environmental incidents has not fundamentally changed [2], and the spatial distribution of incidents exhibits obvious regional clustering characteristics, with the environmental emergency situation still remaining severe [3]. Due to the high randomness, high destructiveness, and uncertainty of sudden environmental incidents, especially major events that seriously threaten public health and property safety, China's ecological civilization construction process has been greatly affected. Studying the spatiotemporal evolution characteristics and influencing factors of environmental pollution incidents and effectively preventing and responding to sudden environmental incidents is a challenging and recurring academic research topic.

Research on sudden environmental incidents has achieved remarkable results both domestically and internationally. Developed countries such as the United States and Japan have started studying emergency prevention and response to sudden environmental incidents since the early 20th century. Developed countries in Europe and America have established comprehensive environmental management systems in terms of emergency management [4]. These systems include risk assessment and policy management systems, multi-level coordinated emergency response systems, and information exchange systems, which provide a basis for emergency decision-making regarding sudden environmental incidents [5]. Most domestic scholars study sudden environmental incidents from two angles. The first aspect is the research on the response to sudden environmental incidents. Since The State Council of China promulgated a contingency plan for environmental emergencies in 2006, it has initially formed a risk emergency management system for sudden environmental incidents [6]. Some scholars have conducted research on emergency monitoring, risk assessment [7], pollution tracing [8], early warning response [9], damage assessment [10], emergency management, impact and assessment [11], and issues

and prevention in response to sudden environmental incidents [12]. The main viewpoints proposed are as follows: sudden environmental incidents exhibit complex situations, multiple types, complex causes, and high public attention, presenting a high-frequency and high-risk situation. The successful experience in dealing with sudden environmental incidents includes solid grassroots environmental emergency preparedness, an efficient and smooth emergency command system, a sound early warning and control system, strong technological support and material storage and transportation guarantees, and a sound information disclosure mechanism. Secondly, the study of the characteristics of sudden environmental incidents: the methods of spatial autocorrelation and spatiotemporal geographically weighted regression models were used to analyze the spatial dependency relationship and spatiotemporal heterogeneity of sudden environmental incidents [13]. GIS and non-parametric correlation analysis methods were used to analyze the dynamic change trends and spatial distribution of environmental pollution and damage accidents in China [14]. The methods of ESDA and Matlab spatial panel econometric models were used to analyze the spatiotemporal evolution characteristics and influencing factors of environmental pollution incidents that occurred in various regions of China from 1995 to 2012 [15]. Origin software was used to statistically analyze 3,203 sudden environmental incidents in China from 2011 to 2017, which were from six aspects, the overall trend of sudden environmental incidents shows a downward trend over time, the high-frequency risk areas in space gradually decrease, and the high-frequency areas are concentrated in the Pan-Pearl River Delta region. Water pollution and air pollution are the main accident types.

In summary, previous research has mainly focused on the event response and evolutionary characteristics of sudden environmental incidents. However, there is a clear lack of research on the influencing factors and distribution characteristics of regional sudden environmental incidents. Therefore, the research aims to explore the spatiotemporal evolutionary characteristics and influencing factors of sudden environmental incidents in China from 2008 to 2021 through geographic exploratory analysis and geographic detector analysis. The goal is to provide a new perspective for studying changes in human-environment systems and offer decision-making references for China's ecological civilization construction in the new development stage.

Materials and Methods

Data Sources

The research selected 31 provinces, autonomous regions, and municipalities in China as the research area. Due to reasons such as missing statistical data, the scope of the study temporarily does not include Hong

Kong, Macao, or Taiwan Province. The data used in the study on the number of sudden environmental incidents and other related economic indicators primarily comes from the China Statistical Yearbook [16] and China Environmental Statistics Yearbook [17] for the years 2009 to 2022. The specific occurrence time data for the sudden events is sourced from domestic emergency environmental incidents excerpted from the Journal of Safety and Environment from 2008 to 2021.

Research Methods

Exploratory Spatial Data Analysis

Exploratory Spatial Data Analysis (ESDA) involves measuring the global spatial autocorrelation index (Moran's I) and local spatial autocorrelation index (Moran scatterplot) to analyze the spatial autocorrelation of sudden environmental incidents from 2008 to 2021 in China.

