

Article

Spatial and Temporal Characterization of the Development and Pollution Emissions of Key Heavy Metal-Related Industries in Typical Regions of China: A Case Study of Hunan Province

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Abstract

At present, there is a lack of in-depth knowledge of the effects of heavy metal-related industries (HMI) in China on the environment. Hunan Province, as a representative gathering place of HMIs, is among the regions in China that are the most severely polluted with heavy metals. This paper selected Hunan Province as the study area to analyze the development trend, characteristics of pollution emissions, and environmental impacts of seven HMIs based on emission permit information data from Hunan Province. The results of this study show that (1) from 2000 to 2022, the number of heavy metal-related enterprises in Hunan Province increased overall. Among the seven industries, the chemical product manufacturing industry (CPMI) had the largest number of enterprises, whereas the nonferrous metal smelting and rolling industry (NSRI) had the highest gross industrial product (27.6%). (2) HMIs in Hunan Province had significant emissions of cadmium (Cd), arsenic (As), and hydargyrum (Hg) from exhaust gas and wastewater. Heavy metal-related exhaust gas and wastewater outlets from the NSRI constituted 43.9% and 35.3%, respectively, of all outlets of the corresponding type. The proportions of exhaust gas outlets involving Cd, Hg, and As from the NSRI to total exhaust gas outlets were 44.27%, 60.54%, and 34.23%, respectively. The proportions of wastewater outlets involving Cd, Hg, and As from the NSRI to total wastewater outlets were 61.13%, 57.89%, and 75.30%, respectively. (3) The average distances of heavy metal-related enterprises from arable land, rivers, and flooded areas in Hunan Province were 256 m, 1763 m, and 3352 m, respectively. Counties with high environmental risk (H-L type) were situated mainly in eastern Hunan. Among them, Chenzhou had the most heavy metal-related wastewater outlets (22.7%), and Hengyang had the most heavy metal-related exhaust gas outlets (23.1%). The results provide a scientific basis for the prevention and control of heavy metal pollution and an enhancement in environmental sustainability in typical Chinese areas where HMIs are concentrated.

Keywords: heavy metal-related industries; pollution emissions; spatial characteristics; environmental impacts



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1. Introduction

With China's rapid industrialization and urbanization, the production and consumption of heavy metals have increased significantly [1]. The potent toxicity of heavy metals has caused significant threats to human health, the soil environment, and the water environment, and heavy metal pollution has become an environmental problem that has attracted much attention and received high priority [2]. Nonferrous metal smelting, chemical manufacturing, electroplating, and other heavy metal-related industries (HMI) discharge substantial quantities of heavy metals into the ecosystem during production processes, significantly contributing to the contamination of China's aquatic systems and arable land soils [3,4]. The contradiction between the development and pollution of HMI is prevalent. In particular, the nonferrous metal industry, as a core component of China's production industry, plays a vital strategic role in the national economy [5]. However, in areas with dense nonferrous metal industries, production activities have concurrently generated severe heavy metal contamination, underscoring the urgent need for sustainable industrial transition to reconcile economic growth with environmental stewardship. Consequently, an in-depth study of the development characteristics of HMI in China's key industrial regions and their environmental impacts is essential to advance sustainable management practices for the effective prevention and control of regional heavy metal contamination.

Numerous scholars worldwide have carried out regional-scale studies on the risk assessment of heavy metal pollution in water and soil around heavy metal-related enterprises. Extensive research has demonstrated that heavy metal contamination in China's Hunan Province is a particularly serious problem, with significant human health and ecological risks [6,7]. Recent scholarly investigations have systematically elucidated heavy metal emission profiles within Chinese sector-specific industries and their specific impacts on the environment. For example, Li et al. [8] quantified the spatial and temporal distributions of heavy metal emissions from nonferrous metal industries in China. The results of the study revealed that the emission of heavy metal pollutants from four industries, including copper smelting, lead smelting, zinc smelting, and lead–zinc ore mining, was the most serious and had the most significant impact on the environment. Huang et al. [9] conducted a nationwide spatial and temporal analysis of heavy metal emissions from industrial wastewater and their environmental impacts in China. The study results indicated that Hunan Province was the area with the most severe industrial wastewater discharge of cadmium (Cd) and hydargyrum (Hg) in China. Five industries, comprising nonferrous metal smelting and rolling, nonferrous metal mining and dressing, chemical product manufacturing, metal product manufacturing, and leather tanning and processing, were the main sources of heavy metals in industrial wastewater. Shi et al. [10] analyzed in depth the spatial distribution characteristics of wastewater and exhaust gas outlets of heavy metal-related enterprises in China. The results of the study revealed that heavy metal-related outlets in China were concentrated mainly in central and southeastern coastal areas. The results of Wang et al. [11] indicated that the distribution of industrial enterprises in Jiangsu Province was spatially consistent with the pollution load index of heavy metals in soil, and there were significant differences in the effects of different types of industrial enterprises on the accumulation of heavy metals in soil. At present, with respect to the typical agglomeration areas of HMI in China, a comprehensive understanding of the development trends of HMI, the emission characteristics of various heavy metal pollutants, and their impacts on water and soil environments is still lacking.

Hunan Province is known as the "Hometown of Nonferrous Metals", with numerous heavy metal-related enterprises. In addition, the province is also known as the "land of fish and rice" in China, with abundant arable land resources and a well-developed water system. Compared with China's industrial giants, such as Guangdong and Jiangsu, and

the rest of the world, Hunan Province is characterized by significant pollution discharges from heavy metal-related enterprises, a complex mix of arable land and water systems, and frequent flooding events. The combination of these factors has made Hunan Province a key area of concern for China's Ministry of Ecology and Environment, as heavy metal pollution is particularly prominent. Toxic metals, such as arsenic (As) and lead (Pb), can enter the food chain, causing permanent damage to the nervous system and posing a serious threat to human health. HMI zones are concentrated in mining areas and riverine industrial zones in Hunan Province, where their emissions continuously seep into the soil, reducing biological activity and degrading soil quality. The leaching of heavy metal-contaminated soil and the direct discharge of wastewater from HMIs can lead to water pollution, posing a threat to aquatic life and water quality [12,13].

Therefore, this research selected Hunan Province as the study area and relied on statistical yearbook information and China Pollutant Emission Permit Information, as well as relevant data on rivers, arable land, and flooded areas in Hunan Province, to explore the development trends in the number of enterprises and gross industrial products of the seven HMIs, including nonferrous metal smelting and rolling industries, etc. At the same time, the emission characteristics of various heavy metal pollutants, such as Cd, Hg, As, Pb, and chromium (Cr), and their impacts on surrounding water bodies, arable land soils, and other environmental elements were analyzed. The research results aim to provide a scientific basis for preventing and controlling heavy metal pollution in Hunan Province and similar regions in China, thereby balancing environmental protection with socioeconomic development, advancing the United Nations Sustainable Development Goals (SDGs), and fostering long-term environmental health.

2. Materials and Methods

2.1. Study Area

Hunan Province is one of the richest provinces in China in terms of mineral resources, with Antimony (Sb), Bismuth (Bi), and other nonferrous minerals occupying important positions globally, as well as iron ore, manganese ore, and other resources with considerable reserves, which are located mainly in Chenzhou, Hengyang, and other areas. The seven types of HMIs distributed in Hunan Province are the nonferrous metal mining and dressing industry (NMDI), leather and footwear manufacturing industry (LFMI), chemical product manufacturing industry (CPMI), nonferrous metal smelting and rolling industry (NSRI), metal product manufacturing industry (MPMI), electrical machinery and equipment manufacturing industry (EMEI), and electric power production and supply industry (EPSI) (Figure 1). Enterprises in the HMIs are highly concentrated in the Zhuzhou–Xiangtan–Changsha area, and there are also many enterprises in Hengyang and Chenzhou (Figure A1 in Appendix A.1). Hunan Province has a total area of 218,800 square kilometers. The existing arable land in the study area covers an area of 4,148,800 hectares, accounting for approximately 3.1% of the total arable land in China, and it is mainly distributed in the Dongting Lake area in the north and the relatively flat hilly area in the central part of the country. The study area has a dense network of rivers and well-developed water systems, mainly belonging to the Dongting Lake system of the Yangtze River Basin, with a total length of approximately 90,000 km and an average water system density of approximately 0.42 km per square kilometer. Owing to the unique climatic, geographic, and hydrological characteristics, floods are frequent and extremely severe in the study area and are concentrated mainly in the area around Dongting Lake in the northwestern part of Hunan Province.

