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Review

A Review of Heavy Metal Migration and Its Influencing Factors in Karst Groundwater, Northern and Southern China

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Abstract: With the substantial increase in karst groundwater pollution, the pollution caused by heavy metal migration has become one of the hottest topics. The migration characteristics of heavy metals in karst groundwater are closely related to the geological environment in which they are found. Therefore, this review focuses on the migration characteristics of heavy metals in karst groundwater in southern and northern China and highlights the effect of different environmental contexts such as atmosphere (precipitation), vegetation, soil, rock, and aquifers on the behavior of heavy metals. It also summarizes existing research methods on heavy metal migration in karst groundwater. Meanwhile, current advances and the future perspectives on karst groundwater heavy metal migration will be presented. It is hoped that this review may shed light on the study of heavy metal migration in karst areas.

Keywords: southern; northern; heavy metal migration; mechanisms of influence; research method

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1. Introduction

Groundwater is an essential freshwater resource worldwide. In China, approximately 70% of the population relies on groundwater as their primary water source [1] Of this, about 25% of the groundwater resources are found in karst areas, which encompass an exposed area of approximately 1.37 million km^2 [2]. Karst areas in China can be categorized into three regions: the northern karst area, the southern karst area, and the Tibetan Plateau karst area [3] (Figure 1). Currently, there is limited research on groundwater in the western karst region. The vulnerability of karst water to contamination is determined by the fragile karst environment in the northern and southern karst regions, the multiple recharge of karst water, the openness of the system, and the fragility of the karst environment [4]. The high permeability of the aquifers and the poor antifouling performance of the karst groundwater systems are key factors that make them susceptible to contamination [5,6]. Karst groundwater systems are complex and rapidly mobile, which means that, once the karst environment is contaminated, pollutants can quickly migrate and spread to deeper groundwater, making monitoring and pollution control measures more challenging [7]. Managing karst groundwater environments with persistent and non-degradable heavy metals is even more difficult [8]. Groundwater pollution is a significant concern due to its negative impacts on human activities and the natural environment [9,10]. In karst areas, agricultural and industrial production heavily rely on groundwater, particularly during the dry season. The availability of groundwater resources plays a crucial role in increasing farmland yield, improving agricultural production conditions, and maintaining socio-economic stability in the karst region of China [11,12].

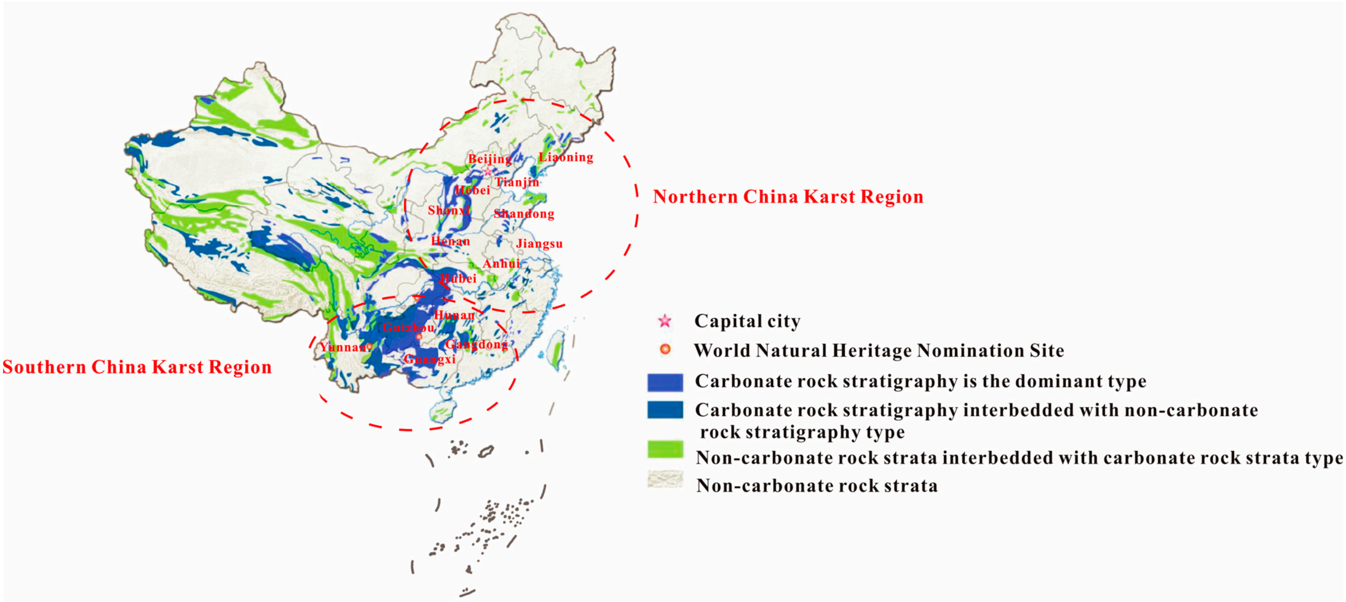

Figure 1. Distribution of karst regions in China.

The main sources of heavy metal pollution in karst groundwater are currently categorized into artificial sources and natural sources. Natural sources refer to the entry of heavy metals into water and soil through geological erosion, weathering, and volcanic activity, which then indirectly or directly infiltrate into groundwater. On the other hand, anthropogenic sources encompass various forms of heavy metal pollution in groundwater caused by human activities, such as industrial pollution sources (mining, metal smelting, metal processing, etc.), agricultural pollution sources (application of pesticides and fertilizers, etc.), and domestic pollution sources (accumulation of domestic waste). In karst areas, the soil and surface water are contaminated by diverse heavy metals resulting from both human and natural activities. Consequently, the substantial amount of pollution in soil layers and surface water serves as a continuous source of groundwater pollution in karst regions [13–15]. Heavy metals can infiltrate vertically along the key karst zone and diffuse with groundwater flow, leading to groundwater pollution. The karst critical zone consists of the atmosphere (precipitation), vegetation, soil, rock, and underground aquifers. The presence of various aquifer media, such as pores, fissures, and pipelines, complicates the movement of heavy metals. Additionally, the movement of heavy metal pollutants in the medium is also influenced by the complexation, adsorption–desorption, dissolution–precipitation, oxidation–reduction, and acid–base effects of the soil system [16] Therefore, heavy metal pollution in groundwater is often closely associated with the physical and chemical properties of soil. Heavy metals are typically introduced into the environment through various human activities, such as mining, metallurgy, fertilizer manufacturing, and wastewater discharge [17]. Subsequently, they migrate and transform through different mediums, like the atmosphere, water, and soil. They can also reach groundwater through karst channels or seepage via the atmosphere, water, and soil [2]. The migration and accumulation of heavy metals in the environment pose certain risks due to their resistance to degradation and ability to bioaccumulate [18]. For instance, Pb can adversely affect the nervous system by competitively inhibiting calcium ions, leading to various neurological diseases. Hg can form toxic methylmercury, which is harmful to the nervous systems of organisms. Additionally, hexavalent chromium ions are known to be carcinogenic. Consequently, the cumulative effect of these heavy metal elements in the human body poses a significant potential risk to the health of regional populations. The harm caused to human organs is exceptionally severe [19–23].