(1) Global spatial autocorrelation: Moran's I index is used to analyze the overall level of the spatial autocorrelation of sudden environmental incidents, reflecting the clustering and correlation degree of variables. The formula is as follows:

$$I = \frac{n\sum_{i}\sum_{j}w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\left(\sum_{i}\sum_{j}w_{ij}\right)\sum_{i}(x_i - \bar{x})^2} \tag{1}$$

In the formula, *I* is the global Moran's I index, n is the total number of provinces and regions (n =3 1 in the research), x_i and x_j are the sudden environmental incident counts of provinces i and j, respectively. w_{ij} is the spatial weight matrix obtained through the nearest neighbor classification algorithm based on the adjacency relationship. The value of *I* ranges between -1 and 1. If *I*<0, it indicates a negative spatial correlation among sudden environmental incidents in the provinces. If *I*>0, it indicates a positive spatial correlation among sudden environmental incidents in the provinces. If *I* = 0, it indicates that sudden environmental incidents are randomly distributed among provinces. The significance level test was conducted through the Monte Carlo method using Geoda software [18].

(2) Local spatial autocorrelation: Global spatial autocorrelation reflects the spatial differentiation level of variables at the national level and cannot reflect the local spatial differentiation and changes of provinces [19]. Thus, Moran scatterplots and local Moran's I statistics are employed for local spatial autocorrelation methods to examine the spatial interaction relationship between adjacent geographic units at the provincial level. The Moran scatterplot describes the correlation between the variable and its spatial lag vector and reflects the degree of correlation and difference among spatial unit observation values. It consists of four quadrants, including H-H (High-High) indicates that the values

of sudden environmental incidents are both high in its neighboring provinces and in itself. H-L (High-Low) indicates that the value of sudden environmental incidents is high in the self-province but low in neighboring provinces, L-H (Low-High) indicates that the value of sudden environmental incidents is low in the self-province but high in neighboring provinces, L-L (Low-Low) indicates that the values of sudden environmental incidents are both low in neighboring provinces and themselves.

Geographical Detector

Geographical Detector is used to explore the spatial differentiation pattern of certain geographic attributes and their explanatory factors. The core idea is based on the hypothesis that if a variable has a significant impact on another variable, the spatial distributions of both variables should be similar. Geographical Detector can not only detect numerical data but also qualitative data, which is its significant advantage [20]. The research used a Geographical Detector to explore the influencing factors of the spatial differentiation pattern of sudden environmental incidents in China from 2008 to 2021. The model is as follows:

$$p = 1 - \frac{1}{\sigma^2}\sum_{h=1}^{L}N_h\sigma_h^2 \tag{2}$$

In the formula, h (h = 1, 2,..., L) is the layer of the dependent variable Y or detecting factor X, which is the variance of sudden environmental incident density in the first-level region (the whole country) or second-level region (province h). N and N_h are the number of units in the whole country and province h, respectively. P is the detecting power value of a certain detecting factor X, with a value range of [0, 1]. The larger the P value, the greater the influence of the detecting factor on the spatial distribution of sudden environmental incidents [21].

To investigate the driving factors affecting the spatial distribution of sudden environmental incidents' occurrence, the research selected five indicators from four dimensions: population, level of economic development, level of pollution control, and legal environment. The specific data item description is shown in Table 1.

Results and Discussion

Temporal Characteristics of Sudden Environmental Incidents

Overall Temporal Variation of Sudden Environmental Incidents

Over the past 14 years, the number of sudden environmental incidents has shown an increasing

Table 1. Exploratory factors of the frequency of sudden environmental incidents in China from 2008 to 2021.

Influencing factor	Impact factors	Code	Grading
Population	Year-end population	X_1	5
Level of economic development	GDP per capita	X_2	5
	Added value of secondary industries	X_3	5
Level of pollution control	The ratio of total investment in industrial pollution source control to GDP	X_4	5
Legal environment	Development of market intermediary organizations and legal system environment index	X_5	5

and then decreasing trend, with an overall downward trend (Fig. 1). The maximum and minimum values occurred in 2013 and 2021, with 712 and 199 incidents, respectively. The range is 513 incidents. Furthermore, there was a significant change in the total number of sudden environmental incidents in 2013, dividing the data into two periods. Linear regression analysis shows that from 2008 to 2013, the total number of sudden environmental incidents in China increased significantly (48 per year). The regression equation passed the 0.05 significance level test, with an average of 518 incidents per year. The total number of sudden environmental incidents in China decreased significantly (32 incidents per year) from 2014 to 2021. The regression equation passed the 0.01 significance level test, with an average of approximately 296 incidents per year.