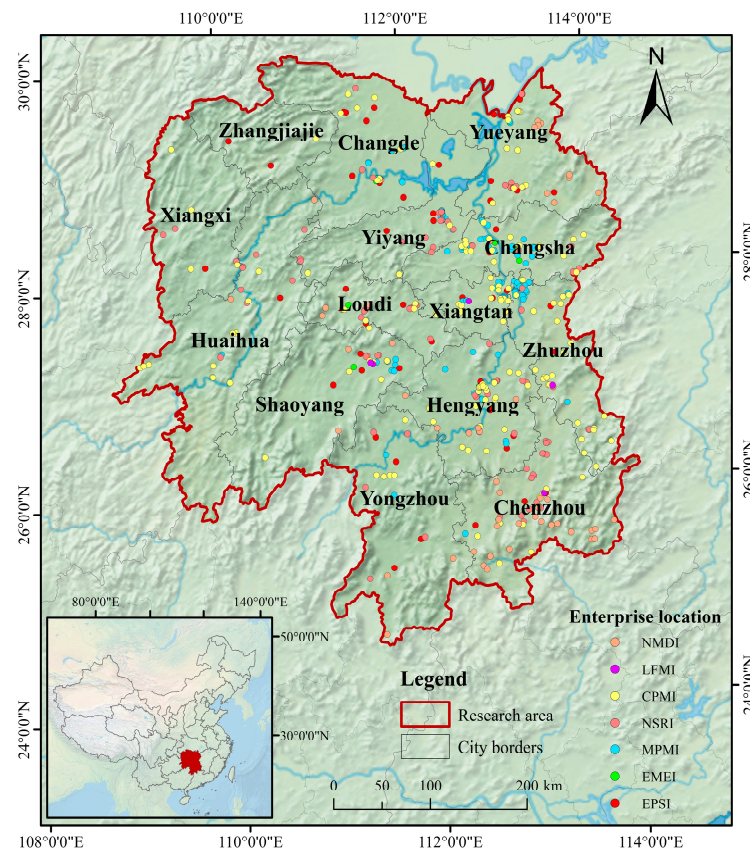


Figure 1. Study area. (1) Nonferrous metal mining and dressing industry (NMDI); (2) leather and footwear manufacturing industry (LFMI); (3) chemical product manufacturing industry (CPMI); (4) nonferrous metal smelting and rolling industry (NSRI); (5) metal product manufacturing industry (MPMI); (6) electrical machinery and equipment manufacturing industry (EMEI); (7) electric power production and supply industry (EPSI).

2.2. Study Data

In this study, seven HMIs, including the NMDI, LFMI, CPMI, NSRI, MPMI, EMEI, and EPSI, which are the key concerns of China's Ministry of Ecology and Environment, were selected. Considering the accessibility and completeness of the data, we collected data on the number of heavy metal-related enterprises in Hunan Province from 2000 to 2022 and the gross industrial product in 2017. The number of enterprises in the HMIs used in this study was derived mainly from the China Industrial Statistical Yearbook, 2000–2022, and the Social and Economic Statistical Yearbook of Hunan Province and Municipalities, 2000–2023. The data on the gross industrial product of the HMIs employed here were obtained from the China Industrial Statistical Yearbook; the Xiangxi data were substituted by the adjacent year, and the Zhuzhou data were projected based on the relevant data of the previous year.

In this study, the emission information of heavy metal-related enterprises in Hunan Province was obtained from the China Pollutant Emission Permit Management Information Platform (<http://permit.mee.gov.cn>, accessed on 28 June 2025). The platform records detailed information on emission units, including the unit's name, location, the type of industry it operates in, the number of exhaust gas and wastewater outlets, and the pollutants present in the exhaust gas and wastewater.

The data on administrative boundaries (provincial, municipal, and county boundaries) and the spatial distributions of arable land and rivers in Hunan Province used in this research were obtained from the Resource and Environment Science Data Platform of the Chinese Academy of Sciences (<http://www.resdc.cn>, accessed on 28 June 2025). The

flooded area data for Hunan Province were sourced from the Global Flood Database on Google Earth Engine [14].

2.3. Study Methods

This study analyzed the development of HMIs based on data such as the number of heavy metal-related enterprises and gross industrial product in Hunan Province over a long time series. Python3.6 was used to collect enterprise emission data from the China Pollutant Emission Permit Management Information Platform. Based on the emission permit data, the percentages of the number of exhaust gas outlets and wastewater outlets involving different heavy metal pollutants (Cd, Hg, As, Pb, and Cr) were calculated. In addition, all of the above data were characterized spatially via ArcGIS10.8. Furthermore, the spatial distance of each heavy metal-related enterprise from rivers, arable land, flooded areas, etc., was calculated via the spatial analysis function of ArcGIS 10.8. Moreover, the percentage of heavy metal-related enterprises with different distance thresholds was analyzed. Finally, GeoDa1.18 was used to calculate the bivariate Moran index (I_{xy}) of the number of emission outlets involving Cd in each county of Hunan Province and the average spatial distance of enterprises involving Cd from rivers, arable land, and flooded areas in each county to analyze the characteristics of the pollution discharges of enterprises and the spatial clustering patterns of environmental elements.

Unlike the univariate Moran's I, which measures spatial autocorrelation (clustering of similar values) within a single variable, the bivariate Moran index (I_{xy}) is a measure of the spatial correlation between two variables, quantifying the dependence relationship of one attribute at a given location with another attribute at neighboring locations in geographic space. The bivariate localized Moran index (I_{xy}) is calculated as follows:

$$I_{xy} = \frac{n \sum_{i=1}^n \sum_{j=1}^n W_{ij} (x_i - \bar{x})(y_j - \bar{y})}{\sum_{i=1}^n \sum_{j=1}^n W_{ij} \sum_{i=1}^n (x_i - \bar{x})^2} (i \neq j)$$

where n denotes the total number of samples for a given variable, x_i is the observed value of the variable in region i , y_j is the observed value of the variable in region j , $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$ denotes the mean value of x_i , $\bar{y} = \frac{1}{n} \sum_{j=1}^n y_j$ denotes the mean value of y_j , and W_{ij} denotes the spatial weighting matrix. The values range from -1 to 1 . $I_{xy} > 0$ means that there is a positive spatial correlation, and the larger the value is, the more obvious the positive spatial correlation. $I_{xy} < 0$ means that there is a negative spatial correlation, and the smaller the value is, the greater the negative spatial correlation. $I_{xy} = 0$ means that there is no spatial correlation.

According to the results of the bivariate localized index (I_{xy}), four types of spatial agglomeration can be classified as the high–high type, low–low type, high–low type, and low–high type. Specifically, the high–low type means that the number of emission outlets involving Cd in a county is high, but the average spatial distance of enterprises involving Cd from rivers, arable land, flooded areas, etc., is small. This type of spatial aggregation can indicate that pollution emissions from heavy metal-related enterprises in a county have a greater impact on the environment and should be emphasized.

3. Results

3.1. Development Characteristics of Heavy Metal-Related Industries in Hunan Province

Before 1998, the number of enterprises in HMIs increased as a whole, but after a rapid growth in 1998–1993, it dropped sharply (Figure A2 in Appendix A.2). Between 1998 and 2022, the number of enterprises in most HMIs in Hunan Province fluctuated in

an increasing manner, whereas the number of enterprises in certain industries decreased (Figure 2a). The chemical product manufacturing industry (CPMI) boasted the highest number of enterprises and the most significant growth among the seven industries. The number of CPMI enterprises increased sharply from 1998 to 2010; after 2010, it essentially remained stable. The number of enterprises in the metal product manufacturing industry (MPMI) and electrical machinery and equipment manufacturing industry (EMEI) generally showed a growth trend from 1998 to 2022. Notably, the MPMI experienced a significant acceleration in growth starting in 2017, with the number of enterprises doubling within just five years. The trends for the nonferrous metal mining and dressing industry (NMDI) and nonferrous metal smelting and rolling industry (NSRI) were similar: between 1998 and 2010, the number of enterprises in both industries exhibited growth; however, between 2011 and 2021, the number of enterprises declined, and by 2022, the number of enterprises increased slightly. For the NMDI, the number of enterprises in 2022 decreased to 84 percent of the 1998 level. The number of enterprises in the leather and footwear manufacturing industry (LFMI) continued to grow, with a significant increase in the growth rate from 2011 to 2020 compared with the period from 1998 to 2011. Between 1998 and 2022, the number of enterprises in the electric power production and supply industry (EPSI) was expected to double. In 2017, there were significant differences in the gross industrial product among various HMIs in Hunan Province (Figure 2b). The category with the highest gross industrial product was the NSRI, which accounted for 27.6% of the total gross industrial product of all HMIs, closely followed by the CPMI, with a share of 26.4%.

