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Spatial Distribution Characteristics of Coal Mine Drainage Water Quality in China

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Abstract
Coal mine drainage (CMD) reuse is an important method for optimizing water resource supply in arid/semi-arid regions. This study analyzed the spatial distribution of water quality, management, and utilization strategies for CMD in China. In northwest, northeast, and north China, CMD was characterized by high levels of suspended solids, high salinity, neutral/weakly alkaline pH, and low levels of Fe/Mn. Based on existing water treatment processes, mine water reuse is safe and can support local water supply in these areas. In southern China, especially the southwestern regions, the CMD was characterized by low pH, high salinity, and high levels of Fe/Mn. These areas face high costs associated with mine water reuse and ecological and environmental risks. Therefore, the prevention and control of water pollution should be the focus of mine water management in these areas. To maximize the utilization of CMD, improving the norms and standards for mine water utilization is necessary, policy support for CMD reuse should be fortified, and a complete chain of coal mine water utilization should be developed. This study provides a reference for implementing water environmental protection strategies and mine water reuse policies.

Keywords pH · Salinity · Fe · Mn · Suspended solids · Utilization strategies

Introduction

Mine water reuse can be important for optimizing the water supply structure in water-scarce regions (Liu and Li 2019; Peng et al. 2019). Laws and regulations, macro-management, and policy support are gradually being established for mine drainage utilization in China. The annual discharge of coal mine drainage (CMD) is ≈7.1 billion m^3, accounting for 97% of the total mine drainage in China (Cao et al. 2020a, b; Sun et al. 2020). Improving the reuse of CMD has been added to the national agenda, and the mine water utilization rate is expected to increase from 55% in 2025 to 80% in 2035 (Gu et al. 2021a, b). To use CMD as a suitable water resource in the coming decades, it is necessary to understand the spatial distribution characteristics of the water quality in China's coal mines.

Mapping the regional distribution of water quality is essential to determine the spatial geochemical processes and implement technical standards for water utilization in different geographical regions. Moreover, it provides a better understanding of the links between endemic disease distribution and water use (Sun et al. 2014a, b). Groundwater flow and water balance can be significantly altered by the destruction of underground aquifers and rock structures caused by coal mining, and the chemical characteristics of the groundwater are often transformed (Liu et al. 2019; Qian et al. 2018; Xu et al. 2018). In China, the chemical properties of CMD differ significantly between different regions. China's national standard of mine water classification divides CMD into five categories: acidic mine water, mine water containing suspended solids (SS), highly saline mine water, mine water containing toxic and hazardous elements, and clean mine water (Shao and Li 2012; Sun et al. 2012). The presence of hazardous elements in CMD causes environmental and health concerns regarding its reuse. Moreover, using CMD with high hazardous elements content as a domestic water supply can still pose a health concern, even

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if the content is reduced by water treatment technologies (Rebello et al. 2021; Sankhla et al. 2016). Clean mine water with suitable salinity, low SS, neutral pH, and low levels of hazardous elements is an ideal water source. However, the geospatial distribution of clean mine water is limited. Therefore, water reuse usually involves water with low levels of harmful elements, high levels of SS and Fe/Mn, and high salinity (Feng et al. 2014; Liu and Liu 2010).

The spatial distribution of CMD quality in China remains unclear, so this study attempted to analyze the spatial distribution of CMD quality at a national scale using ArcGIS technology. This can aid in implementing water conservation strategies and mine water reuse policies.

Methods

Overview of China's Water Resources

The spatial distribution of water resources in China is unbalanced and does not match land distribution, mineral resources, and productivity. There is more water in the south and east than in the north and west (Burke 2000; Jiang 2009; Li et al. 2016). Annual precipitation is the lowest in the northwest at < 50 mm, gradually increasing to > 3000 mm along the southeast. The distribution of annual potential evapotranspiration shows an increasing trend from the southeast to the northwest (OSGeo-China Center 2016). Most cities with high water consumption for coal mining are located in water-scarce regions, further exacerbating the strain between water resources and use in these regions (Lin et al., 2020).

Data Source and Processing

China's coalfields can be divided into five regions: the northern, southern, northeastern, northwestern regions, and the Tibet-western Yunnan area. The coal mining in Shanxi, Inner Mongolia, Shaanxi, Xinjiang, Guizhou, Anhui, Henan, Shandong, Ningxia, Heilongjiang, Yunnan, and Hebei provinces and autonomous regions accounted for 97% of the country's coal production in 2021. The survey data on mine water quality were obtained from the Trace Elements in Coal of the China Database Management System (TECC; Yang et al. 2017). As a database system managing trace element data in coal, TECC has provided support to coal energy and the environment in recent years, such as spatial distribution of hazardous elements in coal and evaluation of coal elements content benchmarks (Cao et al. 2020b, 2021).