The turning point was the year 2013, and the total number of sudden environmental incidents decreased significantly after 2013. This may be related to the issuance of the National Ecological Protection for Twelfth Five-Year Plan by the Ministry of Environmental Protection in January 2013. The plan clarified the responsibilities of various departments, started to strengthen the construction of ecological monitoring and evaluation systems, initiated ecological environmental quality assessment in disaster-prone areas at the county level, conducted comprehensive surveys and assessments of the ecological environmental situation in disaster-prone areas, proposed integrated measures for ecological disaster reduction for mountainous geological disasters such as floods, flash floods, debris flows, landslides, and collapses, ensured the ecological safety of disaster-prone areas, strengthened ecological environmental regulation in resource development and infrastructure construction, and played an important role in preventing sudden environmental incidents and reducing their impact. This is a significant reason for the significant decrease in the total number of sudden environmental incidents in China after 2014.

Overall Temporal Variation of Sudden Environmental Incidents

Due to adjustments in statistical yearbook indicators, the Ministry of Environmental Protection did not categorize sudden environmental incidents during the period of 2008-2010. Therefore, an analysis of the time characteristics of different levels of sudden environmental incidents between 2011 and 2021 has been conducted (Fig. 2).

There were no particularly serious environmental incidents in China between 2011 and 2021, and the trend was positive. The occurrence of major environmental incidents decreased at a rate of 0.6818 per year and passed the 0.05 level of significance test. The frequency of significant environmental incidents
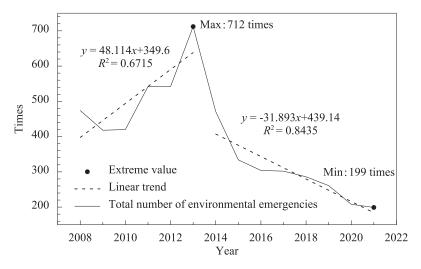

Fig. 1. Temporal variation trend of sudden environmental incidents in China from 2008 to 2021.
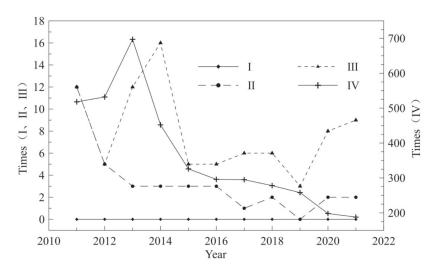
Fig. 2. The time trend of sudden environmental incidents of different levels in China from 2001 to 2021.
Annotation: Extraordinarily Serious Environmental Emergencies (I); Serious Environmental Emergencies (II); Comparatively Serious Environmental Emergencies (III); Ordinary Environmental Emergencies (IV)

varied considerably from year to year, with a peak of 16 incidents in 2014 and a minimum of 3 incidents in 2019, resulting in a range of 13 incidents. The overall trend showed a decreasing pattern at a rate of 0.4455 per year based on linear fitting, but the regression equation did not pass the significance level test. The frequency of general environmental incidents was relatively high, with a peak of 697 incidents in 2013 and a minimum of 188 incidents in 2021, resulting in a range of up to 509 incidents. The overall change showed a significant decrease at a frequency of 42.564 incidents per year,

and the regression equation passed the 0.01 level of significance test.

Changes in the Number of Sudden Environmental Incidents in China's Eight Major Economic Zones

Due to the similarities in natural conditions, economic relations, spatial location, and social structure in different regions, it may have an impact on the frequency of the occurrence of sudden environmental incidents. Therefore, we analyzed the eight economic

Table 2. The number of sudden environmental incidents in eight major economic zones from 2008 to 2021.

Year	Northeast region	Northern coast region	East coastal region	South coastal region	Mid-yellow river	Middle yangtze river	Southwest region	Northwest region
2008	18	57	161	5	37	74	76	46
2009	6	54	178	23	29	39	51	38
2010	13	37	203	6	41	67	33	20
2011	9	61	255	35	52	36	82	12
2012	16	39	292	29	47	28	66	25
2013	13	24	429	22	152	21	52	26
2014	5	20	205	46	96	22	37	40
2015	13	32	59	50	71	41	43	21
2016	16	21	32	39	62	55	52	27
2017	15	21	21	67	57	43	51	27
2018	14	38	17	49	52	41	45	30
2019	10	31	19	35	53	58	40	15
2020	6	14	22	31	34	31	42	28
2021	9	5	19	30	52	29	30	26
Total	163	454	1912	467	835	585	700	381

regions in China as geographical units based on the Development Research Center of the State Council's classification in regional coordinated development strategy and policy. The study examined the regional characteristics of the total number of sudden environmental incidents in the eight economic regions from 2008 to 2021.