The migration of heavy metals in karst areas is not only affected by human activities, but also closely related to the unique rock characteristics and ecological vulnerability of karst areas. The intricate nature of the karst environment and the variability of environmental conditions pose challenges for accurately predicting the large-scale migration of heavy metals in karst groundwater [24–26]. In recent years, research reviews have focused on the progress of heavy metal transport and transformation during sludge pyrolysis [27–29]. There has also been a review of transported contamination in plant and soil heavy metal systems, with a main focus on the phytoremediation of soils [30–33]. Another review has examined the migration of heavy metals in wastewater, specifically looking at the effectiveness of biological treatment [34–36]. The adsorptive transport of heavy metals by microplastics in sediments, soil, and surface water systems has also been studied [37–39]. The transport of heavy metals in surface water, including the process of lateral transport, influencing factors, and modeling, has been summarized [40,41]. Reviews on karst groundwater have primarily focused on the migration of heavy metals in groundwater at sites such as landfills and mines (Figure 2), with limited attention given to the migration characteristics and influencing factors in karst areas affected by both anthropogenic and natural sources. Therefore, this study aims to systematically summarize and analyze the differences in the influencing mechanisms of precipitation, soil, vegetation, and aquifers on the migration of heavy metals in the key karst zone structures in southern and northern China. The study also considers the current situation of numerical simulation technology for heavy metal migration in karst groundwater in both regions and highlights differences in the construction of heavy metals models. By the end of this review, challenges and future developments in the migration of heavy metals will have been presented.

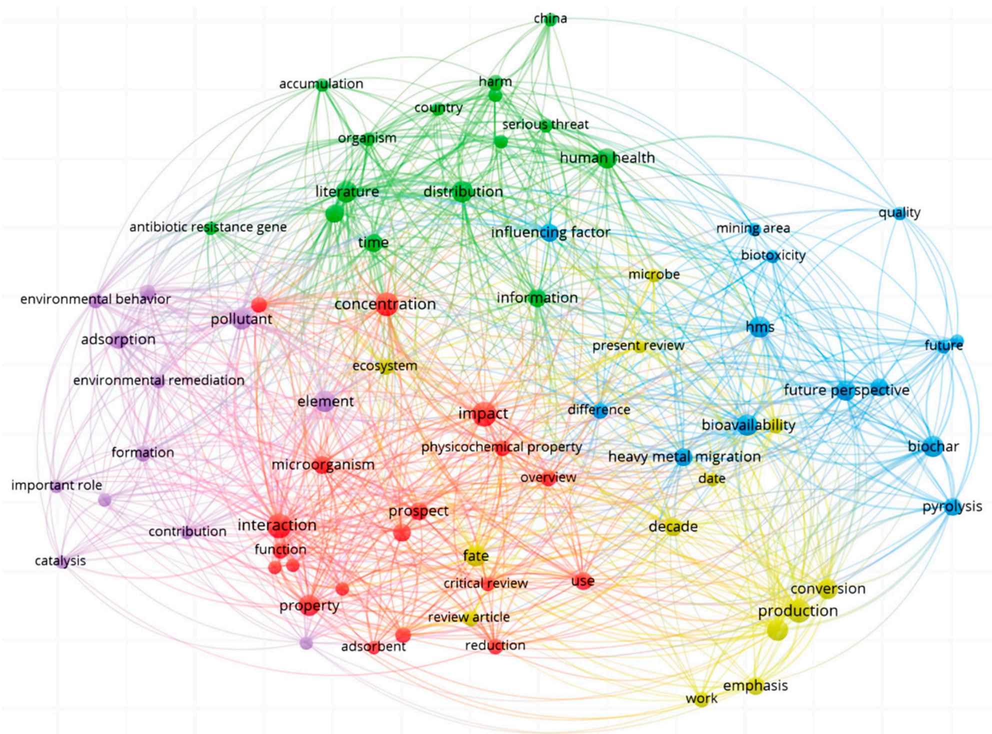

Figure 2. Progress of research on heavy metal migration in karst groundwater at home and abroad based on Web of Science.

2. Migration Pathways of Heavy Metal Elements in Contaminated Groundwater in Karst Groundwater

2.1. Migration Pathways of Heavy Metals in Karst Groundwater

Table 1 presents a comparison of the migration pathways of heavy metals in groundwater between the southern and northern areas, considering factors such as pollution sources, pollution processes, aquifer structure, and aquifer media. It is evident that the instillation-type pollution modes are less prevalent in karst groundwater in the north, as opposed to the migration pathways of heavy metal in groundwater in the southern karst area. The migration pathways in karst groundwater refer to the routes through which heavy metal contaminants enter the groundwater from the contamination source. While a few gaseous and liquid pollutants can directly infiltrate groundwater through rock voids, most pollutants enter groundwater alongside the water sources that recharge it [42,43]. The special karst structure of karst areas is closely related to the migration pathways of heavy metals. There are significant differences in the occurrence and distribution of karst groundwater between the northern and southern karst areas. In the southern karst areas, karst groundwater is mainly distributed in the underground river system, which is composed of exposed carbonate rock layers and shallow overlying karst areas. On the other hand, in the northern region, karst groundwater is mainly composed of pore-fracture seepage groundwater, which is characterized by concentrated distribution and is dominated by buried carbonate rocks and overlying karst areas. Therefore, the influence of karst systems in the south and north on the migration of heavy metals varies according to geographical characteristics.

Table 1. Migration pathways of heavy metals in contaminated groundwater in karst groundwater in southern and northern China.