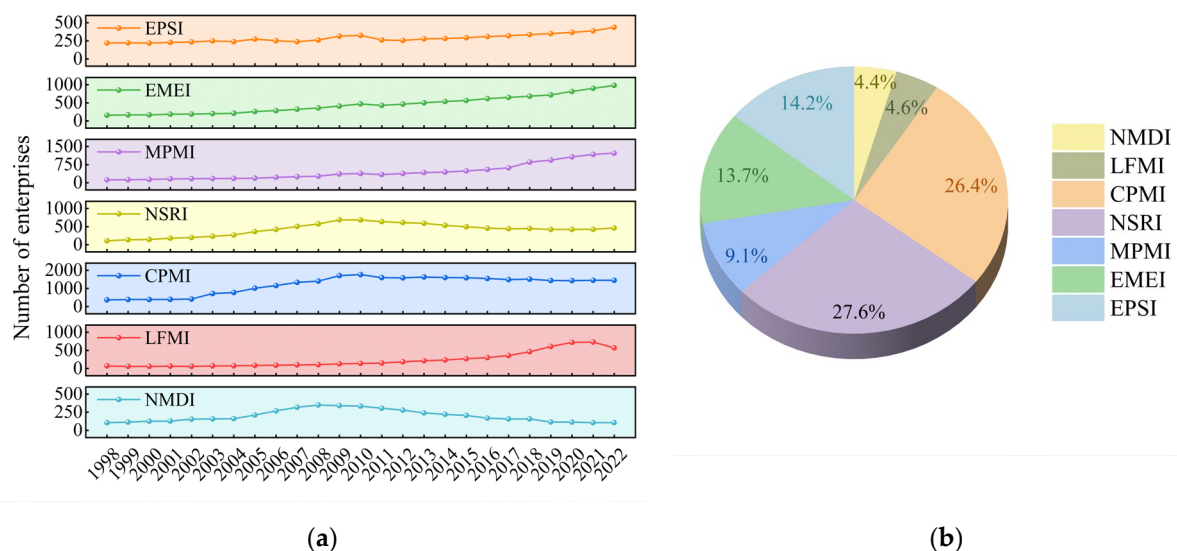


Figure 2. Development characteristics of the HMIs in Hunan Province. (a) Trends in the number of enterprises from 1998 to 2022; (b) percentage of the gross industrial product of the HMIs in 2017.

The distribution of the gross industrial product of the HMIs in Hunan Province exhibited an obvious regional imbalance (Figure 3). Among them, the cities with higher gross industrial products of the NMDI are Huaihua, Chenzhou, and Hengyang, while the cities with high gross industrial products of the LFMI are significantly clustered in southern Hunan Province, including Shaoyang, Chenzhou, and Xiangtan. The cities with high gross industrial products of the CPMI, NSRI, EMEI, and EPSI are located mainly in the eastern and western parts of Hunan Province, including Huaihua and Changsha; the cities with higher gross industrial products of the MPMI included Changsha, Shaoyang, and Loudi.

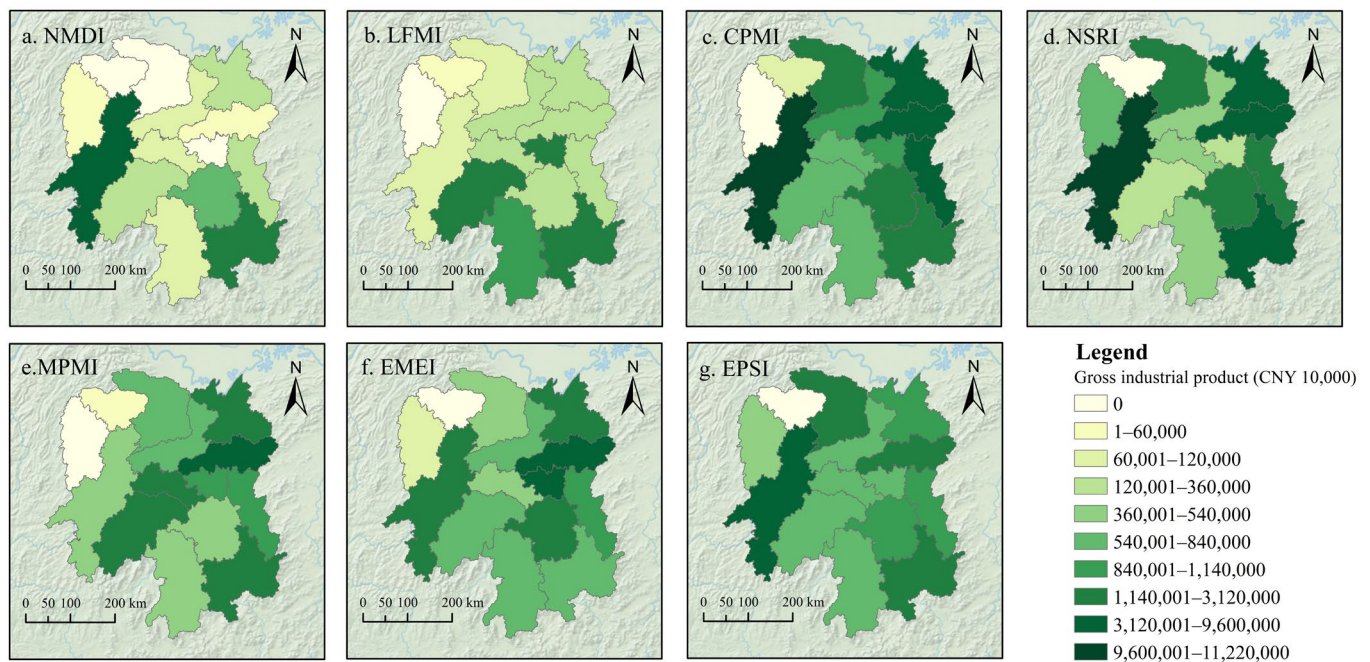


Figure 3. Spatial distribution of the gross industrial product of the HMIs in Hunan Province, 2017.

3.2. Characteristics of Pollution Emissions from Heavy Metal-Related Industries

The pathways of pollutant emissions from HMIs include exhaust gas and wastewater. The intensity of pollution emissions can be effectively reflected by the number of emission outlets. There were significant differences in the number of emission outlets in the HMIs in Hunan Province (Figure 4a). Among them, the NSRI and CPMI had the highest number of outlets, with their total emission outlets accounting for as much as 31.3% of all HMI total emission outlets, followed by the MPMI, with a share of 21.2%. In comparison, the LFMI and EMEI had the lowest number of total emission outlets. In addition, the CPMI had the highest number of exhaust gas outlets, accounting for 33.7% of all HMI exhaust gas outlets, and the NSRI had the highest number of wastewater outlets, accounting for 31% of all HMI wastewater outlets.

Accordingly, among the HMIs in Hunan Province, the NSRI also had the largest number of heavy metal-related total emission outlets, accounting for 41.3% of all heavy metal-related total emission outlets (Figure 4b), followed by the CPMI, with a share of 31.8%. In addition, the NSRI also had the largest number of heavy metal-related exhaust gas outlets and heavy metal-related wastewater outlets, accounting for 43.9% and 35.3%, respectively, of the corresponding types of outlets in all HMIs. The CPMI had the next largest number of heavy metal-related exhaust gas outlets and heavy metal-related wastewater outlets, accounting for 37.7% and 18%, respectively.

The number of total emission outlets, wastewater outlets, and exhaust gas outlets significantly differed among the cities in Hunan Province (Figure 5a). Among them, Hengyang, Changsha, and Chenzhou had the highest number of total emission outlets, accounting for 17.1%, 14.3%, and 12.4% of the total number of total emission outlets in all cities, respectively. Hengyang and Changsha had the highest number of exhaust gas outlets, accounting for 18% and 15.7% of the total number of exhaust gas outlets in all cities, respectively, and Chenzhou had the highest number of wastewater outlets, accounting for 19.9% of the total number of wastewater outlets in all cities. In addition, the cities with a greater number of total emission outlets were, in order, Loudi, Xiangtan, Zhuzhou, and Yueyang. The cities with fewer total emission outlets in Hunan Province were Yiyang, Shaoyang, Zhangjiajie, and others.