It can be seen that there were significant changes in the number of sudden environmental incidents in China from 2008 to 2021 (Table 2). The changes in the Eastern Coastal Comprehensive Economic Zone were particularly significant, with a difference of about 200 incidents around the year 2014. In the past 14 years, the total number of sudden environmental incidents in the Eastern Coastal Comprehensive Economic Zone accounted for 34.78% of the total number in the country, followed by the Yellow River Middle Reaches Comprehensive Economic Zone, which accounted for about 15.19%. The economic zone with the least proportion is the Northeast Comprehensive Economic Zone, accounting for about 2.97%. The range is 1749 incidents, reflecting a significant spatial imbalance characteristic.

Distribution Characteristics of the Occurrence Time of Sudden Environmental Incidents

Combining the detailed statistical information on sudden environmental incidents in each month provided in the Journal of Safety and Environment, this article divided the whole year into six periods according to their occurrence time to analyze the time characteristics of sudden environmental incidents.

It was found that the months with the most sudden environmental incidents during the study period were July and August, accounting for about 23.01% of the total occurrences, followed by May and June, accounting for about 21.11%. The time period with the least number of incidents was from November to December, accounting for 12.29% of the total occurrences, with a range of up to 10.82%. The statistical data on the occurrence month showed that the number of sudden environmental incidents from May to August accounted for 44.12% of the total. Emergency prevention, management, and monitoring measures should be strengthened during this period to reduce the damage.

The Spatial Characteristics of Sudden Environmental Incidents

Spatial Characteristics of Sudden Environmental Incidents

The occurrence of sudden environmental incidents was processed using image processing techniques in ArcGIS software from 2008 to 2021. The number of sudden environmental incidents in each region was classified into five levels each year, ranging from the high-frequency zone (50-300 incidents) to the medium-high frequency zone (15-50 incidents), the medium-low frequency zone (7-15 incidents), the low-frequency zone (0-6 incidents), and data unavailable zone. Every five years, starting from 2008 (Fig. 3a), 2013 (Fig. 3b), 2018 (Fig. 3c), and 2021 (Fig. 3d), were selected as time sections for analysis.

There were 15 or more sudden environmental incidents occurring in 9 provinces, 7 provinces, 7 provinces, and 3 provinces among the four selected time points (Fig. 3). The high-frequency area of sudden environmental incidents is gradually decreasing, and there are no high-frequency areas in 2018 and 2021. The mid-low-frequency area increased in 2013. The provinces experiencing sudden environmental incidents showed a spreading trend from the eastern and central parts to the northwest region from 2008 to 2013. In 2013, Shanghai had the highest number of sudden environmental incidents, with 251 occurrences, while the lowest occurrence was 0. The main occurrence of sudden environmental incidents was concentrated in the central region, with fewer occurrences in the northwest and northeast regions, showing an aggregated pattern in 2008 and 2018. The distribution of sudden environmental incidents was relatively even in the western, central-eastern, and southern regions, with a relatively weaker aggregated pattern in 2013 and 2021.

The Overall Spatial Distribution Characteristics of Sudden Environmental Incidents

The occurrence of sudden environmental incidents was analyzed in two stages based on changes in time from 2008 to 2021, and the average number of events occurring during each stage was calculated and analyzed with the characteristics of changes in time (Fig. 4).

