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Spatial and Temporal Characterization of Mine Water Inrush Accidents in China, 2014–2022

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Abstract: Currently, water inrush accidents in China's coal mines are mainly under control, but occasionally, grave water inrush accidents still occur, causing significant casualties and economic losses. Existing studies have primarily focused on accident statistics, and the research on the trend of accident evolution is becoming obsolete to match the current context of coal resource development. This study analyzes the water inrush accidents in China's coal mines between 2014 and 2022. It investigated the spatial and temporal distribution of accidents, the level of accidents, and the extent to which water prevention and control measures vary by zone in coal mines. The study results showed that from 2014 to 2022, water inrush accidents in coal mines exhibited a "decline-stability-fluctuation" stage change pattern. Additionally, the location of water inrush accidents has shifted westward. Paying particular attention to preventing and controlling water disasters in coal mines within the west development zone is crucial. The water disaster accidents in China's coal mines have been effectively controlled, but the problem of unequal levels of preventing and controlling water disasters in coal mines persists. This study can provide a reference for the safe and efficient production of coal mines and the control of the number of deaths in mine water hazard accidents.

Keywords: coal mine safety; water hazard characteristics; west development zone; difference analysis; grave water inrush accidents

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1. Introduction

Coal has traditionally been China's primary energy source, dominating the country's energy production and consumption structure [1]. China produced 4.69 billion tons of coal in 2022, an increase of 9.5% over the year before. A total of 5.41 billion tons of standard coal was used in energy consumption during the year, representing a 2.9% annual rise. Coal consumption accounted for 56.2% of the total energy consumption. In recent years, the pattern of coal resource development in China has shifted towards the western and deeper parts of the country [2,3]. However, the fatalities in coal mine water accidents have fluctuated wildly [4]. Grave water inrush accidents occur from time to time, which can cause many casualties and economic losses [5]. For instance, two notable accidents occurred in 2021 involving water disaster accidents at coal mines. The first accident occurred at the Baiyanggou Fengyuan Coal Mine in Hutubi County, Changji Prefecture, Xinjiang, resulting in 21 fatalities and economic losses of 70.672 million yuan. The second accident occurred at the Chaidar Coal Mine in Gangcha County, Haibei Tibetan Autonomous Prefecture, Qinghai Province, resulting in 20 fatalities and economic losses of 53.91 million yuan [4]. It reveals that the existing model of coal resource development still needs to improve in preventing and controlling water disasters. Therefore, conducting research and analysis on water disaster accidents and safety situations in coal mines is essential to improve coal mine production.

Previous studies on the statistical analysis of water inrush accidents in China's coal mines mainly focused on the distribution pattern, influence mechanism, prevention, and control strategies of water inrush disasters: (1) By examining the statistics of mine water disaster accidents, including factors such as enterprise ownership and level, the aim is to determine the trend of such accidents over the years and the influence of precipitation and other factors on them. The findings indicate that townships and private mining companies have a higher occurrence of sudden water accidents [6,7]. (2) By analyzing the statistics on the occurrence of mine water inrush accidents in the region, including their types and causative elements, specific causes of water disaster accidents in different locations can be identified. Based on this information, targeted prevention and control measures for distinct regions can be provided [8,9]. (3) By analyzing the statistics of mine water inrush accidents based on the year, month, and period, groundwork for an initial investigation into the patterns of these accidents at different time scales can be established [10]. (4) Summarize information on water inrush accidents in China, analyze the provinces where water damage accidents occur in clusters, and propose corresponding resource development suggestions and prevention and control measures for the provinces where water hazard accidents frequently occur [11]. In summary, domestically and internationally, researchers have primarily focused on the distribution characteristics and causal elements of mine water inrush accidents and proposed corresponding prevention and control strategies. However, some issues need to be addressed: First, most studies on accident investigation and analysis are superficial and lack detailed investigation and analysis of water inrush accidents in coal mines, particularly in the context of the shift in the focus of China's coal resources and the construction planning of large coal bases in Xinjiang [12,13]. The summary of the laws of water inrush accidents does not match the current coal resource mining background. Second, due to the complex hydrogeological conditions [14,15] and significant differences in production environments in China, there are apparent differences in the threat of mine water inrush in different regions [16]. However, current research mainly focuses on the characteristics of mine water hazard accidents or the factors causing water disasters. More research is needed on the differentiation between regions and the impact of different regions on the overall difference. However, current research mainly focuses on the characteristics of mine water hazard accidents or water damage disaster factors. More research is needed on the differentiation between regions and the impact of different regions on the overall difference. This must be more conducive to the comprehensive understanding of water damage prevention and control and the regional characteristics of mine water damage accidents.

Given the concerns mentioned above, it is an issue that needs urgent consideration to analyze the current characteristics of mine water damage accidents in China and the intra-regional and inter-regional differences in the level of water damage prevention and control in coal mines in different regions of China. First, we research different time scales of accidents, accident areas, accident levels, and fatalities. We divide China's mine water hazard prevention and control level zones based on China's coal resource development policies, coal resource distribution, and mine water damage occurrences. Finally, we use the Thiel index. The index quantifies the degree of overall spatial differentiation and the degree of influence of different regions on the overall imbalance to provide a reference for accurate monitoring of regional mine water inrush accidents in China and control of the number of deaths from mine water disasters.

2. Materials and Methods

2.1. Data Collection

The mine water inrush accidents and raw coal production in this study mainly come from the statistics collected by national and provincial mine safety supervision bureaus (formerly the National Coal Mine Safety Supervision Bureau). The missing data were collected from the China Coal Mine Safety Production Network, the "China Safety Production Yearbook," and the provincial coal mine safety. The "Annual Report on Production Safety" published on the Supervision Bureau website will be supplemented.

2.2. Accident Level and Data Processing

To determine the occurrence of water inrush accidents in China's coal mines from 2014 to 2022, coal mine safety accidents were reviewed, the specific occurrences and deaths of coal mine safety accidents were counted, and coal mine safety accidents were identified based on the occurrence of mine water disaster. The water inrush accident level reference is shown in Table 1 [15]. From 2014 to 2022, a total of 74 water hazard accidents in China's coal mines occurred, with a death toll of 304. To conduct a more detailed investigation and analysis and ensure the availability of accident data, the final incomplete statistics of China's mine water disaster accidents totaled 71. Since then, the death toll has been 299. Since there are no statistical data related to coal mine production and accidents in Guangdong Province, Zhejiang Province, Tibet Autonomous Region, Hainan Province, Hong Kong Special Administrative Region, Macao Special Administrative Region, Shanghai, and Taiwan during the study period, the content mentioned in this article does not include the above provinces.

Table 1. Level of coal mine water disaster accident.