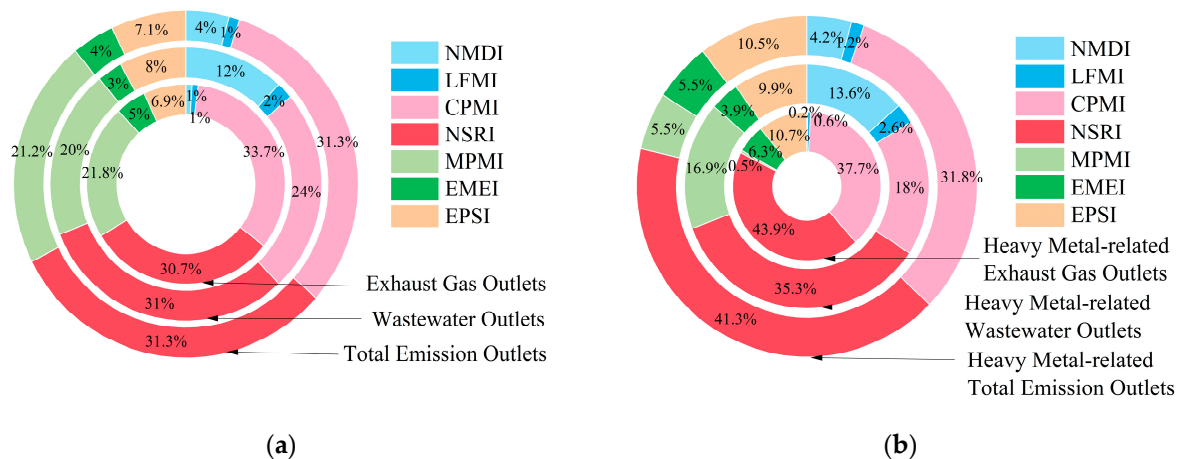


Figure 4. Distribution of the number of pollution emission outlets of the HMIs in Hunan Province. (a) Proportion of exhaust gas outlets, wastewater outlets, and total emission outlets to the total number of corresponding types of emission outlets in all HMIs; (b) proportion of heavy metal-related exhaust gas outlets, heavy metal-related wastewater outlets, and heavy metal-related total emission outlets to the total number of corresponding types of emission outlets in all HMIs. The innermost circle of the figure represents the proportional distribution of (heavy metal-related) exhaust gas outlets for HMIs. The middle circle represents the proportionate distribution of (heavy metal-related) wastewater outlets from HMIs. The outermost circle represents the proportional distribution of (heavy metal-related) total emission outlets in the HMIs, where the (heavy metal-related) total emission outlet is the sum of the (heavy metal-related) exhaust gas outlet and the (heavy metal-related) wastewater outlet.

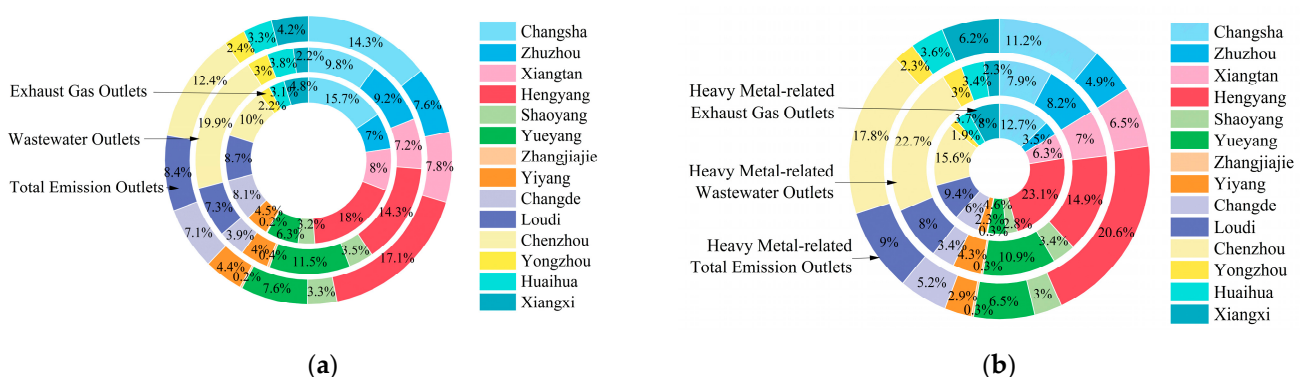


Figure 5. Distribution of pollution emission outlets in Hunan Province by city. (a) Proportion of exhaust gas outlets, wastewater outlets, and total emission outlets to the total number of corresponding types of emission outlets in all cities; (b) proportion of heavy metal-related exhaust gas outlets, heavy metal-related wastewater outlets, and heavy metal-related total emission outlets to the total number of corresponding types of emission outlets in all cities. The innermost circle of the figure represents the proportional distribution of (heavy metal-related) exhaust gas outlets for HMIs. The middle circle represents the proportionate distribution of (heavy metal-related) wastewater outlets from HMIs. The outermost circle represents the proportional distribution of (heavy metal-related) total emission outlets in the HMIs, where the (heavy metal-related) total emission outlet is the sum of the (heavy metal-related) exhaust gas outlet and the (heavy metal-related) wastewater outlet.

Similar to the distribution of the total emission outlets in Hunan Province, the cities with higher numbers of heavy metal-related total emission outlets were mainly Hengyang and Chenzhou, accounting for 20.6% and 17.8% of the total number of heavy metal-related total emission outlets in all cities, respectively, whereas Zhangjiajie had a relatively small number (Figure 5b). Among the cities in Hunan Province, Chenzhou had the largest number of heavy metal-related wastewater outlets, accounting for 22.7% of the total number of

heavy metal-related wastewater outlets in all cities, whereas Hengyang had the largest number of heavy metal-related exhaust gas outlets, accounting for as many as 23.1% of the total number of heavy metal-related exhaust gas outlets in all cities.

Among the heavy metal-related exhaust gas outlets, the NMDI and LFMI were involved in the emission of only one type of heavy metal pollutant, Hg, whereas the MPMI was involved in the emission of three types of heavy metal pollutants, namely, Cd, Pb, and Cr (Figure 6a). The remaining HMI exhaust gas outlets were involved in the emission of five heavy metal pollutants, namely, Cd, Hg, As, Pb, and Cr. Among them, the EPSI, NSRI, and CPMI had more exhaust gas outlets involving Hg, accounting for 99.42%, 60.54% and 52.22% of the total number of heavy metal-related exhaust gas outlets in the corresponding industries, respectively, whereas the EMEI had more exhaust gas outlets involving Pb, with a proportion of 94.06%.

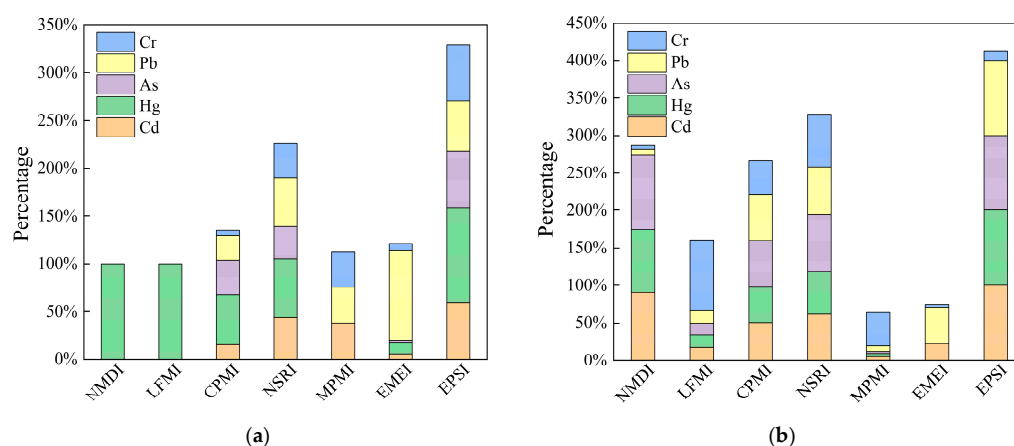


Figure 6. Characteristics of heavy metal emissions of various HMIs in Hunan Province. (a) Proportion of different heavy metal pollutants emitted from heavy metal-related exhaust gas outlets; (b) proportion of different heavy metal pollutants emitted from heavy metal-related wastewater outlets.

Among the heavy metal-related wastewater outlets, the HMIs were involved mainly in the emission of heavy metal pollutants, such as Cd, Hg, and As (Figure 6b). Among them, all heavy metal-related wastewater outlets of the EPSI were involved in the emission of four heavy metal pollutants, namely, Cd, Hg, As, and Pb. All heavy metal-related wastewater outlets of the NMDI involved As, and there were also more wastewater outlets involving Cd and Hg, accounting for 89.47% and 85.26% of the total number of heavy metal-related wastewater outlets of the NMDI, respectively. The LFMI and MPMI wastewater outlets were involved mainly in the emission of Cr, and wastewater outlets involving Cr accounted for 94.44% and 45.74%, respectively, of the total number of heavy metal-related wastewater outlets.