In the first stage, the highest frequency of sudden environmental incidents occurred in the eastern coastal region from 2008 to 2013 (Fig. 4a), accounting for 48.42% of China, with Jiangsu and Zhejiang provinces having relatively high frequencies of 42.83% and 38.17%, respectively. The Yellow River middle reaches and the Southwest region followed, accounting for 11.41% and 11.48%, respectively. The northeastern region had the smallest proportion at only 2.39%, with Shanghai having the highest frequency of sudden environmental incidents, with an average of 167.5 times per year during this period. In the second stage, which was from 2014 to 2021 (Fig. 4b), the highest frequency of sudden environmental incidents occurred in the Yellow River middle reaches, accounting for 20.19%, followed by the eastern coastal and southwestern regions, accounting for 16.67% and 14.34%, respectively. The proportion in the northeastern region remained the smallest, at 3.73%. During this period, Shaanxi province had the most frequent occurrence of sudden environmental incidents, with an average of 36.125 times per year, and Guangdong province showed a significant increase in sudden environmental incidents, increasing by 29.375 times per year compared to the first stage.
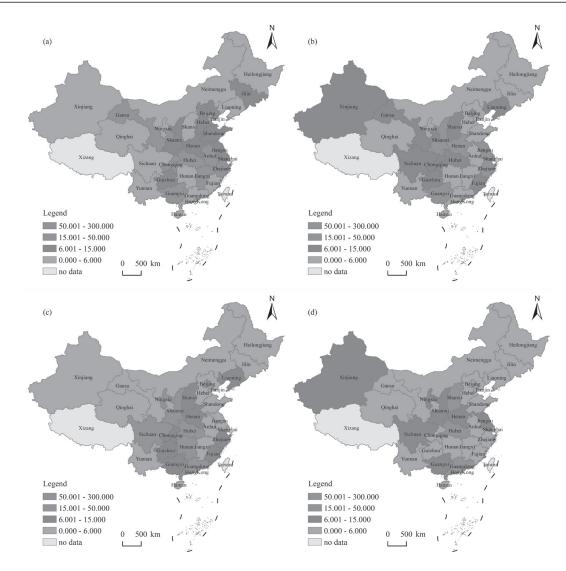
Fig. 3. The spatial distribution characteristics of sudden environmental incidents in China from 2008 to 2021.GS (2022)1873.
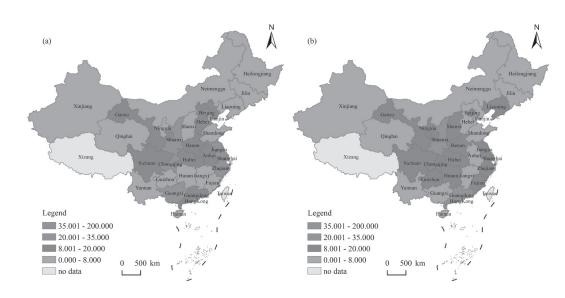

Fig. 4. The spatial distribution characteristics of sudden environmental incidents in China from 2008 to 2013 and from 2014 to 2021. GS (2022)1873.

Overall, the frequency of sudden environmental incidents in each province decreased during the second stage compared to the first stage. The eastern coastal region showed a significant decrease in spatial distribution, while Shanxi and Guangdong provinces showed gradual increases. In the first stage, the occurrence of sudden environmental incidents showed a large difference among provinces and was unevenly distributed, while in the second stage, the frequency of sudden events was relatively stable and the distribution among provinces was relatively balanced.

The Overall Spatial Distribution Characteristics of Sudden Environmental Incidents

The global Moran's I index, significance level, and z-values of the sudden environmental incidents from 2008 to 2021 were calculated using the software of Geoda (Fig. 5).

Based on the analysis of the temporal patterns, the overall Moran's I index, significance level, and z-values can be roughly divided into two stages. In the first stage, from 2008 to 2013, Moran's I index was significant at the 0.1 level except for 2008, with z-values greater than 1.65. Sudden environmental incidents tended to exhibit a clustered distribution, with Moran's I index being greater than 0. Therefore, during this stage, there was a significant positive spatial autocorrelation of sudden environmental incidents. The second stage is from 2014 to 2021. The significance level of the Moran's I index was all greater than 0.1, indicating that it did not pass the significance test and that sudden environmental incidents exhibited a random distribution. The z-values were all less than 1.65 and not less than -1.65, suggesting that sudden environmental incidents in this stage tended to occur randomly. However, Moran's I index was greater than 0 from 2016 to 2019, indicating a positive spatial autocorrelation of sudden environmental incidents during those years.

In the past 14 years, sudden environmental incidents showed spatial positive autocorrelation and the spatial

clustering of interprovincial sudden environmental incidents was enhanced during these years, except for 2015, 2020, and 2021. According to the changes in the global Moran's I index, significance level, and z-values, it can be concluded that sudden environmental incidents were not completely random in terms of spatial distribution and had significant correlations over the past 14 years.

The Local Spatial Relationship Changes to Sudden Environmental Incidents

The phase characteristics were analyzed based on the global Moran index of sudden environmental incidents in China from 2008 to 2021. The local spatial autocorrelation analysis of sudden environmental incidents was conducted at four time points, which were 2008, 2013, 2018, and 2021. It was shown that the spatial visualization of the four types of clustering in the Moran scatter plots of China's sudden environmental incidents (Fig. 6).