Region	Heavy Metal Migration Pathways	Pollution Route	Sources of Pollution	Main Occurrence Location
Southern [44]	Intermittent vadose zone infiltration	Precipitation leaching of solid waste, mining areas, contaminated farmland.	Industrial and domestic solid waste, soluble minerals in mining areas, residual pesticides, fertilizers, and other farmland soils.	In a karst aquifer system with developed karst but thick soil layers.
	Vadose zone continuous infiltration	Canals, pits, leakage of contaminated surface water, etc.	Sewage polluted by human activities.	In a relatively developed karst aquifer system with thin soil layers.
	Injected pollution mode	Wastewater is directly injected into groundwater from wells, holes, tunnels, karst channels, etc.	Wastewater contains heavy metal pollutants from some factories (slaughterhouses and paper mills, etc.) or agricultural production areas.	Conduit-type karst aquifer.
	Overflow infiltration pollution mode	Contaminated groundwater exploitation, hydro-geological skylight, abandoned mining wells, lateral recharge of upstream sewage ditches, etc.	Contaminated aquifers and surface water.	In the double-layer groundwater system; the upper layer is the pore water aquifer and the lower layer is the karst water aquifer.
Northern [45]	Continuous infiltration type	Mainly refers to the vertical leakage of pollutants into karst aquifers caused by the damage to rivers, reservoirs, sewage canals, and sewage pipelines in karst areas.	Domestic sewage or industrial wastewater.	Bare karst area or some areas with shallow buried depth of karst water.
	Cross-flow pattern	Contaminated hole/fissure water (including mine water/old kiln water, etc.) overflows and pollutes karst water.	Over-exploitation of karst water and mine water.	The structure of coal is above, water is below.
	Intermittent infiltration type	Solid waste leaching infiltration and sewage irrigation leakage pollution.	Stacked coal gangue, tailings, industrial waste, domestic waste, and other solid waste.	Karst bare area and shallow coverage area.

2.2. *Migration Characteristics of Heavy Metals in Southern and Northern Karst Groundwater*

Research on karst in China is mainly focused on the southern region. The heavy metal contents of groundwater in southern and northern karst areas also differ in various water-bearing media, comparing the differences in heavy metal concentrations in fissure water, pore water, and karst pipeline groundwater in southern Hunan [46]; Pb, Zn, Cu, and Cd are higher in Quaternary pore water, whereas As is higher in the deeper fissure groundwater that has migrated from the localized discharge zone. Therefore, differences in the water-containing medium directly affect the migration characteristics of heavy metals. Karst research in China mainly focuses on the southern region. In the karst areas of southern China, groundwater mainly consists of pipe flows, such as the Gejiu underground river in Yunnan and the Four Rivers Basin in Guilin (Table 2) [44,47]. In addition, there are many underground rivers and karst cave waters. The direction of migration of heavy metals and other pollutants in southern China is mainly along the direction of groundwater flow in karst pipes or underground rivers. By comparing the concentrations of heavy metals at the inlet and outlet of karst pipe water in the Guilin Sishui River Basin, it was found that the concentrations of Zn, Cu, Cd, and Pb exceeded Chinese Groundwater Quality Standards [48] and the standard limits set by the World Health Organisation (WHO) [49] (Table 2). This indicates that although heavy metal concentrations decreased as the piped water flowed to the outlet, and the karst pipeline had a certain purifying effect on heavy metals, there was still a serious heavy metal pollution problem, so heavy metal migration in the southern groundwater had a certain directionality. On the other hand, the northern region mostly had pore-fracture seepage groundwater, such as fissure water in the Shandi River Basin of Yangquan City [50], Xuzhou Yangquan Shandi River Basin [51], and Jinan karst groundwater [52,53], and the existence of pore fractures makes the direction of heavy metal migration uncertain.

Table 2. Contents of heavy metals in the groundwater of different karst structures in southern and northern China (mg/L).

Region		Mn	As	Zn	Cu	Cd	Pb
Southern	Yunnan Gejiu underground river pipeline water [44]	0.44	0.06	6.30	-	0.03	0.19
	The karst conduit water inlet of the river basin in Sishui, Guilin [47]	-	-	315	-	3.5	1.3
	The karst conduit water outlet of the river basin in Sishui, Guilin [47]	-	-	272	-	1.9	2.1
	Pore–pipe karst groundwater in Guanghua Basin, Guangdong Province [44]	-	0.07	-	-	-	0.18
	Hunan Province Quaternary pore water (Wet Season) [46]	-	0.0400	0.4000	0.0200	0.0100	0.0350
	Hunan Province Quaternary pore water (Dry Season) [46]	-	-	0.3900	-	-	0.0020
	Hunan Province Cretaceous fracture water (Wet Season) [46]		0.0100	0.0280			0.0020
	Hunan Province Cretaceous fracture water (Dry Season) [46]		<0.0020	0.0100	<0.0020	<0.0010	<0.0020
	Hunan Province Jurassic fracture water (Dry Season) [46]		<0.0020	0.0112	<0.0020	<0.0010	<0.0020
	Hunan Province karst water (Wet Season) [46]		-	0.0143	-	-	0.0140
	Hunan Province karst water (Dry Season) [46]		0.0080	0.0190	<0.0020	<0.0010	0.0170
Northern	Fissure water in the Shandi River Basin of Yangquan City [50]	3.0	-	0.1	-	0.2	0.1
	Fractured karst groundwater in Xuzhou [51]	0.4	-	0.005	-	0.12	
	Jinan underground fissure-karst water [52,53]	-	-	-	0.52	0.0011	0.0045
	China groundwater quality standard [48]	0.3	0.05	1	1	0.005	0.01
	WHO guidelines for drinking water quality, 4th ed. [49]	0.4	0.01	4	2	0.003	0.01

In the northern region, atmospheric precipitation has to travel through thick coal seams or landfills in the upper part of the buried carbonate zone before reaching near-piston recharging karst aquifers. This process involves the dissolution of fissures and the creation of pipe fissures, which slows down the migration rate of heavy metals in groundwater. As a result, lower levels of heavy metals enter the groundwater. For instance, the heavy metal content in Xuzhou landfill fissure water [51] and Jinan underground fissure karst groundwater [52,53] is minimal. On the other hand, heavy metals in karst groundwater in southern China migrate faster due to the high rainfall, causing constant changes in the storage and movement conditions of groundwater. The velocity of groundwater flowing through the pipes is significantly faster than that of normal pore water, resulting in a positive response to rainfall. This transient nature of groundwater flow leads to higher heavy metal concentrations during the wet season. A study by Guo et al. [54] found that Pb, Mn, and As concentrations were higher before entry into underground streams compared to after exit from karst aquifers. This suggests that high humidity and precipitation help dilute and wash away heavy metals in soil or other media, reducing the retention times of heavy metals in soil and groundwater bodies.