The heavy metal emissions from HMIs in various cities in Hunan Province were clearly characterized (Figure 7). The cities with the largest number of exhaust gas outlets involving Cd, Hg, and Pb were Hengyang, Chenzhou and Xiangxi, among which the number of exhaust gas outlets involving Hg and Cd in Hengyang was the highest, accounting for 16.54% and 7.7% of the total number of heavy metal-related exhaust gas outlets in all cities, respectively, and the number of exhaust gas outlets involving Pb in Chenzhou was the largest, accounting for 9.1%. The cities with the largest number of exhaust gas outlets involving As were Chenzhou, Hengyang, and Changde, accounting for 8.88%, 8.56%, and 4.76%, respectively; the cities with the largest number of exhaust gas outlets involving Cr were Loudi, Chenzhou, and Changde, accounting for 8.56%, 4.89%, and 4.57%, respectively. The cities with the highest number of wastewater outlets involving Cd, Hg, As, and Pb were

Hengyang, Chenzhou, and Yueyang, where the number of wastewater outlets involving As, Cd, and Hg in Chenzhou was the highest, accounting for 19.68%, 12.93%, and 12.5% of the total number of heavy metal-related wastewater outlets in all cities, respectively. The number of wastewater outlets involving Pb was the largest in Hengyang, accounting for 10.92%; the cities with the largest number of wastewater outlets involving Cr were Chenzhou, Hengyang, and Xiangtan, accounting for 11.06%, 7.33%, and 5.03%, respectively.

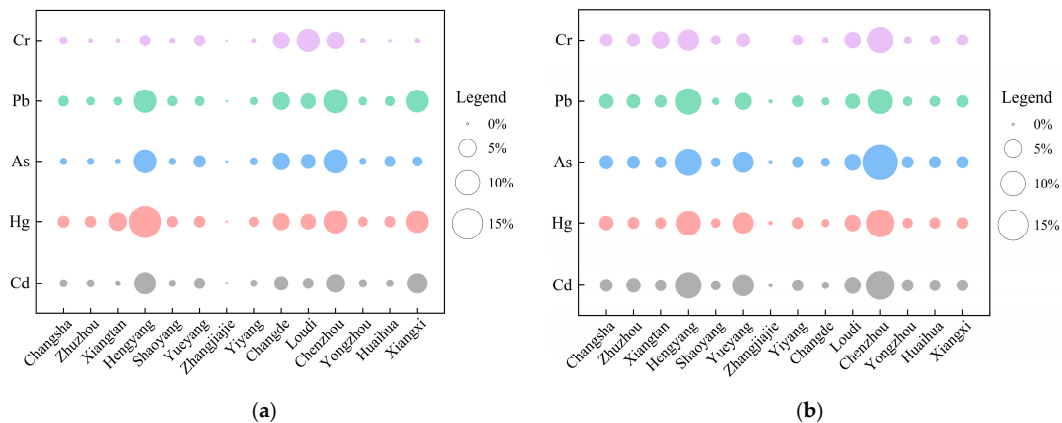


Figure 7. Characteristics of heavy metal emissions from heavy metal-related emission outlets in Hunan Province. (a) Proportion of exhaust gas outlets involving heavy metals to the total number of heavy metal-related exhaust gas outlets in all cities; (b) proportion of wastewater outlets involving heavy metals to the total number of heavy metal-related wastewater outlets in all cities.

The number of emission outlets involving Cd in several counties in southeastern and northern Hunan Province was relatively high, accounting for between 3% and 10% of the total number of emission outlets involving Cd in all counties (Figure 8). Among the counties with the largest number of emission outlets involving Cd were Changning of Hengyang and Huayuan of Xiangxi, accounting for 9.98% and 9.38%, respectively. The next highest number of emission outlets involved Cd, mainly in Guiyang, Su Xian, and Zixing of Chenzhou, accounting for 6.15%, 4.84%, and 4.64%, respectively. In addition, emission outlets involving Cd from Lengshuijiang of Loudi accounted for a relatively high proportion (5.24%). In contrast, there were relatively few emission outlets involving Cd in the western part of Hunan Province.

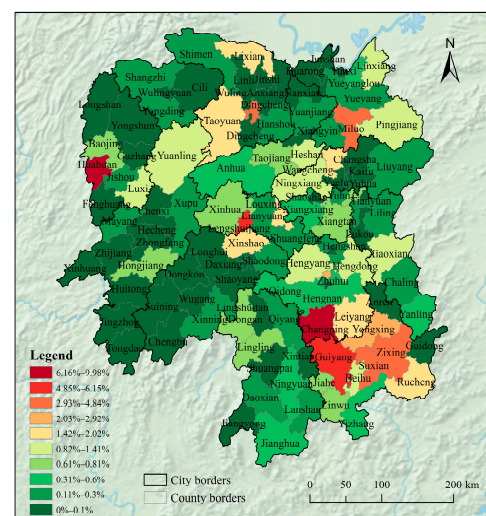


Figure 8. Distribution of the proportion of emission outlets involving Cd in each county in Hunan Province to the total number of emission outlets involving Cd in all counties.

3.3. Environmental Impacts of Pollution Emissions from Heavy Metal-Related Industries

The average distances of heavy metal-related enterprises from arable land, rivers, and flooded areas were 256 m, 1763 m, and 3352 m, respectively (Figure 9). Among them, arable land existed within 2 km of all enterprises in the HMIs: the proportion of enterprises within 1 km of arable land to the number of all enterprises in the HMIs was 96.44%, and the proportion of enterprises in close proximity to arable land was 25.08%. Rivers existed within 10 km of all enterprises in the HMIs: 94.17% of the enterprises were no more than 5 km from rivers, and 50% were within 1.5 km of rivers. Flood areas existed within 23 km of all enterprises in the HMIs: 95% of the enterprises were not more than 10 km away from flooded areas, and 53.49% of the enterprises were within 2 km of flooded areas.

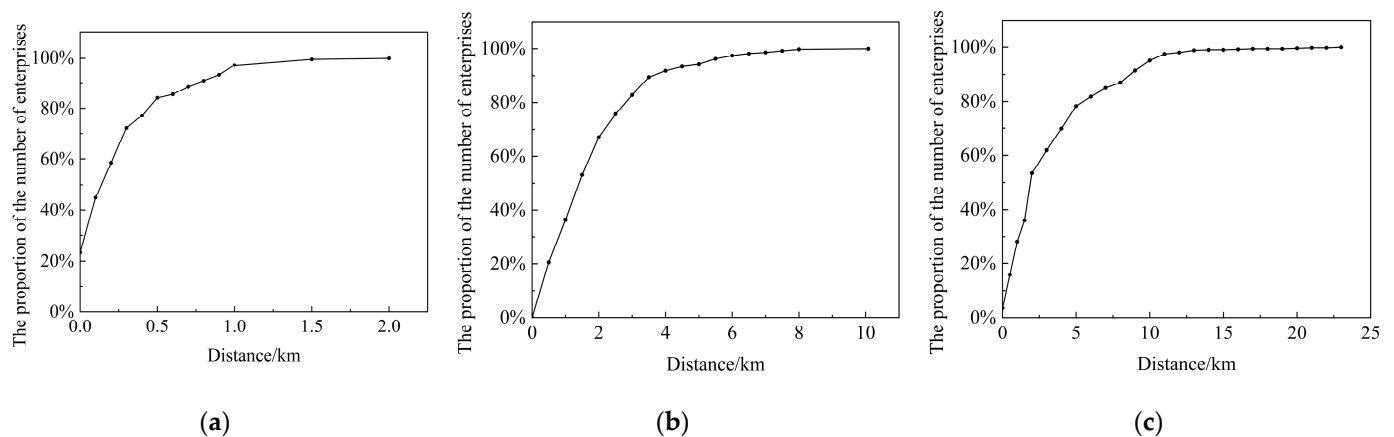


Figure 9. Cumulative percentage analysis of the distance of heavy metal-related enterprises from (a) arable land, (b) rivers, and (c) flooded areas.

Enterprises involving Cd in most counties in western and northern Hunan Province were close to rivers and flooded areas, whereas enterprises involving Cd in most counties in western and central Hunan Province were close to arable land (Figure 10). Except for Yueyanglou, the average distance between enterprises involving Cd and arable land in the remaining counties in Hunan Province was less than 1 km. Among them, the counties where the average distance between enterprises involving Cd and arable land was less than 30 m were mainly concentrated in Shaoyang and Yongzhou. In contrast, enterprises involving Cd in most counties of Yueyang, Shuangfeng of Loudi, and Xinning of Shaoyang were relatively far from arable land, with average distances ranging from 0.4 km to 1 km. The counties where enterprises involving Cd were adjacent to rivers were mainly concentrated in Huaihua and Xiangxi, and the average distance between enterprises involving Cd and rivers in these areas was less than 0.5 km. In contrast, some counties in Yiyang, Shaoyang, and Hengyang had enterprises involving Cd that were relatively far from a river, averaging approximately 5 km. The distance between enterprises involving Cd and flooded areas in most counties in Yueyang, Changde, Zhangjiajie, Xiangxi, Huaihua, and Shaoyang was relatively small, at less than 2.5 km on average. In contrast, the distance between enterprises involving Cd in some counties in Chenzhou and the flooded area was greater than 5 km on average.