It can be seen that the H-H region increased from 3 provinces in 2008 and 2013 to 8 provinces in 2018 and then decreased to 3 provinces in 2021, indicating that the spatial clustering ability of sudden environmental incidents increased and then decreased after stabilizing. The spatial clustering of sudden environmental incidents was strongest in 2008 and 2013, mainly concentrated in coastal areas such as Shanghai, Zhejiang, and Jiangsu, which may be related to the large number of heavy chemical enterprises in Shanghai and surrounding areas or natural disasters such as typhoons and heavy rains in coastal areas. The L-L region had relatively more provinces, mainly concentrated in regions with relatively backward industrial development levels, such as the Western Economic Region and the Southwest Economic Region, which may be related to the extensive methods used in industrial development in these provinces. The provinces in the L-H region had basically no change in the number of sudden environmental incidents. The provinces in the H-L region showed a trend of

Fig. 5. Global Moran's I index, significance level, and z-values of sudden environmental incidents in China from 2008 to 2021.
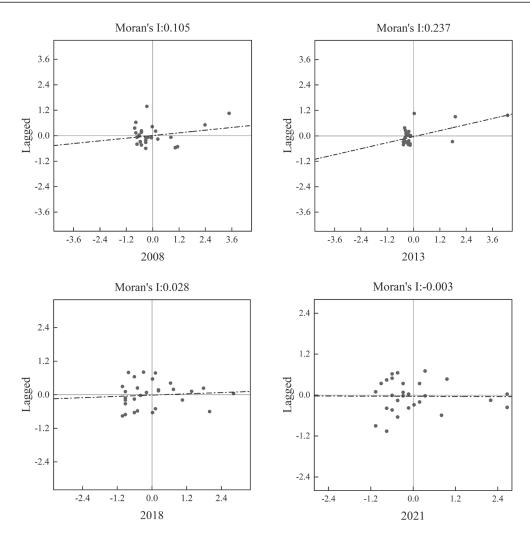
Fig. 6. Moran scatter plot of sudden environmental incidents in China from 2008 to 2021. (Normalized values of sudden environmental incidents in 2008, 2013, 2018, and 2021, respectively).

decreasing, then increasing, and then decreasing in the number of sudden environmental incidents, indicating that the spatial heterogeneity of sudden environmental incidents was weakening overall.

Analysis of Factors Influencing Sudden Environmental Incidents

Overall Spatial Distribution of Sudden Environmental Incidents

Combining spatial analysis results, the spatial distribution differences without considering temporal variations were plotted using ArcGIS software for the nationwide distribution of the number of sudden environmental incidents from 2008 to 2021 (Fig. 7).

It can be observed that in the past 14 years, sudden environmental incidents in China showed an overall distribution pattern of more in the south and less in the north, more in the east, and less in the west. The areas with higher frequencies of events were mainly concentrated in the southeastern part of China. Shanghai had the highest number of sudden environmental
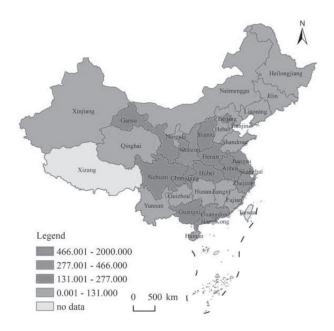

Fig. 7. The spatial distribution of the total number of sudden environmental incidents in China from 2008 to 2021. GS (2022)1873.
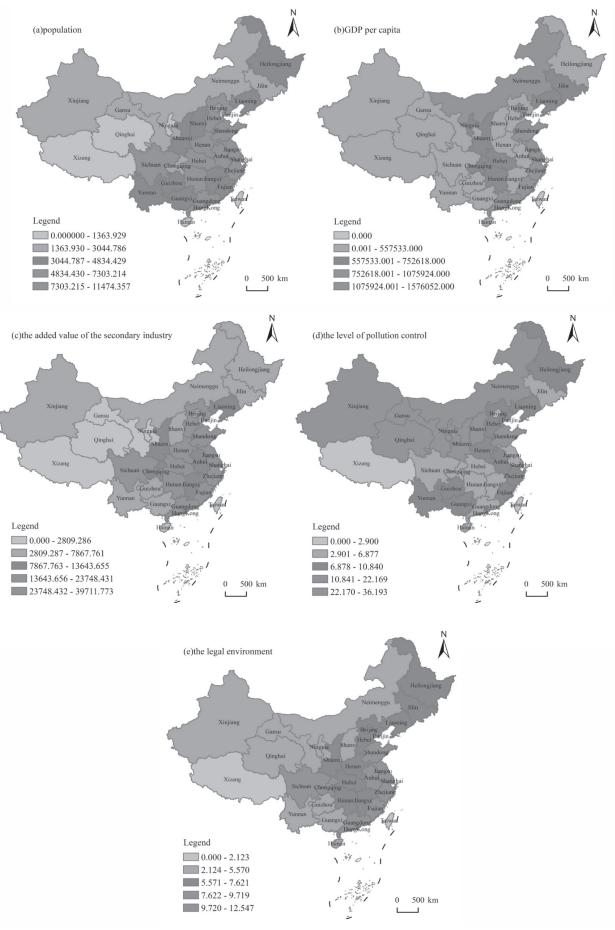
Fig. 8. The spatial distribution of the five influencing factors of sudden environmental incidents. GS (2022)1873.