Pollution and migration of heavy metals in karst groundwater exhibit notable variations in different karst structures between the southern and northern regions. In the southern karst area, the migration of heavy metals in pipe flow groundwater occurs in a specific direction and at a rapid pace, demonstrating directionality and transience. On the other hand, heavy metal migration in the seepage groundwater of the northern karst pore-fracture type is multidirectional and occurs at a slower rate, displaying the characteristics of non-directionality and hysteresis [55,56] (Figure 3).

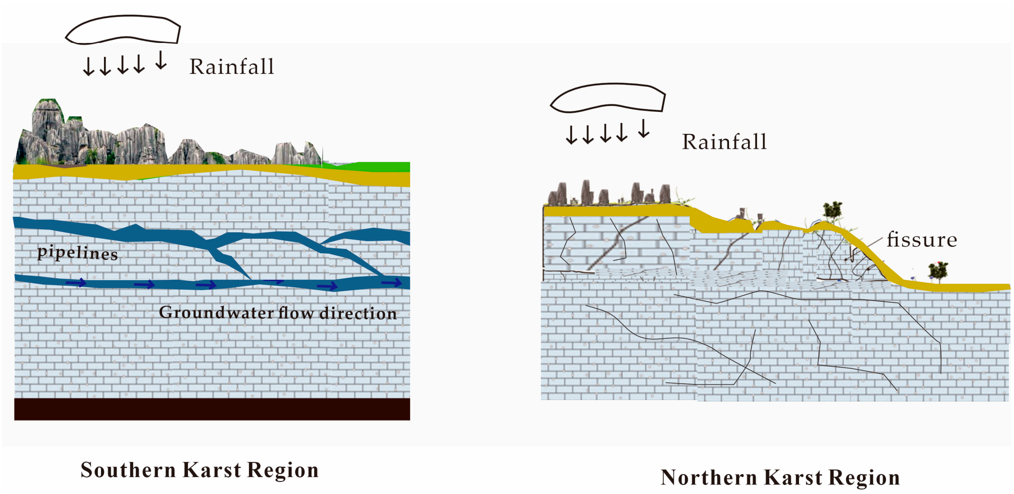

Figure 3. Comparison of heavy metal migration characteristics in karst groundwater between southern and northern China [56].

3. Studies on the Influencing Mechanisms on Heavy Metal Migration in Karst Groundwater

The vertical structure of the key karst zone, from top to bottom, consists of the atmosphere (precipitation), vegetation, soil, rock, and underground aquifers. The content of heavy metals in karst groundwater changes with space and time due to their interaction with rock, soil, and other media during migration. As a result, the migration of heavy metals in karst groundwater is closely linked to the atmosphere (precipitation), vegetation, soil, and rock. Therefore, the influencing mechanisms on heavy metal migration in karst groundwater are systematically discussed across the vertical structure of the karst key zone.

3.1. The Influencing Mechanism of the Atmosphere (Precipitation) on the Migration of Heavy Metals in Karst Groundwater

The influence of rainfall on the migration of heavy metals in groundwater in karst areas can be attributed to the following aspects: (1) Rainfall infiltrates the groundwater through fallout holes, causing the dissolution and erosion of heavy metals. (2) The erosion, scouring, and infiltration of soil by rainfall results in the entry of heavy metals from the soil into the groundwater. (3) The leaching of solid waste containing heavy metals from human activities by rainfall results in the diffuse transport of these heavy metals into groundwater [57]. There is a significant difference in rainfall between southern and northern China. The karst areas in the south generally experience a humid climate with high precipitation [57,58]. This can result in increased surface runoff and water infiltration, leading to the leaching and transportation of heavy metals. As a result, heavy metals are more likely to enter the groundwater system. For instance, in the karst area of Chongqing, located in southern China, heavy metal levels in both groundwater and pore water were higher during the wet season compared to the dry season. The mass concentrations of heavy metals were also greater in pore water than in underground rivers [58] (Table 3). This suggests that heavy metal pollutants in the pore water of the Laolongdong underground river system in Chongqing are more prone to diffuse into the underground river during the wet season due to the larger concentration difference driven by rainfall. Ultimately, this leads to contamination of the underground river. However, it should be noted that the rainfall in the northern region is relatively low [53,59–61]. In Table 3, the variation in heavy metal mass concentrations in the karst groundwater in Jinan during the dry and wet periods indicates that heavy metal mass concentrations are generally lower during the wet period compared to the dry period [53,59–61]. This finding contradicts the conclusion drawn from the variation in heavy metals during the dry and wet periods in the southern region of Chongqing [58]. The reason behind this difference lies in the limited rainfall in the northern region, which exerts higher pressure on porous media such as soil and rock. Consequently, heavy metals migrate from pores and fissures to the underground aquifer at a slower rate due to the scarcity of rainfall, resulting in a weak dilution effect and higher concentrations of heavy metals. This discrepancy in heavy metal migration between the northern and southern regions of the groundwater system can be attributed to the disparity in rainfall. Conversely, in southern China, rainfall recharge occurs rapidly, leading to a larger number of transient recharge flows. Heavy metals are rapidly transported and diluted in groundwater throughout the watershed in a dispersed manner [62]. Additionally, the lower pH of rainfall in the southern region may facilitate the dissolution and transport of heavy metals in rocks [63].

Table 3. Comparison of heavy metals in groundwater in southern and northern China (mg/L).