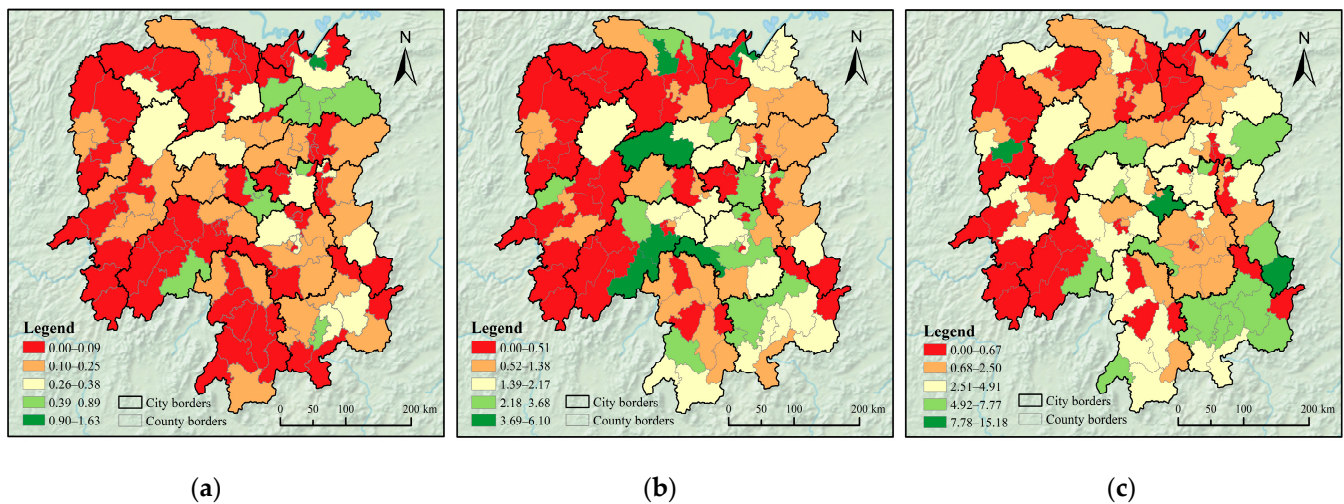


Figure 10. Spatial distribution of the distance between enterprises involving Cd in HMIs and environmental elements in Hunan Province. (a) Average distance between enterprises and arable land; (b) average distance between enterprises and rivers; (c) average distance between enterprises and flooded areas.

The spatial clustering characteristics between the number of emission outlets involving Cd and the average distance of emission outlets involving Cd from arable land, rivers, and flooded areas in various counties in Hunan Province differed significantly (Figure 11). Counties of the high–high type were clustered mainly in the eastern part of Hunan Province, including Guiyang of Chenzhou and Taojiang of Yiyang. These counties had a larger number of emission outlets involving Cd, as well as a longer average distance from these aspects of the environment. The counties of the high–low type were distributed mainly in the eastern part of Hunan Province, covering some counties in Chenzhou, Hengyang, Loudi, Yueyang, Anxiang of Changde, etc. These counties had many emission outlets involving Cd and, at the same time, relatively short average distances from rivers, arable land, and flooded areas. In addition, a small amount of high–low type agglomeration also existed in areas such as Guzhang in Xiangxi, in the western part of Hunan Province, which needs to be focused on.

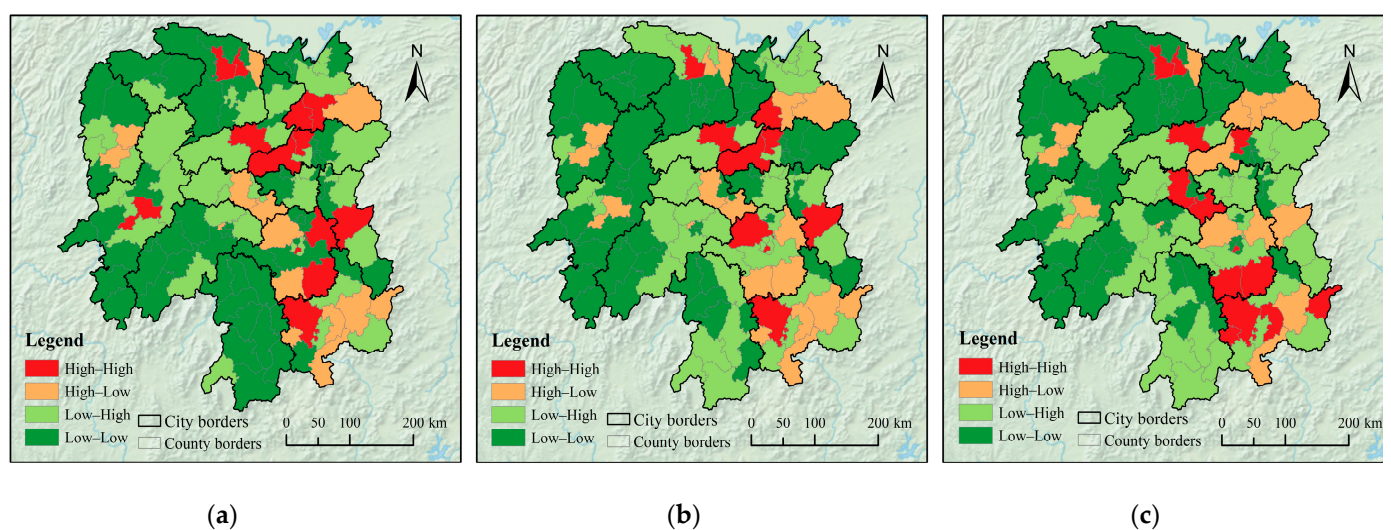


Figure 11. Cluster analysis of the number of emission outlets involving Cd in Hunan Province and the distance of emission outlets involving Cd from (a) arable land, (b) rivers, and (c) flooded areas.

4. Discussion

4.1. Development and Pollution Emissions from Heavy Metal-Related Industries

Although the industrialization level of Hunan province is higher than the national average level, its industrial structure is dominated by nonferrous metal smelting, machinery manufacturing, and chemical production. Hunan Province, as a representative Chinese region characterized by the rapid development of HMIs and significant pollution emissions, is a vital base for nonferrous metal mineral resources in China [15]. The NSRI, NMDI, and other HMIs are extensive in scale within Hunan Province, and the gross industrial product of the NSRI ranks first among all HMIs, accounting for 27.6%. Following the policy loosening and macro-control in the early stage of reform and development, the number of enterprises in HMIs increased sharply and then decreased sharply from 1988 to 1993. The NSRI and NMDI showed rapid growth in the number of enterprises between 1998 and 2009 due to policy incentives and increased demand from HMIs, increasing by 3.71 and 1.71 times, respectively. However, with the implementation of environmental pollution control policies in China [16], the number of nonferrous metal enterprises has continued to decrease since 2010. Moreover, environmental policies have been effective in reducing heavy metal emissions from the nonferrous metals industry and are crucial for environmental sustainability. Although the development speed of HMIs may slow down to a certain extent in the early stage of emission reduction measures (Figure A3 in Appendix A.3), in the long run, heavy metal enterprises will significantly improve the stability and operation efficiency of production process and reduce resource consumption, energy cost, and treatment cost after the innovation of production technology and the transformation of clean production technology.

While making great contributions to the economic prosperity and social progress of Hunan Province, HMIs, such as nonferrous metal mining and smelting, have also led to increasingly serious issues with heavy metal pollution emissions [17–19]. Heavy metal-related industrial production activities release large quantities of Cd, Hg, As, and other pollutants into the environment. Among them, the problem of Cd emission from heavy metal-related enterprises is particularly prominent. In the emissions of exhaust gas and wastewater from HMIs, Cd accounted for 16.4% and 21% of all heavy metal pollutants, respectively. Nonferrous metal mining, smelting, and the uncontrolled emission of exhaust gas, wastewater, and sludge from various HMIs constitute the main emission pathways for Cd [20,21]. Heavy metal pollution also has a significant impact on local society and the economy. Discharge of metals like Cd can cause cancer and neurological damage, as well as increase medical and social security costs. It also harms agriculture and fisheries, leading to unemployment and hindering economic development.