incidents during the study period, with a total of 1128 occurrences, averaging about 81 events per year, making it the highest value area. The second highest was Shanxi Province with 466 occurrences, while Tianjin had the fewest occurrences at 13 occurrences.

Spatial Distribution of Influencing Factors

To investigate the spatial heterogeneity of the influencing factors of sudden environmental incidents from 2008 to 2021, the spatial distribution maps of five factors were plotted, as shown in Fig. 8.

The spatial distribution of population shows that areas with a higher total population are mainly concentrated in the central, central-eastern, and central-southern regions (Fig. 8a). Cities with a higher total population have a higher overlap with cities with a higher frequency of sudden environmental incidents, indicating a highly similar spatial distribution pattern. Based on this, it could be inferred that the total population is a major driving factor for the occurrence of sudden environmental incidents.

According to the spatial distributions of economic development levels shown in Fig. 8(b) and 8(c), the higher GDP per capita in the southeastern coastal region of China was similar to the spatial distribution of sudden environmental incidents. However, it should be noted that the Inner Mongolia Autonomous Region, Jilin, and Liaoning in the northern and northeastern parts of China had higher GDP than most inland regions, showing some differences in the spatial distribution of sudden environmental incidents. On the other hand, the spatial distribution of the added value of the secondary industry showed a strong similarity with the spatial distribution of the frequency of sudden environmental incidents. Based on this, it can be inferred that, within the factors of economic development levels, the added value of the secondary industry had a stronger driving force for sudden environmental incidents compared to GDP per capita.

According to the spatial distribution of the level of pollution control in Fig. 8(d), as a whole, the investment in environmental pollution control as a percentage of GDP was higher in northern China compared to southern China. This corresponds to a higher frequency of sudden environmental incidents in the South and a lower frequency in the North. The Ningxia Hui Autonomous Region showed a typical negative correlation. Overall, there was a strong correlation between the level of pollution control and the occurrence of sudden environmental incidents, indicating that the level of pollution control had a suppressing effect on the occurrence of sudden environmental incidents.

According to the spatial distribution of the development of market intermediary organizations under the legal environment index in Fig. 8(e), Beijing and the southeastern coastal region of China had the highest rule of law environment index, followed by the inland and northeastern regions, and the northwest region had the lowest index. Compared with the spatial distribution of the frequency of sudden environmental incidents, it can be observed that the northeastern region with a relatively higher legal environment index had a lower frequency of sudden environmental incidents, showing a good negative correlation. On the other hand, the southeastern coastal region with a higher legal environment index also had a higher frequency of sudden environmental incidents, showing a positive correlation. Taking into account the influence of natural disasters in different geographical locations, it can be inferred that the legal environment index had a suppressing effect on the occurrence of sudden environmental incidents.

Analysis of Factor Detection Results

The results of the geodetector showed that all five independent variables had a certain degree of impact on the frequency of sudden environmental incidents, as shown in Table 3. The explanatory power of the level of pollution control (X_4) as an influencing factor is only 5.96%, while the explanatory power of other influencing factors ranges from 20% to 40%. Based on the magnitude of the explanatory power, they can be classified as core influencing factors and secondary influencing factors. Among them, the legal environment (X_5) had the strongest explanatory power and passed the significance level test at 0.05, confirming it as a core influencing factor. Overall, the influence of the five factors was relatively weak, which may be related to the random nature of sudden environmental incidents.

Based on this single-factor analysis, an interaction detection method was used to detect the interaction effects of different factors on the spatial distribution of sudden environmental incidents. There were a total of 10 pairs of interaction effects among the 5 influencing factors, and the detection results are shown in Table 4. After conducting interaction detection, all 5 influencing factors showed a phenomenon of dual-factor enhancement, meaning that their explanatory power significantly increased after conducting bivariate interactions. This indicated that the impact of any two influencing factors had stronger explanatory power after interaction than when they were considered separately.