Accident Type	Accident Level	Deaths
Water inrush disasters	ordinary	<3
	Major	$3 \leq$ deaths < 10
	Grave	$10 \leq$ deaths < 30
	Extremely grave	≥ 30

2.3. Statistical and Graphical Analysis

Excel 2021 was used to organize and build a database of mine water inrush accidents in China from 2014 to 2022, which was used to characterize the occurrence of water disasters in coal mines as well as the spatial and temporal distribution of accidents. When analyzing the time distribution characteristics, the daily scale was used as the basic scale for statistics, and the monthly and annual scale series of the number of water hazard accidents and the number of fatalities were also established. We divided the monthly water inrush accident series into different stages and calculated the average value to analyze the time characteristics of the accident. Statistics on the number of water inrush accidents in coal mines in each province of China were compiled separately, and the differences in the distribution of water damage accidents in coal mines were analyzed at the provincial level. We counted the county-level distribution of different levels of water disasters in mining areas in stages, drew a spatial distribution map of water accidents, analyzed the spatial characteristics of water accidents, and completed the drawing of the spatial distribution map of water hazard accidents by using ArcGIS 10.8 software. This provided comprehensive and in-depth understanding of the spatiotemporal pattern of water inrush accidents in China's coal mines in the past nine years.

2.4. Measures of Differences

The Thiel index has been widely used in evaluating the fairness of water resource allocation [17], the analysis of the spatial variability of resources [18], the assessment of the differences in the distribution of natural disasters [19], the degree of spatial differentiation of agricultural pollution [20], etc. The Thiel index is decomposable and can be decomposed by intra-regional and inter-regional differences, thus measuring the contribution of intra-regional and inter-regional differences to the total differences [21]. In this study, the index is selected from two aspects of coal resources and water hazard accidents, and the million-ton mortality rate of mine water hazard accidents measures the level of mine water disaster prevention and control. The degree of difference in mine water disaster prevention and control levels within and between regions is quantified by the Thiel index. Furthermore, the regions significantly impacting the spatial differences in mine water disaster prevention and control levels across the country are identified. The Thiel index equation used in this study is shown in Equation (1).

$$T = +T_{inter} \quad (1)$$

where T is the overall national difference, T_{intra} is the intra-region difference, and T_{inter} is the inter-region difference, defined as follows:

$$T_{intra} = \sum i \frac{R_i}{R} \sum j \left[\frac{R_{ij}}{R_i} log \left(\frac{\frac{R_{ij}}{R_i}}{\frac{P_{ij}}{P_i}} \right) \right] \quad (2)$$

$$T_{inter} = \sum i \left[\frac{R_i}{R} log \left(\frac{\frac{R_i}{R}}{\frac{P_i}{P}} \right) \right] R_{i_j} P_{i_j} \quad (3)$$

where R is the number of deaths in mine disaster accidents; P is the raw coal production (million tons); R_i is the number of deaths in mine inrush accidents in region i; P_i is the raw coal production (million tons) in region i; R_{ij} is the number of deaths in coal mine inrush accidents in region i and province j; and P_{ij} is the raw coal production (million tons) in region i and province j.

3. Results

3.1. Basic Information on Water Inrush Accidents

In recent decades, the number of water accidents and fatalities in China's coal mines has generally trended downward, especially after 2010, when water accidents were effectively curbed and the overall safety situation in coal mines improved [2]. From 2014 to 2022, 2104 coal mine safety accidents occurred in China, resulting in 3739 deaths. Among them, there were 74 water inrush accidents and 304 deaths. They accounted for 3.4% and 7.5% of the total number of coal mine accidents and the total number of coal mine accident deaths, respectively (Figure 1). Figure 2 displays the data on China's raw coal production and the occurrences of water disaster accidents in coal mines over the previous nine years. Coal production rose from 3.87 billion tons in 2014 to 4.496 billion tons in 2022, indicating a growth of 16.18%. The average annual growth rate over multiple years was 2.04%. There was a decrease in raw coal production from 2014 to 2016, followed by a continuous increase in raw coal production from 2017 to 2022, with the highest rate of growth occurring in the year-on-year rise in 2018, which was 4.62%.

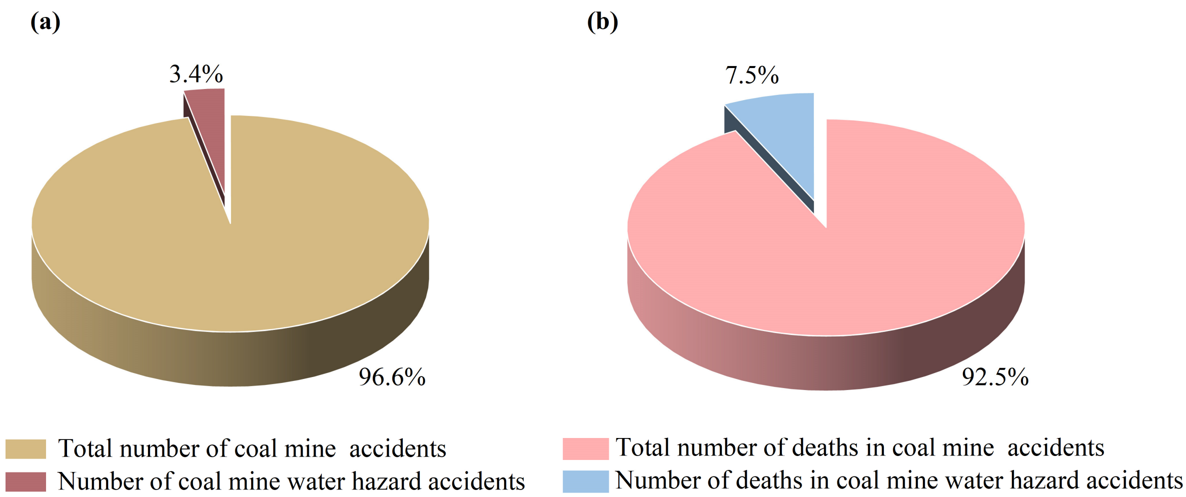

Figure 1. Distribution of water inrush accident types in coal mines in China: (**a**) water inrush accidents as a percentage of the total number of coal mine accidents, 2014–2022; (**b**) number of deaths in mine water inrush accidents as a percentage of the total number of deaths in coal mine accidents, 2014–2022.