Heterogeneity in the degree of development and types of dominant industries among cities is an important reason for the spatial heterogeneity in heavy metal emissions in Hunan Province [22]. Unlike previous studies that often focused on the mining areas in western or northern Hunan, the counties with more serious emissions of heavy metal pollution in Hunan Province are mainly concentrated in the southeastern part of Hunan Province, especially in Hengyang and Chenzhou, which have particularly serious problems with the emission of heavy metal pollution [23]. In Hunan Province, heavy metals accounted for 43.1% and 50.3% of the emissions of waste gas and wastewater from the heavy metal industries in Hengyang City and 37.1% and 66.1% of the emissions of waste gas and wastewater from Chenzhou City.

Hengyang is located in the polymetallic metallogenic belt of the Nanling Mountains, with the Shizhuyuan polymetallic mining area and the Shuikoushan lead–zinc mining area. The Shuikoushan mine is the largest and oldest mine in Hunan Province [24], which makes nonferrous metal mining one of the pillar industries. In recent years, Chenzhou has also

focused on unique and characteristic nonferrous metal resources and has strived to build “nonferrous metal capital” as its industrial brand, which has contributed greatly to the economic development of HMIs there. These two cities have a relatively large number of enterprises involved in heavy metal emissions, and the pollution emission pressure is relatively greater because of the disorderly mining of minerals and extensive production. The findings identify Hengyang City and Chenzhou City as areas with high levels of heavy metal pollution and significant risks in Hunan Province. This result shows that the pollution center of Hunan Province is shifting to the emerging industrial area, and the evolution of this spatial pattern reveals new environmental risks in regional development. For such areas with high pollution emissions, stricter policy measures should be implemented, such as controlling the emission ceiling of heavy metal industries and adopting cleaner technologies, to provide a Chinese solution for pollution control in global heavy metal-concentrated industrial areas. This is in line with the industrial innovation component of the SDGs.

4.2. Environmental Impacts of Heavy Metal Pollution Discharge

In recent years, the industrialization process of HMIs has accelerated, and the impact on soil heavy metal pollution has become increasingly significant [25]. Long-term industrial activities have resulted in the accumulation of heavy metal pollutants in surrounding farmland soils [26], threatening food safety and human well-being and destroying the ecological sustainability of agricultural systems, which highlights the importance of the health goals in the SDGs. In particular, the rapid development of the NMDI and NSRI has led to a sharp increase in the level of metal pollution in the soil, and the emission of heavy metal pollutants, such as Cd, Hg, and As, has also become the main source of serious soil pollution in Hunan Province, which has attracted widespread attention [27,28]. In addition, relevant studies have shown that areas with high exceedance rates of heavy metals, such as Cd, Hg, As, and Pb, are distributed mainly in the dense areas of HMIs, such as Chenzhou and Hengyang [22], which basically coincides with the areas of aggregation of the H-L type with a high number of emission outlets involving Cd and close proximity to arable land, as revealed by the results.

Hunan Province has a mining history of 120 years, but the water pollution problem in this area is particularly severe and is characterized by high toxicity, difficult degradation, and easy accumulation [29]. The problem of heavy metal pollution in the water in Hunan Province is usually considered to be closely related to the discharge of wastewater from the NSRI and CPMI [30]. Hunan Province is rich in nonferrous mineral resources, such as Pb, Zn, Cu, and Mn, and the mining and smelting of nonferrous metals over the centuries have caused severe heavy metal pollution in river ecosystems, especially in Hengyang [31]. The discharge of heavy metal-containing acidic wastewater into the environment without effective control may cause significant risks [32]. The H-L type areas, which have a high number of emission outlets involving Cd and are in close proximity to rivers, are mainly concentrated in Hengyang and Chenzhou. Therefore, the effective control of heavy metals is necessary for regional sustainability and the well-being of residents in regions of Hunan Province with high levels of heavy metal contamination in water bodies by comprehensively monitoring pollution data for water quality and purifying water bodies by using bioremediation and other technologies. All of this will help achieve the clean water component of the SDGs.

Flooding is one of the ways in which heavy metals in river water bodies enter farmland soil [33]. Heavy metal enterprises are often in close proximity to rivers; the heavy metal pollutants discharged by them easily infiltrate river systems, and some heavy metals are adsorbed by particles and stored in sediments [34]. Owing to the mining, smelting,

and manufacturing activities of nonferrous metals in Hunan Province, soil heavy metal pollution along the main river systems of the Xiangjiang River, Zi River, and Leishui River in Hunan Province is serious [35]. Related studies have shown that during floods, the sediment of a water system containing heavy metals migrates to the adjacent floodplain area with the diffusion of floods, resulting in heavy metal pollution of the soil in this area [36,37]. Heavy metals emitted into the air by companies can also be deposited into the soil and water to form secondary pollution. This continuous trans-media transport establishes pervasive contamination pathways of heavy metals. The heavy metal content in Yueyang and Changsha in the Xiangjiang River Basin of Hunan Province is significantly higher than that in other regions [22], and it is also the main concentration area of H-L-type regions with a high number of emission outlets involving Cd and proximity to flooded areas.

4.3. Limitations

This study has several limitations. One limitation is the incompleteness of the enterprise data. There were omissions in the number of enterprises searched by the national Pollutant Emission Permit Management Information Platform, and some small and medium-sized enterprises, informal enterprises, or enterprises that have not actively declared may not be included in the platform, which leads to an incomplete pollution source list. These gaps likely led to an underestimation of the total emissions. On the other hand, owing to the lack of heavy metal monitoring data, heavy metal contents in rivers, arable land, water, and soil around flooded areas were not analyzed. However, when relevant studies are compared, the results of this study can better reflect the spatial pattern of the development trend and environmental impacts of HMIs in Hunan Province. We will continue to collect data on companies and heavy metal levels through web searches or on-site monitoring to enhance accuracy.

5. Conclusions

Relying on gross industrial product data and emission permit information from HMIs in Hunan Province, this study conducted a comprehensive and in-depth analysis of the development trend of HMIs in Hunan Province, and the characteristics of pollution emissions and their environmental impacts were determined via ArcGIS 10.8 spatial analysis technology. The results show the following:

(1) In terms of industry development, the number of enterprises in HMIs in Hunan Province from 2000 to 2022 showed an overall growth trend. Among them, the CPMI had the highest number and the most obvious increase, while the number of NMDI enterprises clearly decreased. In addition, the NSRI had the highest gross industrial product, accounting for 27.6% of the gross industrial product of all HMIs.

(2) In terms of pollution emission characteristics, the NSRI and CPMI had the largest number of emission outlets in Hunan Province, with NSRI heavy metal-related exhaust gas outlets and heavy metal-related wastewater outlets accounting for as many as 43.9% and 35.3%, respectively, of the corresponding types of emission outlets in all HMIs. All HMIs resulted in significant emissions of Cd, Hg, As, and other pollutants, but there were obvious differences in the types and quantities of heavy metal elements involved in the exhaust gas outlets and wastewater outlets of different HMIs. Chenzhou had the highest number of heavy metal-related wastewater outlets, and Hengyang had the highest number of heavy metal-related exhaust gas outlets, accounting for 22.7% and 23.1% of the same type of heavy metal-related emission outlets in Hunan Province, respectively. In addition, the number of emission outlets involving Cd in some counties of Chenzhou and Hengyang was also high among all cities.

(3) At the level of environmental impact, the average distances of heavy metal-related enterprises from arable land, rivers, and flooded areas were 256 m, 1763 m, and 3352 m, respectively. Enterprises located at a distance of 1 km from arable land, rivers, or flooded areas accounted for 97.21%, 36.33%, and 28.14%, respectively, of all heavy metal-related enterprises. In addition, counties where enterprises involving Cd were closer to environmental elements were clustered mainly in the western part of Hunan Province, and counties where the spatial aggregation type of the number of emission outlets involving Cd and the distance from environmental elements was high–low were clustered mainly in the eastern part of Hunan Province.

The results identified two industries (NSRI, CPMI) with a large contribution rate in the HMIs and two regions (Chenzhou, Hengyang) with serious heavy metal pollution, which can provide a valuable reference and guidance for HMIs to formulate pollution reduction policies. Based on this research, the control of HMIs can be further increased to reduce the risk of heavy metal pollution effectively and ensure the safety of the ecological environment by upgrading and transforming processes, developing cleaner production technology, and establishing a full-caliber list of enterprises in HMIs. In addition, for areas that have been seriously polluted by heavy metals, it is also important to take timely remediation measures, such as microbubble coupling detergent technology, to prevent the spread of pollution. In the future, we will continue to research the characteristics of heavy metal pollution, including the measurement of heavy metals in soil and water, so as to comprehensively analyze the characteristics of heavy metal emissions in Hunan Province and make better reference suggestions for national and global prevention and control.