Table 3. Results of factor detection analysis.

Detection factor	X_1	X_2	X_3	X_4	X_5
q statistic	0.20084	0.345571	0.305225	0.059635	0.37456
p value	0.254059	0.096977	0.109196	0.776839	0.038762

Table 4. Scores of interaction effect factors.

q	X_1	X_2	X_3	X_4	X_5
X_1	0.20084				
X_2	0.663736	0.345571			
X_3	0.539338	0.864654	0.305225		
X_4	0.923776	0.51336	0.491767	0.059635	
X_5	0.643098	0.430804	0.883577	0.511897	0.37456

Based on the q-value analysis, the interaction between the total population at the end of the year (X_1) and the level of pollution control (X_4) is the strongest, with a q-value as high as 0.923776. The interaction between the added value of secondary industry (X_3) and the legal environment (X_5) is relatively strong, with a q-value of 0.883577. The interaction between GDP per capita (X_2) and the legal environment (X_5) is relatively weaker, with a q-value of 0.430804.

Combining the mentioned factor detection results, it could be concluded that the five driving factors were all important factors influencing the distribution of sudden environmental incidents. The spatial distribution of sudden environmental incidents was weakly influenced by individual factors, but was actually the result of the comprehensive impact of multiple factors.

Conclusions

The research analyzed the spatiotemporal evolution and influencing factors of sudden environmental incidents in China from 2008 to 2021, using data analysis methods such as univariate linear regression, exploratory spatial analysis, and geographic detector. The main conclusions are as follows:

(1) China's sudden environmental incidents showed an increasing trend from 2008 to 2013 and then a decreasing trend, with a range of 513 incidents overall showing a decreasing trend. There were no particularly significant sudden environmental incidents from 2011 to 2021. By studying the eight major economic zones, the space showed a significant imbalance. It was found that the frequency of sudden environmental incidents in the coastal economic zone in the eastern region was the highest, accounting for 34.78% of the total national incidents, followed by the Yellow River middle reaches and the northeast economic zone. In addition, the months with the most sudden environmental incidents during the study period were July to August, accounting for 23.01% of the total number of incidents, followed by May to June. The least frequent period was November to December, accounting for 12.29% of the total incidents.

(2) The spatial distribution characteristics of sudden environmental incidents showed that the mid-to-high frequency zones were gradually decreasing. In 2008 and 2018, sudden environmental incidents were mainly concentrated in the central region, and the northwest and northeast regions had relatively fewer incidents, showing an aggregated pattern. The distribution of sudden environmental incidents was relatively uniform in 2013 and 2021, and the aggregated pattern was relatively weak. In the second stage, from 2014 to 2021, the number of sudden environmental incidents was less than that in the first stage, from 2008 to 2013. Moreover, the frequency of incidents in each province was relatively stable, showing a more balanced distribution. The spatial distribution of sudden environmental incidents in China was not completely random and had a correlation. The provinces in the H-H region first increased and then decreased. The provinces in the L-L region had relatively more incidents and were mainly concentrated in areas with relatively lagging industrial development, such as the western and southwestern economic zones. The incidence of sudden environmental incidents in the L-H region did not change significantly. The provinces in the H-L region showed a trend of first decreasing, increasing, and then decreasing.

(3) The selected detection factors had certain similarities with the spatial distribution characteristics of sudden environmental incidents in China, specifically the total population at the end of the year. GDP per capita and the added value of the secondary industry were the driving factors for the occurrence of sudden environmental incidents, and the added value of the secondary industry had a stronger driving force than GDP per capita. The level of pollution control and the legal environment had an inhibitory effect on the occurrence of sudden environmental incidents. The results of the geographic detector analysis showed that the spatial distribution of sudden environmental incidents in China from 2008 to 2021 was weakly influenced by a single factor, while the interaction of any two influencing factors had a stronger explanatory power than the original single factor. The interaction between the total number of people and the level of pollution control had the strongest q value of 0.923776. The occurrence of sudden environmental incidents was the result of the combined effects of multiple factors.

The research described the temporal variability, spatial distribution, and spatial heterogeneity of the influencing factors of sudden environmental incidents in China from a macro perspective. Future research can further explore the spatiotemporal mechanisms

of sudden environmental incidents for specific disaster types and subdivide the incidents according to specific causes, whether they can be controlled and prevented, and how to establish more efficient and accurate emergency response management mechanisms. These issues are still to be further analyzed and will also be the focus of research in the future.

Conflict of Interest

The authors declare no conflict of interest.

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