In this study, water quality data of (323 pH, 99 SS, 241 total dissolved solids (TDS), 264 Mn, and 374 Fe indicators) in CMD from major coal mining areas were obtained to determine the spatial distribution characteristics of CMD quality in China (Table 1). The geographical coordinates and concentration data were integrated into a geographic information system using ArcGIS 9.0 software, and inverse distance weighting was applied to construct spatial distribution maps of the water quality parameters.

Results and Discussion

Spatial Distribution of SS in Coal Mine Water

Coal and rock powder produced by mining operations are the main forms of suspended solids (SS) in CMD. The particle size of the vast majority of SS is < 50 μm; particles this small are difficult to settle naturally. High SS levels cause visibly heavy chromaticity and high turbidity, with extremely poor sensory effects in mine water. Based on water quality indicators from 99 coal mines across China, the spatial distribution of SS content in the CMD is shown in Fig. 1. The spatial coverage area of CMD with an SS content < 1000 mg/L accounted for ≈80% of the total area. The CMD SS content was relatively low, and in most samples, SS content was < 800 mg/L. The SS content in the CMD of northwest and northeast China (except Inner Mongolia) was higher than in southern China, in the range of 1000–3000 mg/L. In north China, the SS distribution in the CMD was uneven. Higher SS content was mainly found in parts of Shaanxi, Shandong, and Hebei, while the content in other areas was < 1000 mg/L.

Spatial Distribution of pH in Coal Mine Water

Based on 323 pH detection indicators from the major coal mining areas, the spatial distribution pattern of CMD pH in China is shown in Fig. 2. Acid mine drainage (AMD) was mainly distributed in southern China and local areas of the Shanxi province in northern China. Weak acidic mine water accounted for most of the acidic mine water distribution areas, with a pH range of 5–7. Mine water with pH < 5 was mainly concentrated in the southwest regions, such as the Guizhou and Guangxi provinces. CMD pH in the other areas was neutral or slightly alkaline. It has been reported that the lowest pH in CMD in abandoned and active mines in Guizhou is 1.90 and 2.78, respectively (Zhang et al. 2021). AMD is a global challenge for the mining industry due to its potential ecological hazards and health risks (Naidu et al. 2019). For example, numerous water quality surveys have reported that elements such as Fe, Mn, Cu, Zn, Pb, and Ni tend to be more concentrated in AMD (Mahato et al. 2014, 2017; Sheoran and Sheoran 2006). Shylla et al. (2021) assessed the intensity of pollution in water systems affected by AMD (pH = 2.67) from rat-hole coal mines in India and noted that the water was rich in Fe (121.3 μg/L),

Table 1 Water quality data of Chinese coal mine water (SS, TDS, Fe, Mn content are expressed in mg/L)

Region		pH	SS	TDS	Fe	Mn
Anhui	Range	7.48–10.90	24–274	138–3765	0–2.63	0–11.01
	Number	36	7	30	40	11
Guizhou	Range	2.6–8.3	55–727	136.7–8194.2	0–1100.70	0.05–21.83
	Number	32	18	15	74	60
Chongqing	Range	7.33–8.19	–	165.1–16,644.0	0.54–2.83	0–0.47
	Number	13	0	13	10	9
Hunan	Range	8.20–8.56	–	–	–	–
	Number	2	0	0	0	0
Yunnan	Range	5.20–7.87	386–920	1118.8	117.04	3.57
	Number	2	2	1	1	1
Liaoning	Range	7.40–8.46	–	1364.0	0–11.28	0–0.92
	Number	4	0	1	27	20
Inner Mongolia	Range	7.38–9.00	284–810	210.0–1461.7	0.0005–36.02	0.0007–0.15
	Number	28	2	8	23	23
Ningxia	Range	8.20	60	2911.3	0.03–2.34	0.16–0.98
	Number	2	1	1	6	6
Shandong	Range	6.71–11.10	94–2360	1050.0–8476.3	0–163.55	0.0064
	Number	50	3	64	14	1
Shanxi	Range	3.00–11.61	73–258	467.1–12,247.0	0–195.09	0–3080.68
	Number	50	13	43	46	28
Shaanxi	Range	2.0–9.0	165–6000	4056.0–10,860.5	0–4.45	0–4.8
	Number	22	8	2	56	39
Hebei	Range	7.00–8.81	0–9961	375–5700	0–614	0–77.5
	Number	29	27	17	29	19
Henan	Range	7.00–9.08	10–4593	303.7–4949.3	0–32.1	0–2.35
	Number	45	17	37	42	43
Xinjiang	Range	7.4–9.2	1400	1800.0–9681.6	0.02–0.05	0.05–0.10
	Number	8	1	9	6	4

Mn (2758.5 μg/L), and Cr (1132.5 μg/L), presenting high/moderate pollution levels. Approximately 215,000 km^2 of acid sulfate soils in Australia and 6000 km of eastern U.S. streams were polluted by acid waste materials and mining wastewater (Fitzpatrick et al. 2009; Naidu et al. 2019; Ziemkiewicz et al. 2003). Meanwhile, the vegetative cover and species diversity decreased in the aquatic environment exposed to AMD (Jia et al. 2022).