	Region	**Mn**	**Cu**	**Cr**	**Sr**	**Zn**	**Ni**	**As**	**Cd**	**Pb**	**Fe**	**Annual Rainfall (mm)**
Southern	Guiyang [57]	0.023	0.0005	-	-	0.0026	-	0.0006	-	-	0.067	1929.5
	Chongqing underground river (dry season) [58]	0.142	0.00306	-	-	-	-	0.0028	-	0.0037	-	1180
	Chongqing underground river (wet season) [58]	0.232	0.0056	-	-	-	-	0.0036	-	0.0085	-	1180
	Chongqing pore water (dry season) [58]	1.922	0.18	-	-	-	-	0.17	-	0.22	-	1180
	Chongqing pore water (wet season) [58]	2.745	0.27	-	-	-	-	0.21	-	0.29	-	1180
Northern	Jinan (dry season) [53]	-	0.00061	0.012	0.341	-	0.002	-	-	-	-	671.1
	Jinan (wet season) [53]	-	-	0.009	0.31	-	0.001	-	-	-	-	671.1
	Beijing [59]	0.95	0.018	-	-	4.65		0.0079	0.0005	0.0069	1.39	511.1
	Dongbei (wet season) [60]	0.609	0.0007	0.0006		0.0078	0.0038	0.0021		0.00014	1.501	755.2
	Dongbei (dry season) [60]	0.817	0.0017	0.0030		0.0081	0.0068	0.0031		0.00048	2.779	755.2
	Henan (dry season) [61]	-	3.78	2.46	-	4.56	18.93	1.86	0.02	0.85	-	556.3
	Henan (wet season) [61]	-	3.64	3.44	-	5.45	8.89	1.11	0.03	2.30	-	556.3

3.2. The Influencing Mechanism of Vegetation on the Migration of Heavy Metals in Karst Groundwater

Vegetation has the ability to absorb a certain amount of heavy metal. This is due to the rapid transport capacity for heavy metal from the roots to the aboveground parts of plants, as well as the key roles played by various metal ligands in metal hyperaccumulators. These factors contribute to vegetation's super-enrichment ability and super-tolerance to heavy metals. The heavy metal contents of groundwater in different vegetation types show some differences [64–66]. Jiang et al. [64] found that the migration coefficient of trace element Co increased by 85.9% in the dense forest area of Nonglalandiantang compared with that in the loose forest area of Shangnongla (Table 4). This may be related to the rich organic matter in the forest area, because Co easily migrates due to the chelation of organic components. The difference in ecological environment has a great influence on the migration of elements and the effective states of elements. The carbon cycle of the forest environment can accelerate the migration of elements and the activation of some insoluble components. Therefore, the mass concentration of heavy metals in the open forest area in Shanglangla is smaller than that in the sugarcane plantation area in the Chongzuo region [65]. Heavy metals were lowest in groundwater from broadleaf forests [66]. The vegetation has a remarkable ability to enrich and tolerate heavy metals. According to Chen et al. [67], mycorrhizal microorganisms that parasitize plant roots can increase the surface area of the roots and extend into areas that are inaccessible to the roots. This facilitates the migration of heavy metals into plants. Differences in the content of the same element in different parts of the vegetation are more pronounced, with roots showing higher levels of heavy metal enrichment [68,69] (Table 4). Soil plays a crucial role in the absorption of heavy metals by plants [70,71]. Soil organic matter is the main component responsible for fixing heavy metals [72]. The northern karst areas, characterized by thicker soil layers, higher soil microorganism populations, and more organic matter, exhibit a stronger adsorption capacity for heavy metals, thus limiting their migration to groundwater [73] (Figure 4). Furthermore, the sparse vegetation in the north and the easy exposure of soil may result in faster soil erosion and the migration of heavy metals from soil to groundwater. In the south, dense vegetation and vegetation cover may slow down the scouring effect of precipitation on the soil, thus affecting surface runoff and the migration of heavy metals from groundwater, but it may also increase the uptake of heavy metals by the root system of the vegetation [68]. It can be seen that the question of whether vegetation promotes or inhibits the migration of heavy metals in groundwater is still unclear and needs to be explored in further research.

Table 4. Comparison of different vegetation migration coefficients (μg/L).

Vegetation	Region/Vegetation	Ca	Mg	Fe	Al	Mn	Zn	Cu	Co
different vegetation types	Shangnongla, Guangxi sparse small tree groundwater [64]	0.624	0.303	0.179	0.800	0.021	0.073	0.013	8.889
	Guangxi Landian Hall dense forest groundwater [64]	0.630	0.307	0.633	0.142	0.042	0.180	0.027	15.35
	Guangxi Chongzuo sugar cane crops groundwater [65]	-	-	2.63	15.76	6.97	37.43	0.17	-
	Broad-leaved forest groundwater [66]	-	-	0.077	0.026	0.034	-	-	-
Different organs of vegetation	Guangxi Longhe-Buwu grassland root [68]	1.35	0.10	0.13	0.318	0.036	50.16	19.60	-
	Guangxi Longhe-Buwu grassland stem [68]	0.92	1.12	0.014	0.022	0.008	8.23	8.55	-
	Guangxi Longhe-Buwu grassland leaf [68]	1.62	0.40	0.030	0.065	0.029	30.26	16.72	-
	Aboveground part of Yunnan pine [69]	-	-	-	-	-	44.51	5.76	-
	Belowground part of Yunnan pine [69]	-	-	-	-	-	55.76	17.16	-
	Aboveground part of cryptomeria [69]	-	-	-	-	-	18.56	2.92	-
	Belowground part of cryptomeriastem [69]	-	-	-	-	-	39.86	8.04	-

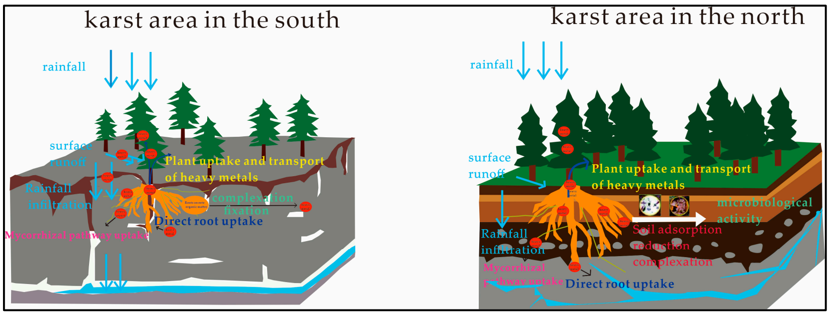

Figure 4. Comparison of the effects of vegetation on heavy metals in southern and northern China.