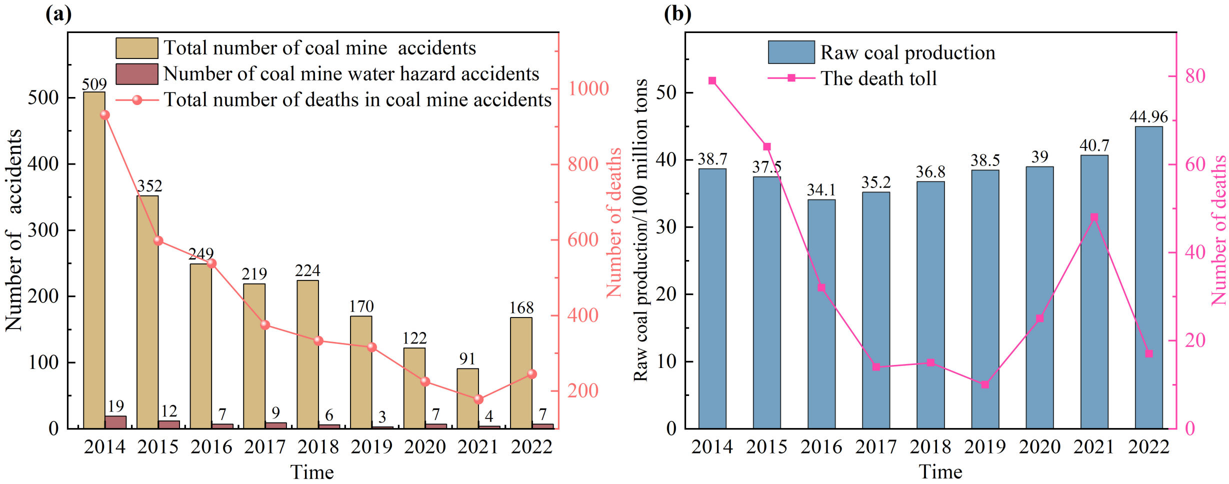

Figure 2. Coal mine accident statistics in China: (**a**) 2014–2022; (**b**) comparison of raw coal production with death toll trend of coal mine water hazard accidents in China, 2014–2022.

There is a noticeable decline in the frequency of water disasters and the associated fatalities in Chinese coal mines. Between 2014 and 2022, there was a significant decrease of 66.99% in water damage accidents and a 63.16% decrease in water damage-related mortality. The number of water inrush accidents in coal mines is highly correlated with the number of deaths from water inrush accidents in coal mines, and the trends are consistent. Since mine water inrush accidents tend to cause mass death and injury, the change in the number of deaths from mine water disaster accidents is greater than the number of water damage accidents. Since 2016, the occurrence of water disasters in China's coal mines has been reduced to single digits, and the deaths resulting from such accidents have been kept under 50 individuals annually, with a consistent downward trend. As China's coal resource development is transitioning towards the western regions and raw coal production gradually increases, the number of water damage accidents and deaths in coal mines has rebounded, indicating that China's water hazard prevention and control work is facing new risks and challenges.

3.2. Characteristics of the Temporal Distribution of Water Inrush Accidents

Statistics show that mine water inrush accidents occur in China an average of once every two months. The monthly number of water damage accidents, the average monthly number of deaths, and the distribution of water damage accident levels show similar stage characteristics. In the past nine years, it can be divided into three time stages: I, II, and III. Notably, May 2017 and November 2020 mark critical transitional periods (Figure 3).

Stage I: From January 2014 to May 2017, 40 water disaster accidents occurred, resulting in 179 deaths. The average number of water damage accidents per month and the average number of deaths from water damage accidents in coal mines are similar to the average of the past nine years. Starting from May 2015, the number of deaths from mine water damage accidents gradually decreased, reaching the lowest level in Stage I from August 2015 to March 2016, with only two general water damage accidents occurring, and then entering the relatively high period of April 2016–May 2017, with the number of fatalities in water hazard accidents showing an overall decreasing trend.

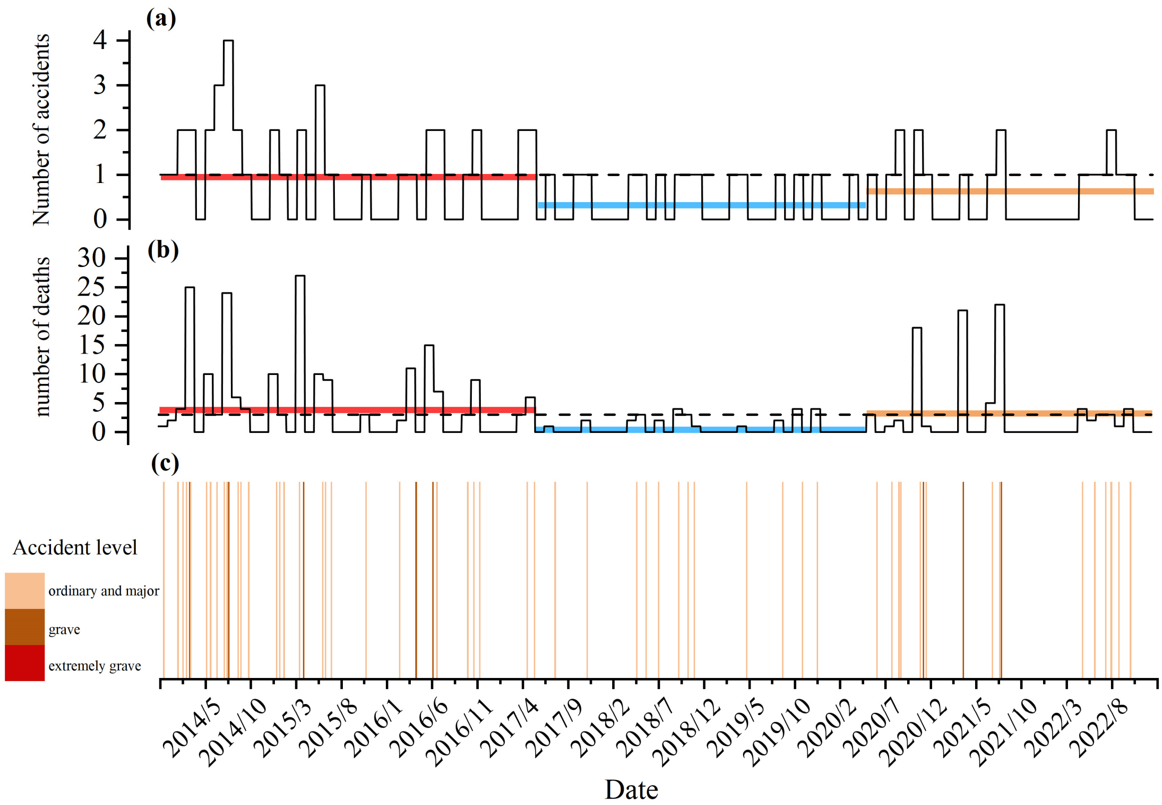

Figure 3. Temporal distribution of coal mine water damage accidents (In (**a**,**b**), the solid black line is the monthly scale series, the dashed black line is the monthly scale mean for 2014–2022, and the short colored line is the monthly scale mean for each of the 3 stages): (**a**) time series of water inrush accidents (monthly scale), 2014–2022; (**b**) time series of water inrush accident deaths (monthly scale), 2014–2022; (**c**) time series of water damage incident levels (daily scale), 2014–2022.

Stage II: From June 2017 to May 2020, 13 water disaster accidents in coal mines occurred, with 30 deaths. In the past nine years, this was a relatively stable low-incidence period for mine water damage accidents in China. The average number of water disasters and deaths was lower than the average in the past nine years; there were no more than two mine water hazard accidents in the same month and no grave water damage accidents. Only five major water inrush accidents occurred between May 2018 and December 2019, with a stable situation in preventing and controlling water damage.