Spatial Distribution of Salinity in Coal Mine Water

According to the Chinese National Standard *GB/T 14,848–2017, Quality Standard for Groundwater* (China National Standardization Administration 2017), the salinity of groundwater fit for drinking should not exceed 2000 mg/L (Class IV standard). However, the salinity of CMD in most areas in China exceeds this reference value (Fig. 3). High TDS levels were found in the southwest, north, and northwest regions. For example, the CMD in Guizhou had typical characteristics of low pH and high Fe and SO_4^{2-} content; its TDS ranged from 254 to 13,944 mg/L, with an average of 2376 mg/L (Zhang et al. 2021). Hussain et al. (2019) demonstrated that mining-induced damage to underground coal seams and rock formations can cause the total hardness of groundwater in mining areas to exceed that in surrounding non-mining areas by 1.6–6.1 times. The reasons for the high salinity in mine water vary according to different distribution areas. The dominant cations in CMD are Ca^{2+}, Na^+, K^+, and Mg^{2+}, and the dominant anions are SO_4^{2-}, HCO^{3-}, and Cl^- (Li et al. 2018; Liu et al. 2019). Given the widespread distribution of AMD in southwest China, the dissolution of carbonate and alkaline minerals in the surrounding rocks and coal seams is enhanced, resulting in the concentration of water-soluble ions (Youlton and Kinnaird 2013). The high TDS content exhibited by the northern and northwest regions is related to the climatic characteristics of scarce precipitation, strong evaporation, and the natural scarcity of water resources, resulting in an evaporative concentration of salinity in the groundwater (Chen et al. 2021).