3.3. The Influencing Mechanism of Soil on the Migration of Heavy Metals in Karst Groundwater

The transport mechanisms of heavy metals in karst groundwater are influenced by the heavy metal contents of the soil [74]. The heavy metal content in groundwater is directly affected by the heavy metal content in soil. Additionally, the soil may contribute additional metals to groundwater through leachate during rainfall [75,76]. Moreover, the porous medium characteristics of karst areas make the transport of heavy metals through the soil easier. The specific situation may vary depending on factors such as geographical location, rock composition, climatic conditions, and human activities. Soil heavy metal contents in southern karst areas (e.g., Guangxi, Yunnan, etc.) are generally higher than those in northern karst areas (e.g., Beijing, Jinan, etc.) (Table 5) [59,77–84]. This difference can be attributed to factors such as the humid climate and dense vegetation in the southern region, which promote chemical weathering and accumulation of soil organic matter. Additionally, limestone, which is more widely distributed in the soil of the southern karst area, contributes to its richness in calcium and alkalinity [85]. Heavy metals can easily accumulate in limestone soils when they become less leachable [86,87]. Furthermore, human activities such as mining, agricultural fertilization, and industrial emissions can also contribute to an increase in soil heavy metal contents. In northern karst areas, the soil typically has low heavy metal contents due to its dry climate, relatively sparse vegetation, and weaker chemical weathering. In southern karst regions, the soil has high levels of heavy metals while the groundwater has low levels. Conversely, in the northern region, the soil has low levels of heavy metals but the groundwater has high levels. For instance, the Zn concentrations in the groundwater in Beijing and Taiyuan were found to be 4650 μg/L and 200.57 μg/L, respectively [77–82,88,89]. Qin et al. [82] conducted a study on heavy metals in groundwater in Guilin. They observed that the concentrations of Cu and Pb varied significantly, and the flow of groundwater correlated with the uneven distribution of fractures. Thus, it is hypothesized that contaminated soil particles are reactivated and infiltrate downwards into the groundwater. Previous research has also demonstrated that heavy metals in the soil can migrate to groundwater through surface soil erosion and subsurface soil leakage, which can be triggered by rainfall or irrigation. Given the climatic conditions in southern China and the relatively high concentration of heavy rainfall, surface soils are prone to erosion. Additionally, the presence of karst fissures and subsurface channels facilitates the migration of heavy metals to groundwater [90].

Table 5. Comparison of soil heavy metals in karst areas of southern and northern China.

Region	Soil (mg/kg)/ Groundwater (μg/L)	Pb	As	Cr	Cd	Zn	Cu	Hg	Ni
Yunnan [77]	Soil	661.2	-	-	12.64	982.2	31.38	-	-
Yunnan [78]	Groundwater	88.81	-	-	5.62	234.7	29.22	-	-
Guangxi [79]	Soil	30.30	14.27	160.39	1.78	112.51	33.82	0.62	32.05
Guangxi [80]	Groundwater	0.21	0.65	0.2	0.35	113	1.45		2.48
Guilin [81]	Soil	637.6	-	-	3.39	1140	89.09	-	-
Guilin [82]	Groundwater	8.13	-	-	13.06	0.11	0.98	-	-

Table 5. *Cont.*

Region	Soil (mg/kg)/ Groundwater (μg/L)	Pb	As	Cr	Cd	Zn	Cu	Hg	Ni
Jinan, shandong province [83]	Soil	-	11.93	71.87	0.20	72.08	26.08	0.05	32.18
Jinan, shandong province [52]	Groundwater	4.5	13.4	7.5	1.2	-	-	-	-
Beijing [84]	Soil	25	9.30	66	0.147	67	23	0.045	27
Beijing [59]	Groundwater	6.9	7.9	0	0.5	4650	18	1.3	-
Shanxi [88]	Soil	10.21	11.29	58.21	0.19	99.80	24.51	0.24	39.48
Taiyuan [89]	Soil	18.8	17.4	43.4	-	42.8	64.3	0.067	17.8
Taiyuan [89]	Groundwater	2.00	-	2.91	-	200.57	11.61	-	40.58

3.4. The Influencing Mechanism of Rock on the Migration of Heavy Metals in Karst Groundwater

The influence of rock on the migration of heavy metals in karst groundwater is primarily observed through the impact of rock weathering. Rock weathering refers to the process of dissolution and transformation of soluble rocks, particularly carbonate rocks. This process is driven by the karst dynamic system [91–94], which plays a significant role in the carbon–water–calcium cycle within carbonate rock areas. The cycle of carbon–water–calcium, in turn, drives the migration of various elements within these areas [95,96]. Therefore, rock weathering is closely linked to the migration of heavy metals in karst groundwater. The intensity of rock weathering varies in different environments, greatly influencing the movement of heavy metals in the environment. Table 6 illustrates that, in karst areas with high values of the geological background of dolomite, the rapid dissolution of carbonate components in the rock leads to the production of alkaline earth metals (Na, Ca, Mg) with a strong migration capacity from the rock to the groundwater. Consequently, this constrains the migration of insoluble elements such as Mn, Si, Fe, and Al [97]. The karst region in southern China is situated in the subtropical zone, known for its favorable hydrothermal conditions and intense water–rock interaction. Limestone and dolomite exhibit differences in terms of the main elements that migrate, karst water quality, and the formation of soils. However, there is a lack of research on this topic. The annual dissolution rate of rocks in the southern region ranges from 85 to 92 $m^3/km^2{\cdot}a$, while in the northern region it ranges from 10 to 30 $m^3/km^2{\cdot}a$. The karst areas in southwestern Guizhou and Zhongdian, Yunnan, are characterized by hot and humid conditions, which result in significant dissolution [98,99]. In these regions, there is a higher migration intensity of soluble elements such as Ca and Mg compared to the relatively dry and cold northern semi-humid karst areas (e.g., Shandong Tumen) and semi-arid karst areas (e.g., Beijing Shidu) [95]. Conversely, insoluble elements like Si, Fe, and Al tend to be more concentrated in these regions (Table 6).

Table 6. Comparison of parent rock properties and compositions between southern and northern karst areas in China.