Stage III: From June 2020 to December 2022, a total of 18 mine water disaster accidents occurred, killing 90 people. This is a period of fluctuation in China's mine water damage accidents in the past nine years. The average number of water damage accidents in this stage is lower than the average of the past nine years, and the death toll from water inrush accidents is higher than the average of the past nine years. The average number of water disaster accidents in Stage III is significantly lower than in Stage I. However, the average death toll is the same as that in Stage I, and the internal changes fluctuate considerably. Three grave water inrush accidents happened between November 2020 and August 2021. However, there were no mine water disasters between September 2021 and April 2022, the most extended period between water damage accidents in the previous nine years. Overall, "low frequency and high intensity" was observed in the accidents. The traits demonstrate how Stage III differs significantly from Stages I and II regarding fluctuation.

Judging from the temporal changes in the frequency and intensity of mine water disaster accidents, although mine water inrush accidents have been effectively controlled, the number of mine water disaster accidents and deaths has rebounded, which can be divided into three distinct stages: In Stage I, China's coal base is in the early stage of integration [22]. The degree of mechanization and intelligence of coal is relatively low [23], and the corresponding prevention and control policies and management regulations are not perfect [3], resulting in frequent water damage accidents in coal mines and causing many casualties and economic losses. In Stage II, with the policy adjustment of China's coal industry, the integration and development of coal resources on a large scale, accelerating the closure and withdrawal of coal mines outside large coal bases, as well as the enhancement of coal mining technology, equipment, and the management level of coal mining enterprises [24], China has entered into a period of stable and low incidence of water damage accidents in coal mines. Since Stage III, the number of deaths in coal mine water damage accidents has fluctuated greatly; for example, in 2021, although only four water damage accidents occurred, the number of deaths was as high as 48 people. On the whole, although the coal mine water damage accidents have been effectively controlled, the number of coal mine water damage accidents and the number of deaths have rebounded, combined with the fact that water damage accidents occur and cause mass deaths and injuries easily [25], it is necessary to strengthen the understanding of the importance of mine water control.

3.3. Characteristics of the Spatial Distribution of Water Hazard Accidents

With reference to the requirements of the "13th Five-Year Plan for Coal Industry Development" formulated by the Chinese government, the overall layout of China's coal development is divided into the east development region (including Hebei, Shandong, Beijing, Tianjin, Jiangsu, Zhejiang, Fujian, Guangdong, Hainan, and Taiwan), central development region (including Shanxi, Henan, Anhui, Jiangxi, Hubei, and Hunan), northeast development region (including Heilongjiang, Jilin, Liaoning), and west development region (Neimenggu, Shaanxi, Ningxia, Gansu, Qinghai, Xinjiang, Tibet, Chongqing, Yunnan, Guizhou, Sichuan, and Guangxi) [24], as shown in Figure 4.

Twenty-two provinces have experienced mine water inrush accidents from 2014 to 2022 (Figure 4a). Judging from the overall distribution of water damage accidents, the central development region of China has the most water damage accidents. In contrast, the west development region has the most significant number of deaths from water hazard accidents in coal mines. The provincial distribution of water inrush accidents over the three periods also varies significantly (Figure 4). I: Water inrush accidents happened in 13 provinces between January 2014 and May 2017, distributed in northeast, east, central, and west development regions. Mine water inrush accidents in the northeast development region are mainly major water inrush accidents. Only three water inrush accidents occurred in the east development region, resulting in fewer injuries and financial losses. The central development region has the highest number of water inrush accidents and fatalities, and the proportions of general and major water inrush accidents in the central development region are similar. Major water damage accidents account for most in the west development region, with fewer ordinary water inrush accidents. Four grave water inrush accidents occurred in the Shanxi, Shaanxi, Yunnan, and Heilongjiang provinces. II: Water inrush accidents happened in 13 provinces between June 2017 and May 2020 and were dispersed among different regions. The majority of them took place in the central development region. However, the west development region saw a rise in both the number of water inrush disasters and the percentage of fatalities. The number of water disasters in coal mines in this stage is the most minor, mainly ordinary water inrush accidents, and no grave water damage accidents have occurred. Major water inrush accidents are only distributed in the west, northeast, and central development regions, and water inrush accidents are well controlled. III: From June 2020 to December 2022, water disasters and deaths from water inrush accidents increased compared with the previous stage. No mine water inrush accidents occurred during this stage in the east development region. Water inrush accidents mainly occurred in the west development region. The number of water disasters accounted for 72.22% of the total number of accidents. The number of accidents and fatalities accounted for 75.56% of the total fatalities in water disaster accidents.