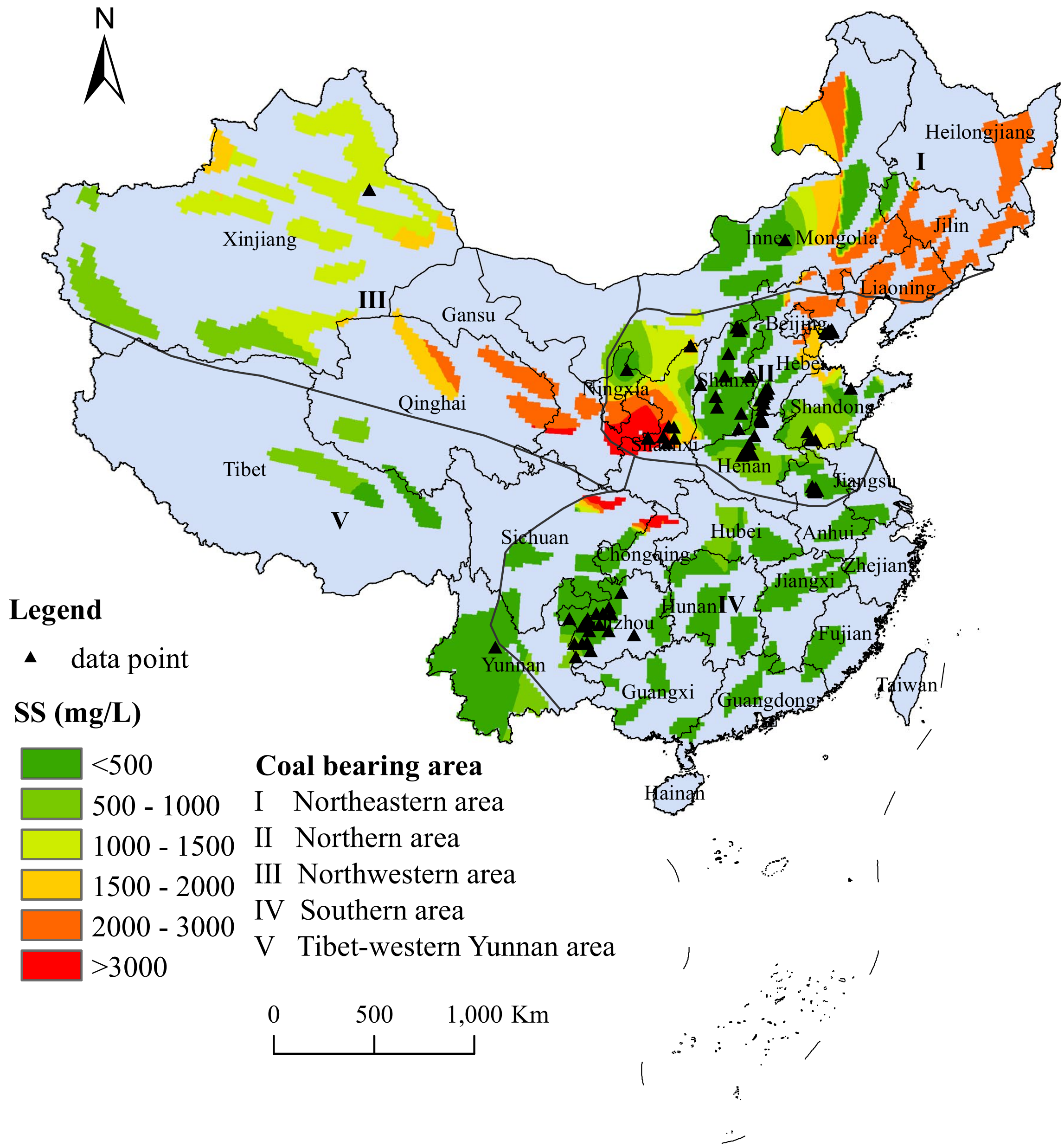

Fig. 1 Spatial distribution of SS content in CMD in China

Spatial Distribution of Fe Concentration in Coal Mine Water

According to the Chinese National Standard *GB/T 14,848–2017, Quality Standard for Groundwater*, the concentration limit of Fe in groundwater should be 0.3 mg/L (Class IV standard). However, most mine waters in China exceed this limit (Fig. 4), with the CMD Fe content in southern China greater than in northern China. For example, the closed, intensivly mined area in Guizhou Province still causes serious pollution to the surface water system. The average Fe concentration in the water samples was 68.48 mg/L (0.095–595.5 mg/L), far exceeding the limits set by China and the World Health Organization (0.3 mg/L) (Liu et al. 2020; World Health Organization 2006). Pyrite and siderite in coal and rock formations are the main sources of Fe in mine water (Sun et al. 2014a, b; Wang et al. 2020). The Fe content in mine water is closely related to its pH; when the pH of mine water is < 6, the dissolution of pyrite and siderite increases with the decrease in pH, leading to greater Fe concentrations. The enrichment of the local Fe concentration is mainly attributed to the high sulfur content of the coal and the low pH of mine water in southwest China.