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Abbreviations

The following abbreviations are used in this manuscript:

HMIs	heavy metal-related industries
NMDI	nonferrous metal mining and dressing industry
NSRI	nonferrous metal smelting and rolling industry
MPMI	metal product manufacturing industry
CPMI	chemical product manufacturing industry
LFMI	leather and footwear manufacturing industry
EMEI	electrical machinery and equipment manufacturing industry
ESPI	electric power production and supply industry
SDGs	United Nations Sustainable Development Goals

Appendix A

Appendix A.1

Figure A1 illustrates the spatial distribution and clustering intensity of enterprises in HMIs, which helps to more clearly illustrate the spatial clustering of pollution. Heavy metal enterprises are mainly concentrated in eastern Hunan Province. The high-density clustering area for heavy metal enterprises is located in the Zhuzhou–Xiangtan–Changsha region, with a core density value of 920.48–1144.98. Additionally, the central regions of Hengyang City and Chenzhou City have a higher concentration of heavy metal enterprises, with the highest core density value of 704.95.

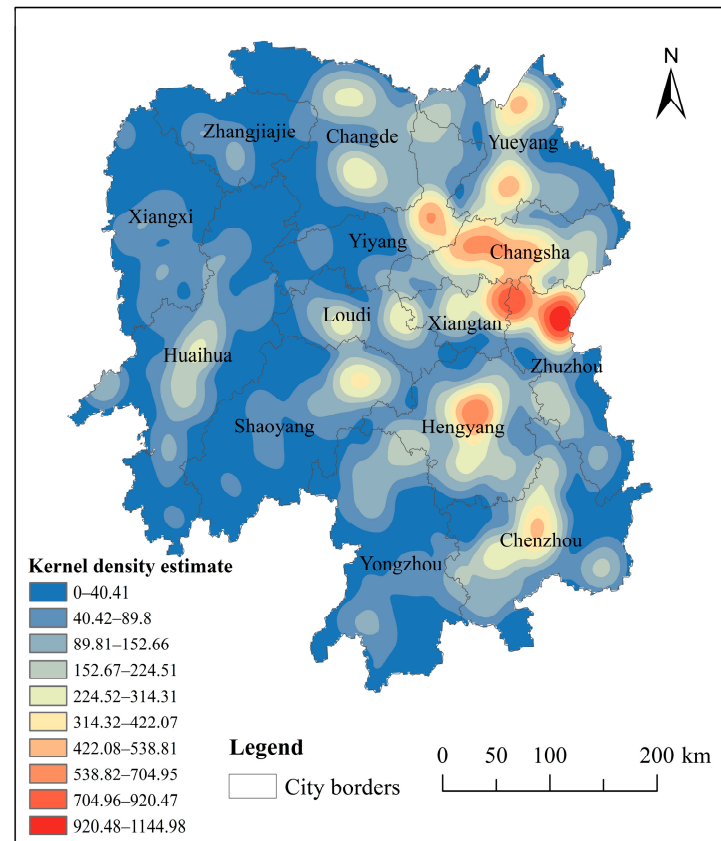


Figure A1. Heat map of HMI enterprises in Hunan Province. The red–yellow–blue color gradient indicates the high-density concentration and gradient distribution in the study area.

Appendix A.2

Figure A2 illustrates the changing trend in the number of enterprises involved in heavy metal industries in Hunan Province from 1985 to 1997; it also analyzes the development status and policy impact of heavy metal industries in Hunan Province. Before 1997, the number of enterprises in HMIs increased as a whole. Following the policy loosening and macro-control in the early stage of reform and development, the number of heavy metal industry enterprises increased sharply and then decreased sharply from 1988 to 1993.

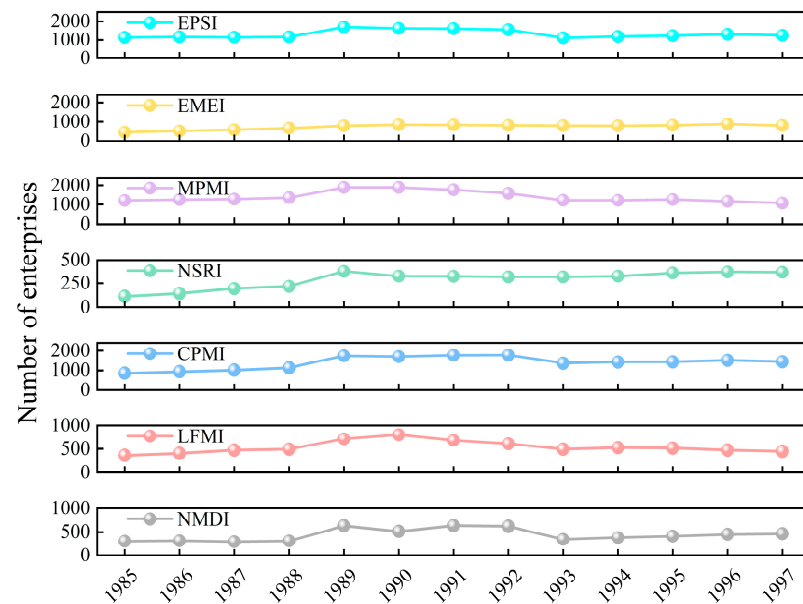


Figure A2. Trends in the number of enterprises from 1985 to 1997. The different colored curves represent seven different heavy metal industries: (1) nonferrous metal mining and dressing industry (NMDI); (2) leather and footwear manufacturing industry (LFMI); (3) chemical product manufacturing industry (CPMI); (4) nonferrous metal smelting and rolling industry (NSRI); (5) metal product manufacturing industry (MPMI); (6) electrical machinery and equipment manufacturing industry (EMEI); (7) electric power production and supply industry (EPSI).

Appendix A.3

Figure A3 illustrates the development trend in the total industrial products of HMIs in Yueyang City from 1998 to 2022 and the impact of heavy metal pollution control on economic indicators. In Yueyang City, Hunan Province, a typical resource-based city and center for HMIs, the implementation of environmental regulations in the short term may slow down the overall growth rate of HMIs.

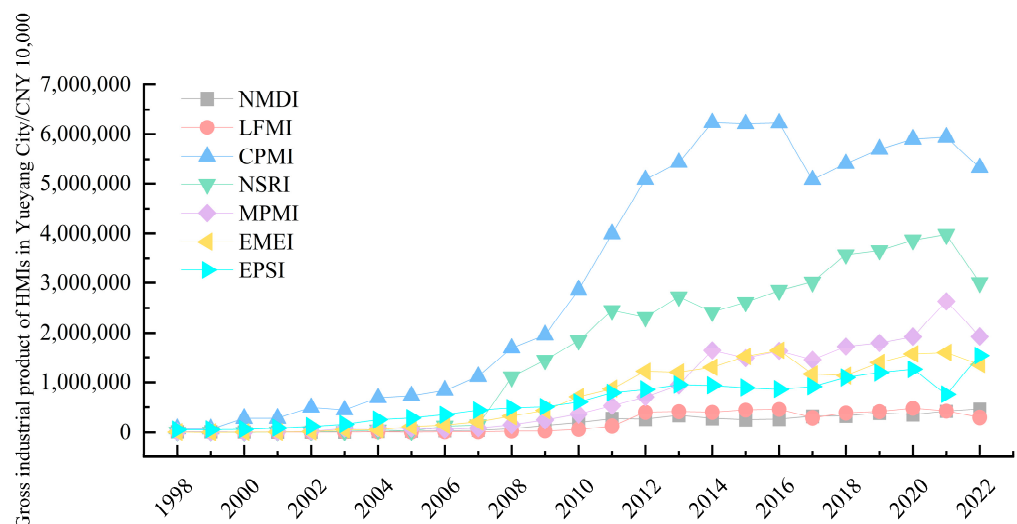


Figure A3. Trends in the gross industrial product of HMIs in Yueyang, 1998–2022. The different colored curves represent seven different heavy metal industries: (1) nonferrous metal mining and dressing industry (NMDI); (2) leather and footwear manufacturing industry (LFMI); (3) chemical product manufacturing industry (CPMI); (4) nonferrous metal smelting and rolling industry (NSRI); (5) metal product manufacturing industry (MPMI); (6) electrical machinery and equipment manufacturing industry (EMEI); (7) electric power production and supply industry (EPSI).

However, by continuously investing in production process innovations and vigorously promoting clean production technology upgrades, heavy metal enterprises are gradually building a modern production system characterized by low energy consumption, low emissions, and high resource utilization. In the long term, this will significantly reduce the resource consumption and energy costs per unit product, enhance the stability and operational efficiency of production processes, reduce the burden and costs of end-of-pipe treatment, and ultimately achieve a sustainable win–win between environmental protection and economic development.

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