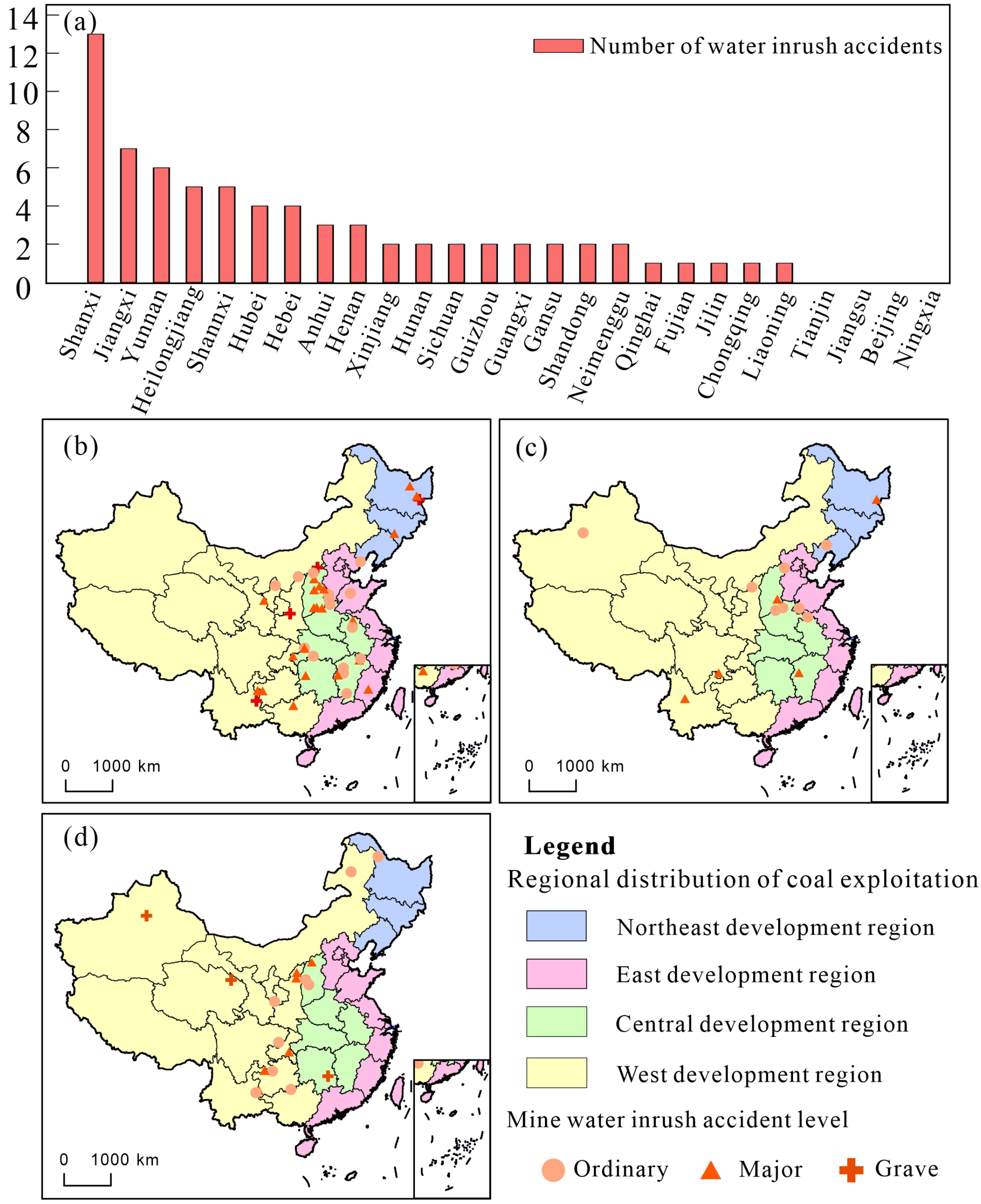

Figure 4. Spatial distribution of water inrush accidents in coal mines: (**a**) Statistics on coal mine water damage accidents by province, 2014–2022; (**b**) Spatial distribution of water inrush accidents in stageI, 2014/1–2017/5; (**c**) Spatial distribution of water inrush accidents in stageII, 2017/6–2020/5; (**d**) Spatial distribution of water inrush accidents in stage III, 2020/6–2022/12.

Currently, China's primary sources of coal supply are the central and west development regions, which may result in more mine water inrush accidents in these regions [20,26]. The northeast, east, and central development regions have more coal resource exploration due to earlier development time, resulting in relatively complete technical systems and production management compared to the west development region [27,28]. However, the west region's technical system for preventing and controlling water disasters is imperfect; the west development region's technical water hazard prevention and control system must be better developed. As coal production steadily increases, shifting the focus of coal resource mining to the west development region may increase the risk of mine water disasters. Therefore, under the current development pattern of China's coal resources, preventing and controlling water damage in coal mines in the west development region is the focus that needs attention.

3.4. Analysis of Spatial Differences

3.4.1. Zoning Determination

This study uses the Theil index to study the spatial differences in mine water disaster accidents between intervals and regions at the provincial scale. From this, the research object is first divided into several zones. The provinces were initially divided based on the development regions divided into four gradients: northeast, east, central, and west development regions as mentioned above, including the northeast development region: Heilongjiang, Jilin, Liaoning; the east development region: Beijing, Tianjin, Hebei, Shandong, Jiangsu, and Fujian; the central development region: Shanxi, Hunan, Hubei, Henan, Anhui, and Jiangxi; the west development region: Neimenggu, Ningxia, Shaanxi, Chongqing, Guizhou, Guangxi, Gansu, Sichuan, Yunnan, Qinghai, and Xinjiang. Since the existence conditions of coal resources are the main factor determining coal mining, and the distribution of coal resources in China is naturally differentiated, different regions have different geological conditions, climate conditions, and water disaster threats. For further reference, please refer to China's coal resource region (Figure 5) [29].

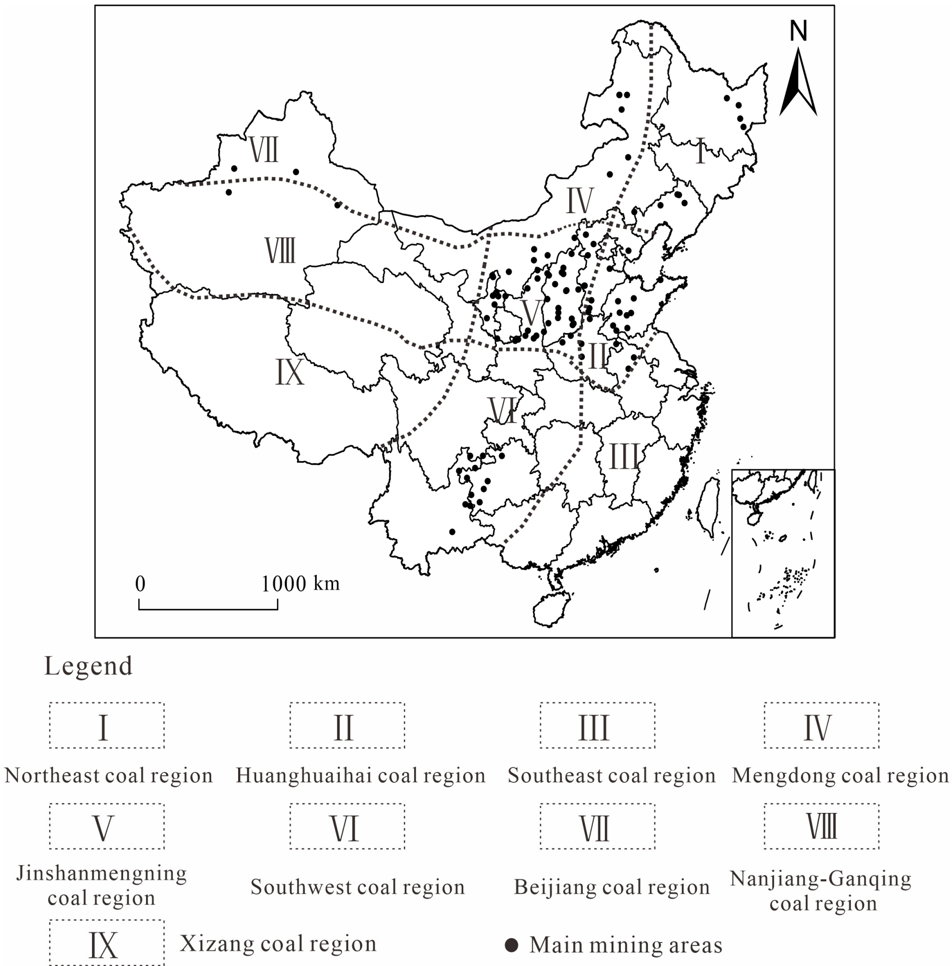

Figure 5. China's coal resource region.