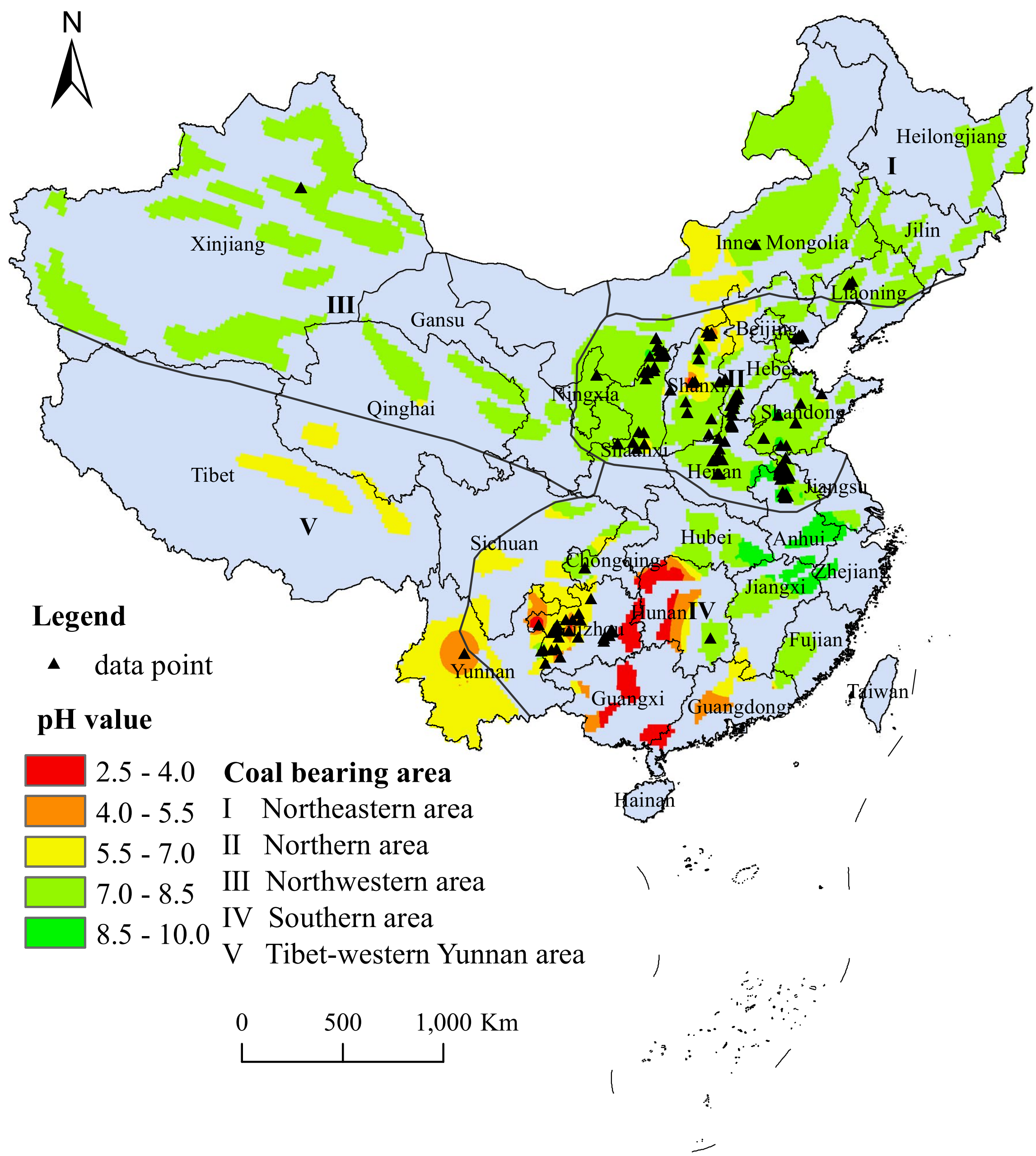

Fig. 2 Spatial distribution of pH in CMD in China

Spatial Distribution of Mn Concentrations in Coal Mine Water

Spatial distribution of Mn in CMD was very similar to that of Fe; the spatial regions of high content overlap. Mine water with Mn contents exceeding 1 mg/L was mainly distributed in parts of Yunnan, Guizhou, Inner Mongolia, Shaanxi, and Shanxi (Fig. 5). The Mn content in Guizhou CMD ranged from below the detection limit to 73.8 mg/L, with an average of 2.9 mg/L, far exceeding the limit set by the World Health Organization (0.1 mg/L; Liu et al. 2020; World Health Organization 2006). Mn in coal mainly exists in carbonates, particularly siderite and fayalite, so AMD is conducive to the dissolution and migration of Mn as Mn^{2+}. In an acidic environment, Mn and pH are significantly correlated.

Utilization Strategies for CMD in China

Regional Targeting of CMD Utilization Strategies

CMD is an important alternative to alleviate the strain between water supply and demand for domestic, industrial,