	Sampling Site	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	CaO (%)	MgO (%)	Zn (mg/L)	Mn (mg/L)	Cu (mg/L)	Co (mg/L)
Southern	Shang Nongla dolomite [97]	0.126	0.168	0.08	21.88	12.75	109	516	207	1
	Shang Nongla groundwater [97]	0.45	0.113	0.24	51.22	14.5	30	40	10	40
	Shang Nongla water–rock migration factor [97]	0.014	0.007	0.016	1.168	0.528	0.061	0.015	0.019	2.092
	Lan Diantang Nongla dolomite [97]	0.196	0.049	0.167	23.20	12.00	22	188	72	1
	Lan Diantang groundwater [97]	0.47	0.157	0.12	73.99	18.64	20	40	10	10
	Lan Diantang water–rock migration factor [97]	0.010	0.008	0.004	1.186	0.568	0.034	0.012	0.035	3.890
	Southwestern Guizhou [98]	45.17	10.39	22.72	1.54	1.27	-	-	-	-
	Zhongdian, Yunnan [99]	45.24	10.66	26.20	0.24	1.35	-	-	-	-
Northern	Shandong Tumen [95]	38.18	4.02	13.11	5.91	3.97	-	-	-	-
	Beijing Shidu [95]	41.68	8.89	17.22	8.34	4.34	-	-	-	-

3.5. Influencing Mechanism of the Aquifer on Migration in Groundwater

As shown in Table 7, researchers have recently focused on the factors that influence the migration behaviors of heavy metals from karst aquifers [82,100–112]. The work carried out in this field can be categorized into three main areas: (i) mechanical factors, such as pH, conductivity, different sources of heavy metals, temperature, and groundwater velocity [82,100–103]; (ii) physico-chemical factors, including SO_4^{2-} concentration, heavy metal concentrations, karstification intensity, oxidation/reduction conditions, ionic strength, organic matter, and heavy metal speciation [101,104–110]; and (iii) biological factors, such as anaerobic bacteria and organisms [111,112]. This review aims to summarize the effects of these factors on the migration processes in aquifers.

Table 7. Influence of environmental factors contained in aquifers on the transport of heavy metals.

Influencing Factors	Mechanism of Influence
• pH, SO_4^{2-}	At a low pH, high concentrations of SO_4^{2-}, Fe, Mn, and Al primarily migrate as sulfate complexes and free ions. As pH increases, the abundant Fe, Mn, Al, and SO_4^{2-} in the water gradually transform into different colloids and secondary minerals in the form of hydroxide and/or hydroxyl sulfate, thus adsorbing more heavy metal ions [100]. These colloids and minerals then undergo adsorption and precipitation, which ultimately restricts their movement rate [101–103].
• Conductivity	Heavy metal contaminants tend to migrate horizontally in higher-conductivity layers and vertically in low-conductivity media [104,105].
• Different sources	Heavy metal ions from agricultural activities and carbonate dissolution are transported to groundwater recharge through diffusive flow [106,107]. Fe, Mn, and Al from soil erosion migrate to groundwater through slope retention [108,109].
• Temperature	In the adsorption and desorption of heavy metals on solid particles, an increase in temperature is generally favorable to the physical desorption of heavy metals [110,111], inhibiting their migration [82].
• Groundwater flow rate	The transport of particulate metals is facilitated when groundwater flows at a high velocity, allowing the metals to be carried along and suspended. Consequently, the movement of solutes with water flow is primarily governed by the velocity of the flow. In regions of southern China, characterized by abundant rainfall and high flow velocities, the predominant mechanism for heavy metal transport in aquifers is convection. On the other hand, in northern China, the transport of metals in aquifers is primarily influenced by diffusion [112,113].
• Concentration of heavy metals	Heavy metals with high concentrations tend to migrate to larger parts of the upper aquifer compared to those with low concentrations [104,114].
• Karstification intensity	In the karst water systems, the transport of heavy metal-free ions with water flow is restricted by the continuous buffering reaction between CO_2 and carbonate rocks. This reaction leads to the formation of abundant hydroxyl and carbonate complexes with metals [115–117].
• Oxidation-reduction	Certain elements, such as chromium, vanadium, and sulfur, are more likely to form soluble compounds under oxidizing conditions, resulting in a strong migratory force [118,119]. However, under reducing conditions, these elements tend to form metal compounds that precipitate, reducing the amount of heavy metals in the water and inhibiting their migration [120–122].
• Ionic strength	The impact of ionic strength on the desorption and adsorption of heavy metal ions can be attributed to competition between an increased ionic concentration and heavy metal ions for adsorption sites [123]. Additionally, an increase in ionic strength in the solution leads to a decrease in the activation coefficient of the solution, resulting in a decrease in the adsorption of heavy metals [124,125].
• Organic matter	Organic matter undergoes various reactions, such as ion exchange, adsorption, complexation, chelation, flocculation, redox, and other reactions with metal ions, oxides, minerals, and organic matter in the water body [126]. These reactions alter the pattern of heavy metal migration and transformation, ultimately influencing their final destination [127–129].

Table 7. *Cont.*

Influencing Factors	Mechanism of Influence
• Heavy metals morphology	Heavy metals in underground aquifers are classified into dissolved and particulate states. Among these, particulate heavy metals exhibit the highest mobility in the exchangeable ionic state [130–132].
• Anaerobic bacterial (dissimilatory) sulfate reduction (BSR)	Anaerobic bacterial (dissimilatory) sulfate reduction (BSR) plays a crucial role in various subsurface flow systems. This process involves the conversion of sulfate to sulfide, which effectively precipitates heavy metals in the form of highly insoluble metal sulfides [82,133]. Thus, sulfate-reducing bacteria are able to exacerbate the uptake of metal ions and reduce the transport of heavy metals [51,134].
• Biotechnology	Organisms exhibit adsorption effects on heavy metals through complexation, ion exchange, transformation, and absorption. When organisms are exposed to an ecological environment containing heavy metals, the cell walls of these organisms are the first to interact with heavy metal ions. The porous structure of the cell walls allows for the adsorption of heavy metals, leading to their migration into the organisms and subsequent enrichment [135,136].

4. Research Methods on Heavy Metal Migration in Karst Groundwater

4.1. Summary of Methods in Heavy Metal Migration Studies

This study analyzes and explores research methods on heavy metal migration in karst groundwater, building upon studies conducted by scholars both domestically and internationally (Table 8). Research methods on heavy metal migration encompass both quantitative and qualitative approaches. Quantitative research involves migration coefficients, simulation experiments, conceptual models, and numerical simulations [137–160]. On the other hand, qualitative research involves heavy metal morphology analysis, which focuses on the characteristics and properties of the elements [102].

Table 8. Methods for the study of heavy metal migration in karst groundwater.

Methods Name	Description	Advantages and Disadvantages
• Migration coefficient		
Relative migration coefficient	$RM_i = \Delta C_{ir}/C_{ir}$ RM_i is the relative mobility of element I, ΔC_{ir} is the ratio of the mass difference of element i in the weathering product and the host rock to the mass of the host rock, and C_{ir} is the content of element i in the host rock.	Fundamentally solves the problem of the quantitative migration of chemical components; it is difficult to apply to highly weathered systems [137,138].
• Simulation experiment		
Dynamic simulation experiment	Simulating the migration of heavy metals in groundwater through indoor soil columns, sand box experiments, and field experiments [139–142].	Dynamic simulation experiments can explore the pollution mechanisms of heavy metals in groundwater, but the series of parameters obtained from simulation experiments can only partially reflect the characteristics of the medium under actual conditions and the natural self-cleaning ability of the underground environment [139].