To optimize the preliminary classification plan and finally form the mine water inrush prevention and control zone, the specific adjustment plan is as follows:

① As the main coal-producing bases in China, the four provinces of Shanxi, Shaanxi, Neimenggu, and Ningxia are often mentioned separately from the perspective of resource exploration and development potential, so these four provinces are separately classified as the central north zone; ② from the perspective of coal resource distribution, seeing that Henan and Anhui are basically located in the Huanghuaihai coal region, and are adjacent to other provinces Beijing, Tianjin, Shandong, and Jiangsu in the Huanghuaihai coal region, they are collectively classified as the north zone; ③ Guangxi, Jiangxi, and Fujian belong to the southeastern region of China, considering that the distribution of the leading mining areas of large coal bases in Hubei and Hunan is similar to the abovementioned provinces, and the distance between them is relatively close, Hubei and Hunan are included in the southeast zone from the west development region; ④ from the perspective of coal resource distribution, Yunnan, Guizhou, Sichuan, and Chongqing all belong to the southwest coal region; Qinghai, Xinjiang, and Gansu all belong to the northwest coal region; and the west development region is further divided into the northwest zone and the southwest zone; ⑤ provinces without coal mining activities from 2014 to 2022 are grouped into one category and marked as data-free zone.

The zoning for the prevention and control of water hazard caused by coal mining was formed (Figure 5), which was divided into six zones: northeast zone, north zone, central north zone, northwest zone, southwest zone, southeast zone (Figure 6).

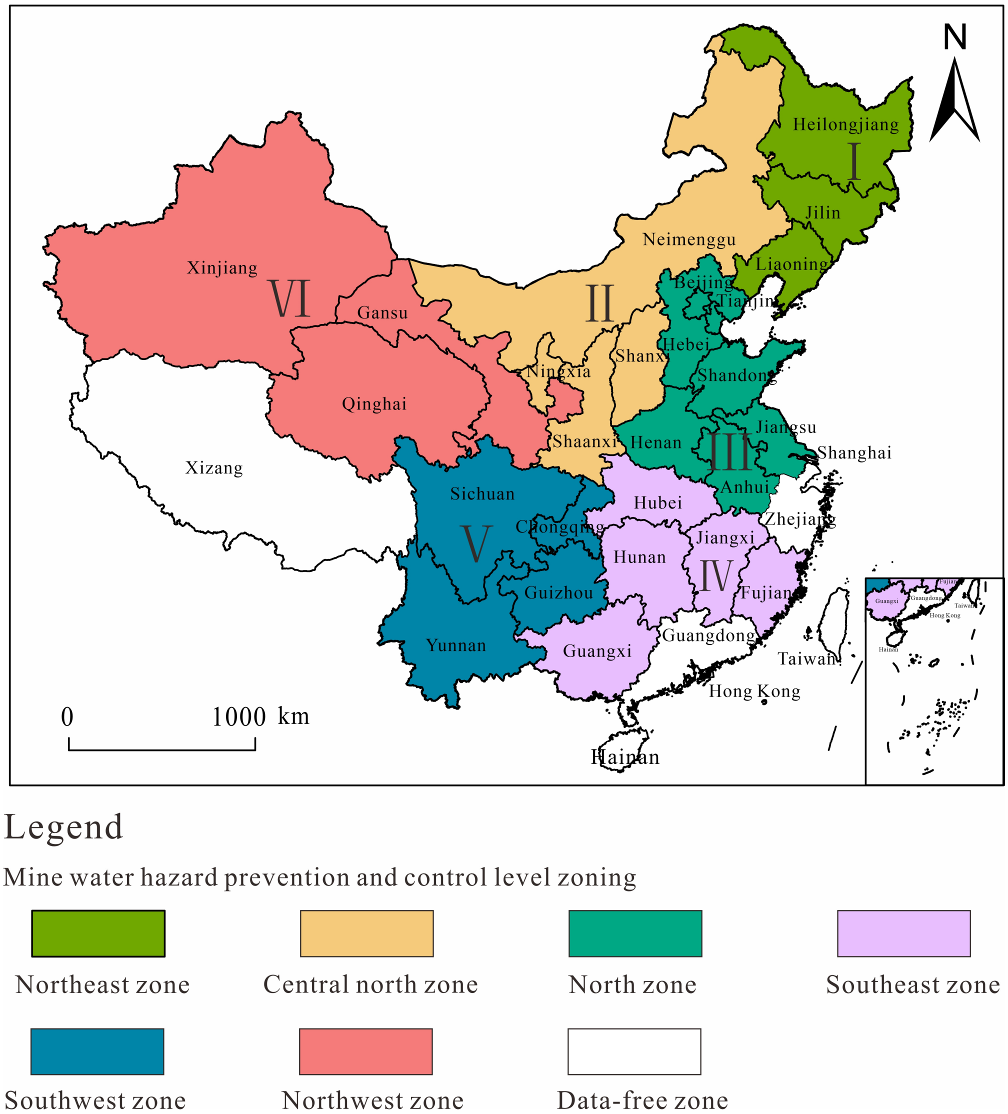

Figure 6. Mine water hazard prevention and control level zoning (provincial level).

3.4.2. Analysis of Spatial Differences

The Theil index (Figure 7) was further computed to study and analyze the overall differences, interval differences, and intra-regional differences in the level of water disaster prevention and control in China's coal mines, as well as the contribution rate of each region to the overall difference, based on the six major zones of mine water hazard prevention and control (Figure 7b). The Theil index (Figure 7a), which measures the overall disparity in the level of water damage accident prevention and control in China's coal mines, displays a "declining-fluctuating" change characteristic, indicating that despite effective control over water damage accidents in China's coal mines, there remains an imbalance in the prevention and control of water inrush disasters. Looking at it in stages, ① the overall Theil index of water damage prevention and control levels declined steadily from 2014 to 2017. Inter-regional and intra-regional differences decreased to varying degrees, but the inter-regional differences decreased even more. Judging from the contribution rate of the interval and the overall difference within the region, the contribution rate between zones showed a downward trend, from 58.79% in 2014 to 23.44% in 2017. However, the difference in contribution rate within the region gradually expanded from 2014 to 2017. It increased from 41.20% in 2017 to 76.56% in 2017, and the degree of spatial differentiation has changed significantly. ② From 2018 to 2022, the Theil index was significantly higher than the previous stage, entering a period of fluctuation. At this stage, the overall Theil index fluctuated between 1.98 and 3.32. Except for 2019, the interval difference contribution rate in other years was higher than the intra-region difference contribution rate, which varied between 32.05% and 71.56%. The imbalance problem reflecting the level of water hazard prevention and control in coal mines has begun to become prominent and continues to intensify.