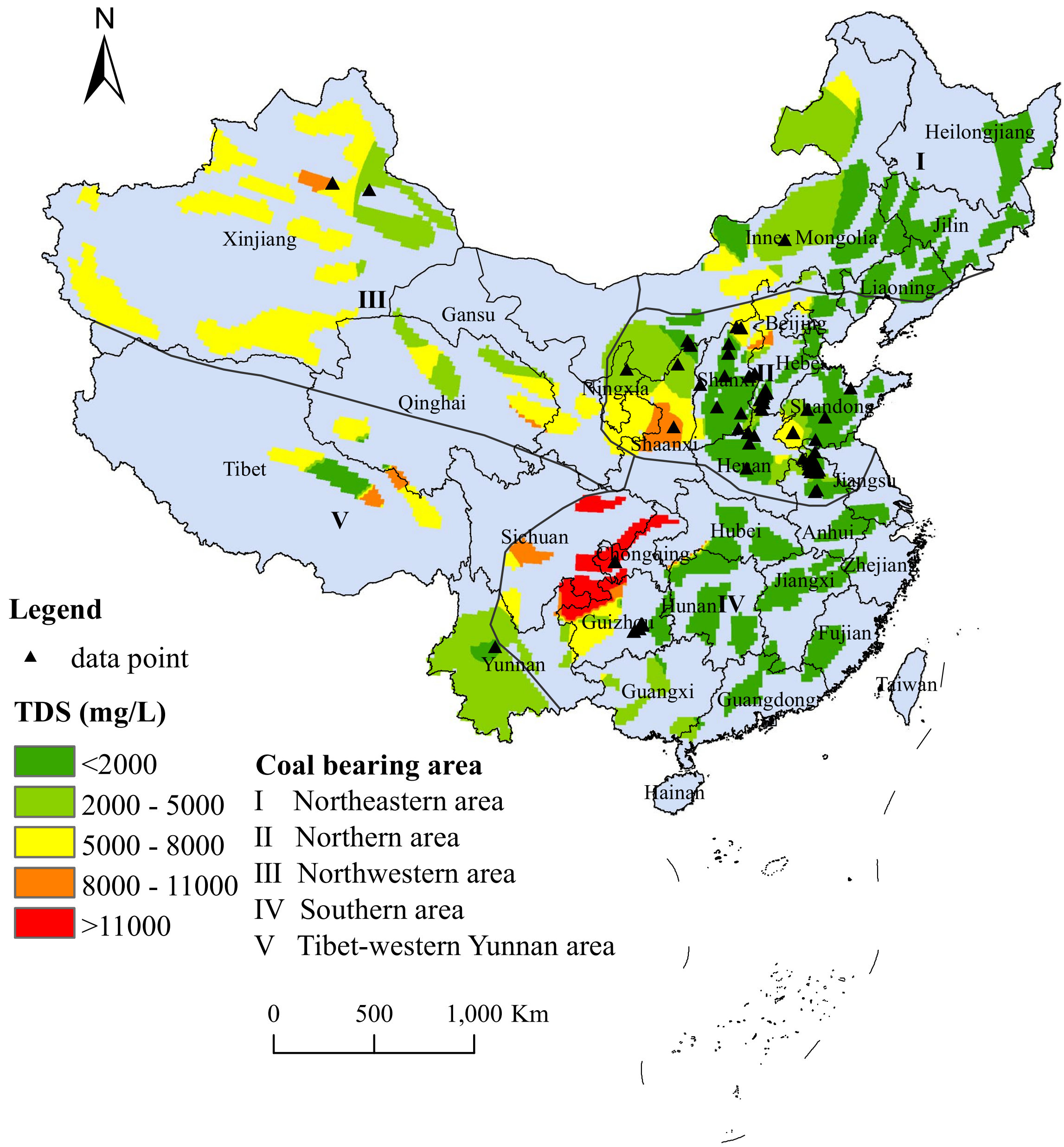

Fig. 3 Spatial distribution of TDS content in CMD in China

ecological, environmental, and irrigation water in water-scarce areas (Liu and Li 2019; Peng et al. 2019). In the northwest, northeast, and north regions of China, the CMD tends to have high SS content and salinity, neutral or weak alkaline pH, and low Fe/Mn content. The CMD in these regions had high SS content and salinity but an extremely low level of hazardous elements, and so can achieve the water supply requirements through coagulation–sedimentation treatment technology, making the reuse of SS-containing mine drainage possible. Water treatment technologies, such as membrane separation, reverse osmosis, and electrodialysis, makes safe and effective utilization of mine water with high salinity possible in water-scarce areas (Wang et al. 2020).

In southern China, especially the southwestern regions, the CMD was characterized by low pH, high salinity, and high enrichment of hazardous elements, indicating significant ecological and health risks. Therefore, this CMD is unsuitable for drinking and domestic use, though some CMD could be used for industrial or other purposes, such as irrigation. However, given the abundant supply of conventional water resources, dependence on CMD is not substantial in southern China. For this region, prevention

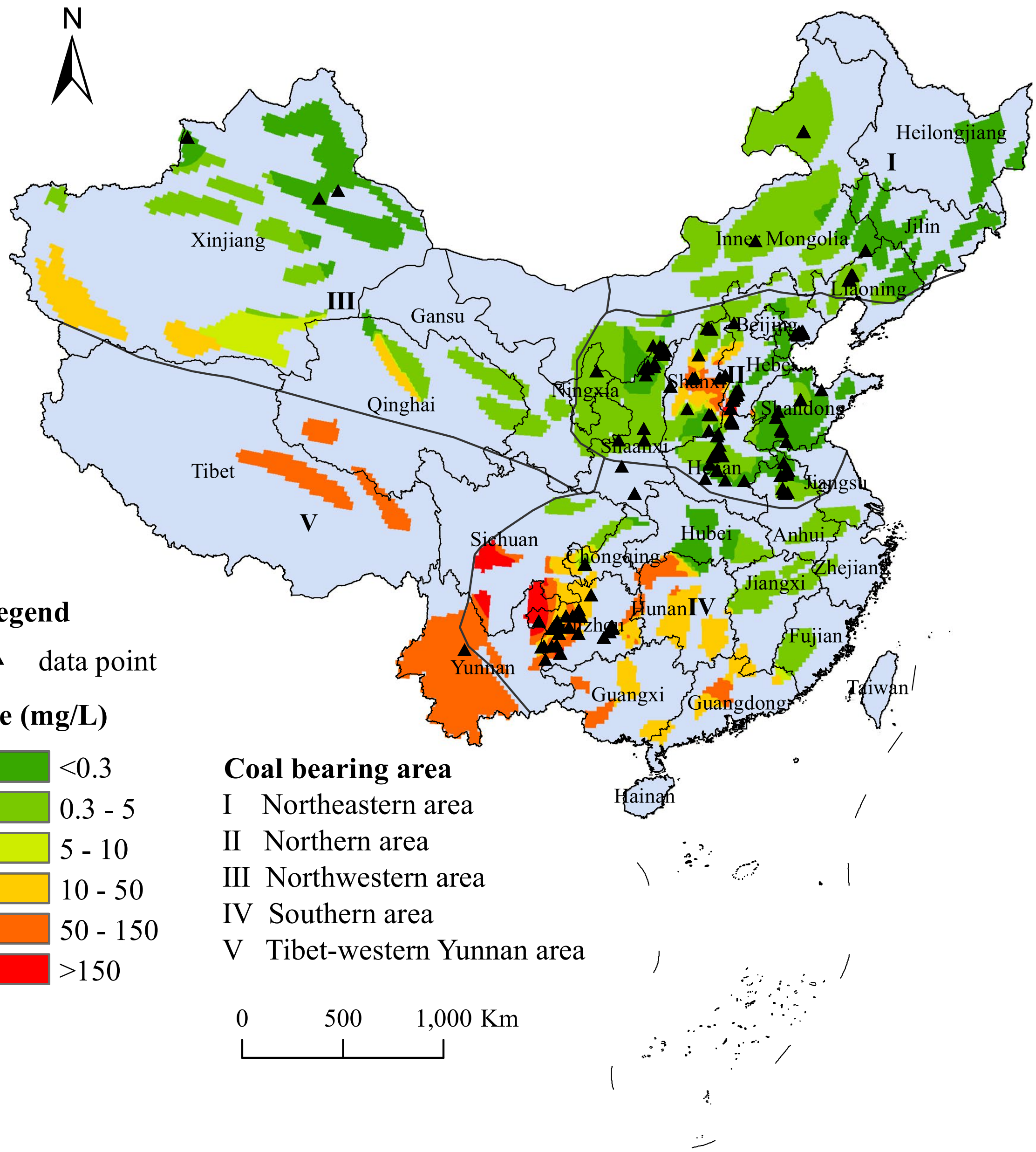

Fig. 4 Spatial distribution of Fe content in CMD in China

and control of water pollution should be the focus of mine water management.

Aspects for Improvement

With the expansion of the industrial chain of coal mining enterprises, the market demand for CMD reuse continues to increase. With water conservation at the core, the water costing mechanism determined that the value and scale of mine water reuse should continue to gradually increase; however, certain aspects should be addressed.

(1) The norms and standards for mine water utilization should be improved. Systematic development of guidelines at a national level would be conducive to promoting safe, efficient, and economical use of mine water. These guidelines should focus on water reuse methods, the selection of water treatment technologies, and the requirements for the quality of reusable water. The requirements for effluent quality differ for different types of water reuse, such as industrial, domestic, landscape, and miscellaneous water. Uniformly treating mine water increases water treatment costs and wastes resources. Therefore, relevant norms and standards