Specifically with regard to the contribution rate of intra-regional differences in different types of zones (Figure 7b) and the interval Theil index (Figure 8), ① from 2014 to 2017, the contribution rate of the central north zone, the southwest zone, and the southeast zone ranked among the top three zones, with an annual average contribution rate of 39.00%, 17.49%, and 15.76% in order of priority, and was the primary spatial source of differences in the level of prevention and control of water disasters in China's coal mines, and in the northeast, north, and west zones of China, the difference in the annual average contribution rate is relatively small, 12.37%, 10.02%, 5.36%, respectively. ② The contribution rate during 2018–2022 is dominated by the southwest, central north, and west zones, with an annual average contribution rate of 30.40%, 22.83%, 20.55%; the average yearly contribution rates of the northeast, north, and southeast zones are more diminutive, 4.8%, 6.22%, and 15.2%, respectively. They are combined with the changes in the contribution rates and interval Theil index of the six major zones. The contribution rates and intra-regional differences in northeast, southeast, and north China continued to decline after fluctuations, and the degree of impact on the uneven characteristics of the national mine water hazard prevention and control levels also increased. As it decreased, intra-regional differences fluctuated the least in the northeastern zone. The contribution rate of the southwest and central north zones is relatively stable. It has always been the primary zone determining the degree of spatial differentiation in water hazard prevention and control in China's coal mines. The internal state is always unstable, and in the southwest zone, compared with the central and north zones, the intra-regional differences fluctuate more. The influence of the west zone on the spatial differentiation of national mine water hazard prevention and control levels has steadily increased against the backdrop of the shift in the focus of coal resources.

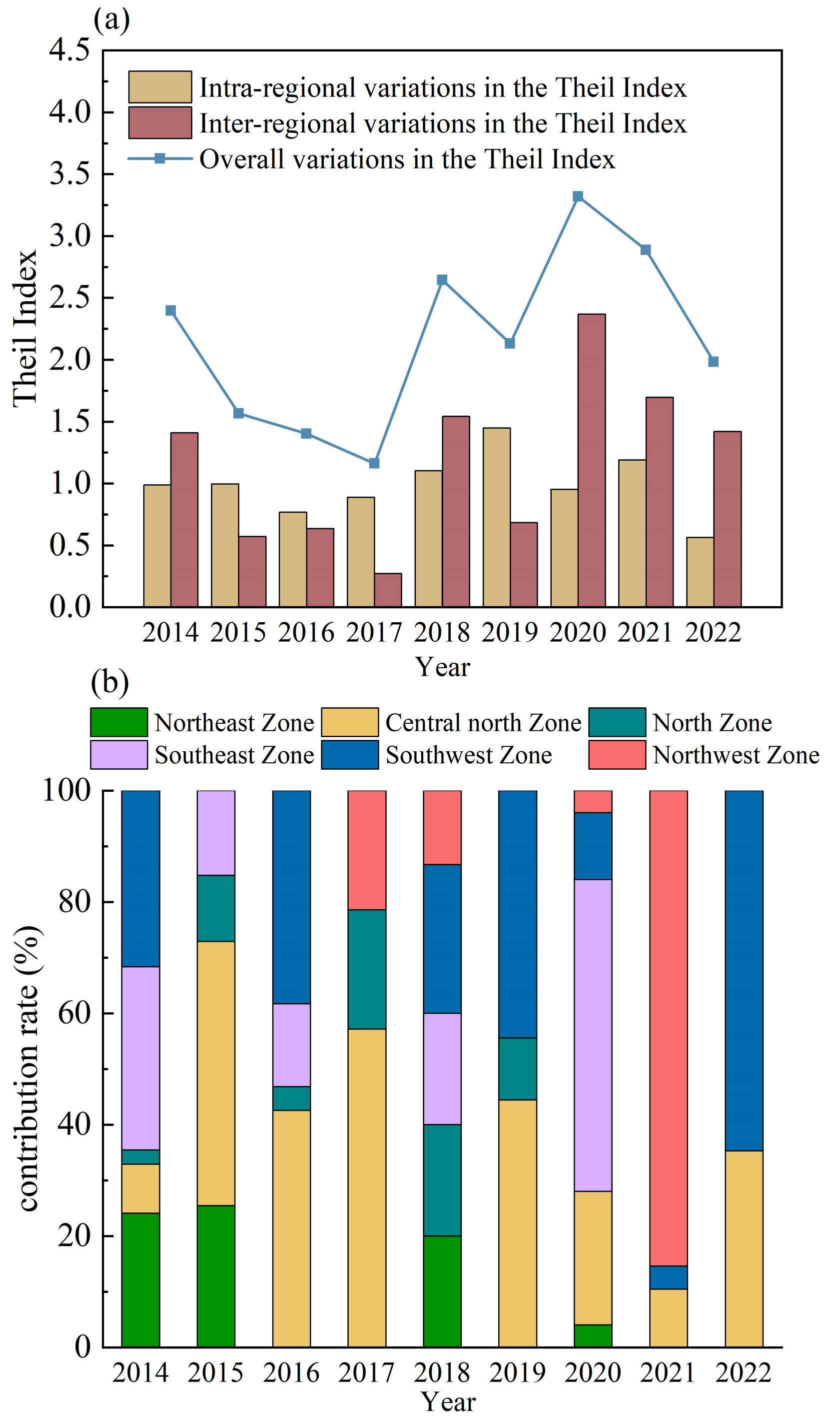

Figure 7. Results of the Theil index and the contribution rate of each region of China to the overall difference: (**a**) Theil index; (**b**) contribution rate.

With the development of China's coal industry and the changes in the coal resource development pattern, new differentiation characteristics have begun to appear in the space. The state of prevention and control of water hazards in coal mines among the six major zones and the provinces within the zone has yet to reach a relatively stable state, resulting in the overall degree of differentiation. In light of the shift in the focus of coal resource development, it is necessary to define the development trend of mine water hazard prevention and control levels in each region and reduce the discrepancies between the six zones.

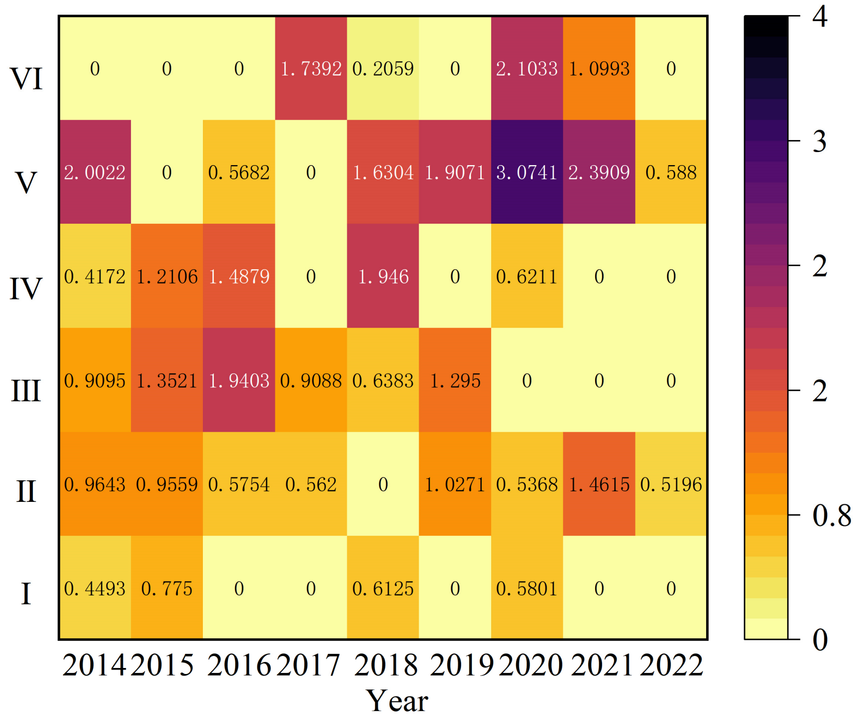

Figure 8. Zoned Theil index heat map.