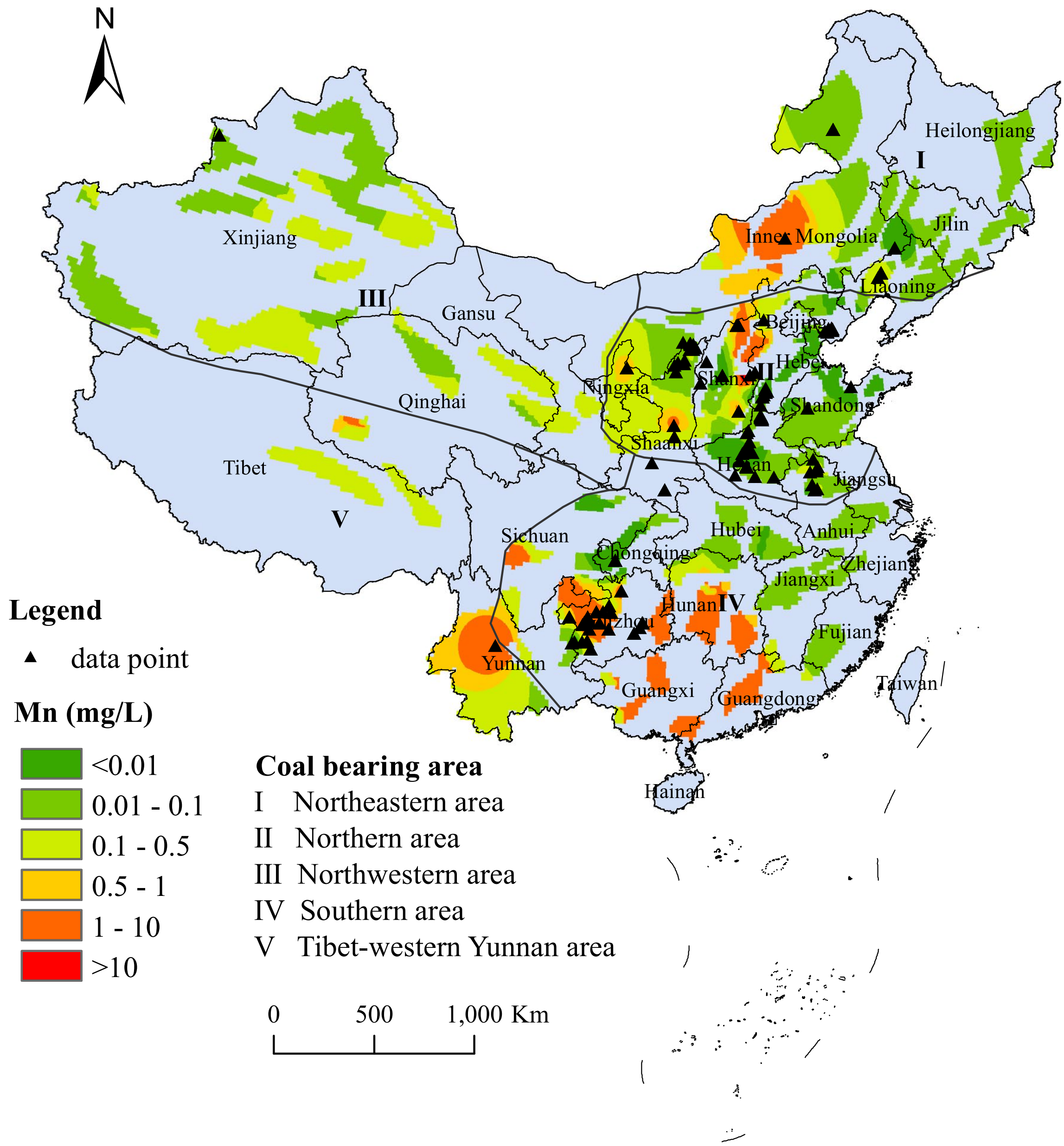

Fig. 5 Spatial distribution of Mn content in CMD in China

should provide detailed guidance on water use principles for graded treatments and cascade utilization.

(2) Policy support for mine water reuse should be strengthened. The construction of mine water treatment and utilization of engineering facilities requires considerable investment. For small- and medium-sized coal production enterprises, a high engineering cost input severely restricts the comprehensive reuse of mine water. Therefore, government departments should strengthen policy support, such as financial subsidies, government-enterprise co-construction, and licensing of water supply operations to mobilize the enthusiasm of enterprises and ensure their economic benefits.

(3) An entire coal mine water utilization chain, including water storage, treatment, and user matching, should be developed. However, the lack of groundwater storage space restricts the use of mine water, and so large amounts of water can only be discharged after treatment. The use of a coal mine goaf as an underground reservoir should be considered. If the water can be stored in coal mines without degrading its water quality, the unified management and dispatch of multiple

underground coal mine reservoirs could achieve effective protection and reuse of mine water. If the scheme is promoted in the main coal-producing areas in western China, the effective use of mine water could be increased by 1.0–2.0 × 10^9 m^3 per year (Li and Xiong 2016). The lack of matching channels between coal mines and downstream users also restricts the utilization of mine water. Therefore, it is necessary to establish a communication channel between the mine water resources in the mining areas and potential users, based on the different requirements of the users for water quality, reasonable management, and allocation of mine water to maximize the efficiency of mine water reuse.

Conclusions

The reuse and management policies of CMD in the various regions of China should be reconsidered. The CMD in southern China, especially the southwestern regions, is characterized by low pH, high salinity, and high Fe/Mn content and cannot be defined as a high-quality water supply source. In contrast, the coal mine water in the northwest, northeast, and north of China had water quality characteristics of high SS content, high salinity, neutral/weakly alkaline pH, and low Fe/Mn content, indicating good water utilization potential. This indicates that the CMD could appropriately be used to alleviate water shortages in the arid/semi-arid regions of northern China. Mine water utilization is supportive and safe for the local water supply in the northern regions, especially in the northwestern region, while in the southwestern regions, prevention and control of water pollution should be the focus of mine water management. In addition, some aspects require strengthening to maximize the utilization of CMD. For example, improving the norms and standards for CMD utilization, strengthening policy support for mine water reuse, and establishing an entire chain of mine water use (water storage, water treatment, and user matching, among others).

Spatial distribution analysis of water quality parameters over a large spatial scale is challenging and relies on existing data reporting and detailed data disclosure. In the future, continuous mine water quality surveys and data records should be collected at more coal mines to present the spatial distribution of China's coal mine water quality more accurately.

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