4. Discussion

The above analysis shows that in the context of the current shift in the development of the coal industry and the focus on coal resource development, water inrush accidents in China's coal mines have further "moved westward," and water hazard prevention and control work is facing new challenges. The following water damage prevention and control countermeasures are suggested in light of the features and difficulties associated with mine water hazard accidents at this point in the problem:

(1) Conducting a survey of mine water disaster risk according to local circumstances

Determining the risk of water damage from coal mines in various regions is challenging due to variations in hydrogeological conditions [16,30], coal resource reserves, and mining depths. China's coal resource development trend involves horizontal expansion in the west and vertical expansion in the depths, leading to a new stage in the layout of coal resource development. To reduce the risk of water inrush accidents in coal mines, it is essential to enhance the survey and research on the risks of water damage in different areas of coal mines. This can be achieved by improving exploration technology and promoting the combination of essential hydrogeological work and geophysical prospecting technology [31]. Additionally, it is essential to explore the hydrogeology of mines and apply electrical prospecting, magnetic prospecting, seismic prospecting, and other relevant technologies to the practical application of coal resource mining.

In the context of the changing mining industry, the utilization of three-dimensional seismic [32] detection technology can adapt to complex ground conditions, such as Gobi, desert, and mountainous terrain. This technology can continuously detect and reduce the consumption of labor and material resources during mining. Simultaneously, it can complement electromagnetic exploration technology. Current is input downwards from the Earth's surface, and the specific hydrogeological conditions are analyzed based on the obtained electromagnetic wave magnetic field. In areas with low exploration degrees, three-dimensional seismic and electromagnetic exploration technology can be combined to reduce construction uncertainty and provide safety guarantees for subsequent coal mining. At the same time, due to the gradual increase in the depth of coal resource mining [33], the difficulty and hazards of exploration are also increasing exponentially. It is difficult to achieve good detection results with a single geophysical method. Comprehensive geophysical technology combines three-dimensional seismic detection, drilling, logging, and hydrogeological testing. Combined with other factors, we conducted a detailed analysis of the various elements of water disaster risk to prevent coal mine water disasters from occurring at the source.

(2) Promoting the intelligent construction of coal mines

The mechanization level of China's coal mining enterprises has reached 99.02%, which has laid the foundation for promoting the construction of intelligent coal mines. We will foster the advancement of automation-driven intelligence and facilitate the implementation of intelligent infrastructure in coal mines, with a focus on achieving the five objectives of "intelligence, efficiency, labor reduction, innovation, and safety." Utilizing big data, advanced information technologies like 5G are employed to establish a 5G+ mine Internet of Things system, connecting different media within coal mines. This system enhances the capacity to perceive and process information, enabling intelligent equipment control [34]. Advocate for implementing coal mine robots to replace workers in hazardous roles to decrease the labor intensity and risk workers face and ultimately lower casualties resulting from water damage incidents. Predicting and forecasting water damage in coal mines is a crucial strategy for preventing water damage. It can be used to predict the occurrence of water damage accidents in coal mines based on parameters such as temperature, humidity, displacement, and stress. A combination of neural networks, random forests, logistic regression, and other algorithms can be employed to construct models for predicting water damage accidents in coal mines. The risk intelligent early warning system [35] continuously monitors the incidence of water damage in coal mines in real time. It performs a risk assessment to minimize the frequency of water disaster accidents in mines.

(3) Enforcement of laws and regulations and market supervision mechanisms

Technical standards, laws, and regulations related to mine water hazard prevention and control are the basis for water damage prevention and control work. With the changes in the development situation of the coal industry, to adapt to the requirements of mine water disaster prevention and control work under the new situation, the mine water hazard prevention and control system has been continuously improved. The "Detailed Rules for Water Damage Prevention and Control in Coal Mines" revised in 2018 and the "Specifications for Hydrogeology and Engineering Geological Exploration in Mining Areas" implemented in 2021 mark the basic formation of China's mine water hazard prevention and control system. As the main production body, coal mining enterprises are the core of implementing technical standards and related regulations. Therefore, it is necessary to strengthen the supervision and accountability system of coal mining enterprises and implement water damage prevention and control responsibilities of coal mining enterprises, ensure the balance of the production environment, and improve water damage prevention and control in coal mines. Due to the lack of awareness of water damage prevention and control and incomplete investigation of water damage disaster factors, these are the subjective causes of water damage accidents. Therefore, coal mining enterprises also need to strengthen professional skills and basic theoretical training for personnel engaged in the coal mining industry, strictly implement various rules and regulations to prevent and control water damage in coal mines, improve the level of safe production in coal mines, and reduce the occurrence of water hazard accidents [36].

5. Conclusions

This paper presents a statistical analysis of China's mine water disaster accidents from 2014 to 2022. It explores the spatial and temporal characteristics of mine water disaster accidents and the degree of spatial differentiation in mine water hazard prevention and control. The specific conclusions are as follows:

(1) From 2014 to 2022, the average monthly number of water inrush accidents, deaths, and distribution of water damage accident levels all show similar stage characteristics.

Generally speaking, although mine water disaster accidents have been effectively controlled, the number of mine water disasters and the number of deaths have rebounded. Combined with the characteristics of mine water disasters that are prone to occur and cause many casualties, it is necessary to strengthen the importance of understanding mine water prevention and control.

(2) From 2014 to 2022, mine water disaster accidents occurred in 22 provinces in the northeast, central, west, and east development regions. The spatial distribution of the three time stages shows different characteristics. As the time stages change, water inrush accidents further shift to the western region, and the number of mine water disasters and the proportion of deaths in the west development region continues to increase. Paying particular attention to preventing and controlling water disasters in coal mines within the west development region is crucial.

(3) The overall difference in the level of water damage accident prevention and control in China's coal mines from 2014 to 2022 is characterized by a "decline-fluctuation" change, and the differences between the six zones are the main reason for the overall difference. The contribution rates and intra-regional differences in northeast, southeast, and north China continued to decline after fluctuations, and the degree of impact on the uneven characteristics of the national mine water hazard prevention and control levels also decreased. The contribution rate of the southwest and central north zones is relatively stable. It has always been the primary zone determining the degree of spatial differentiation in water hazard prevention and control in China's coal mines. The influence of the west zone on the spatial differentiation of national mine water hazard prevention and control levels has steadily increased against the backdrop of the shift in the focus of coal resources.

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