Table 8. *Cont.*

Methods Name	Description	Advantages and Disadvantages
• Conceptual model		
Water tank model	The conceptual model, commonly referred to as the grey box or tank model, categorizes the karst aquifer system into distinct parts based on its structure or hydrological processes. Each part is represented by corresponding tanks, which are interconnected to simulate the flow of karst springs [143,144].	Some conceptual models can simulate solute transport and spring water mass changes [145,146]. It is not yet possible to represent the objective fact of the coexistence of turbulent and laminar flows in karst media, and it is also difficult to take into account the interference of the human factor and to give the distribution of the head in space [147].
• Distributed model		
Fracture model	The fracture model assumes that the permeability of the rock matrix in the karst water-bearing system can be neglected. It considers only the flow of groundwater in the middle fractures, reducing the entire karst water-bearing system to a separate fracture network [148,149].	The fracture model is effective in describing groundwater flow in fractures and the heterogeneity of fracture aquifer systems [150,151]. This law, however, only applies to laminar flow in fissures [152], so the fissure model does not reflect turbulent flow in larger fissures in karst aquifers.
Pipeline model	The pipeline model focuses solely on the flow of groundwater in a karst water-bearing system. It does not take into account the flow of groundwater in the fracture medium and rock matrix (the fracture system), nor the exchange of water between the pipeline and the fracture system. The entire water-bearing system is simplified to a network of individual pipes [153].	The piped flow model is a more accurate representation of the characteristics of piped flow in karst aquifer systems. However, it is only applicable to aquifer systems that have a significant amount of centralized recharge and are predominantly influenced by piped flow. This model may not be suitable for simulating the spring flow in young aquifer systems or the dry season flow of karst springs [154].
Equivalent porous media model	The equivalent porous media model is a generalization of the entire karst aquifer system, which includes the fracture system and the pipe system. It represents the karst aquifer system as a homogeneous porous media aquifer and utilizes Darcy's law to simulate the movement of groundwater within this system [155,156].	The equivalent porous medium model homogenizes the whole karst aquifer system and requires only a small amount of investigation, which makes it very easy to apply to the actual karst aquifer system, but it also leads to difficulty in reflecting the non-homogeneous characteristics of the karst aquifer system in this model [157,158].
Equivalent porous media–pipe model	In the equivalent porous media pipeline model, the pipeline system and the fracture system are represented using distinct units. The pipeline unit is either embedded in or superimposed on the fracture system unit [159].	The pipeline module is used to simulate wide cracks and karst pipelines, and the porous medium module is used to simulate tiny cracks and the rock matrix. The pipeline module is embedded or overlaid in a porous medium module, which can exchange water [160].
Multivariate statistical analysis		
Morphological analysis of heavy metals	This study investigated the migration of heavy metals by considering the hydrogeological conditions, the water chemistry of the study area, human activities, and the distribution of heavy metal forms.	This study focuses on generalized modeling of heavy metal migration in the study area, specifically considering the effects of external influences. It does not take into account the impact of internal structure on heavy metal transport [161].

The migration coefficient is a quantitative study of the migration of chemical components in the process of host rock weathering. It includes two types of host rock-filtrate and host rock-weathering products [137,138]. Simulation experiments are conducted to preliminarily study the upward migration behavior of heavy metals [139–142]. The conceptual model mainly reveals some characteristics within the water-bearing system, but it does not provide a detailed reflection of local characteristics within the system [143–147]. Distributed models, on the other hand ("flow dynamics") are based on hydrodynamic mechanisms and are used to describe and simulate hydrological processes within a watershed. These models effectively capture the non-homogenous and physical hydrological processes in the watershed and are widely used for studying heavy metal transport [148–161].

4.2. Comparison of Research Methods for Heavy Metal Migration in Karst Groundwater in Southern and Northern China

Numerical simulation methods are often used to study the migration of heavy metals in karst groundwater in southern and northern China. Therefore, this research mainly discusses the current situation of numerical simulation methods for heavy metal migration in karst groundwater in southern and northern China and combines the characteristics of karst in southern and northern China. A comparison of karst water models in practical applications in southern and northern China is proposed. Due to differences in the characteristics of karst water systems in the north and south, the complex and diverse movement characteristics of karst multi-media groundwater systems differ significantly between northern and southern China. Therefore, it is important to select an appropriate model based on these differences in practical applications.

Table 9 presents a comparison of numerical models that investigate the migration of heavy metals in karst groundwater in southern and northern China. In the southern region, the karst water system comprises both rapid pipeline flow and diffuse fissure flow, with the majority being classified as karst pipeline groundwater [162]. Atmospheric precipitation primarily replenishes groundwater through sinkholes, while the main route for runoff is through karst pipelines. Groundwater flows at a high rate and is discharged as spring water and underground rivers. Therefore, when constructing the karst water system model in the southern region, it is crucial to focus on the coupling between surface water and groundwater at the karst basin scale, as well as the detailed characterization of karst pipelines and fissures at a smaller scale [163]. To better address the coupled transport of heavy metals between surface water and groundwater at the karst basin scale, it is necessary to establish a strict correspondence between surface and subsurface grid cells during water cycle simulations. In transient simulations, the equations governing surface and subsurface water flow are solved together. Several models, such as HydroGeoSphere [164], MIKESHE [165], MODCYCLE [166], ParFlow [167], PIHM [168], MODHMS [169], and InHM [170], have been developed for this purpose. Among them, the MODHMS model is capable of effectively simulating heavy metal pollutant transport [169]. The MODHMS model integrates two-dimensional land surface flow, one-dimensional river flow, and three-dimensional groundwater flow, and employs the first-order exchange method to couple each hydrological process. It enables simultaneous solution and real-time interaction between surface and subsurface, providing a comprehensive simulation of various aspects of the water cycle and flexible resolution of complex problems. However, it requires the surface and subsurface models to be based on the same discrete approach [171].

Research in the karst area of southern China focuses on the migration of heavy metals in the dynamic changes of groundwater within karst-fractured pipelines. The main approach involves establishing a karst groundwater coupling model, which consists of a distributed watershed hydrological model and a multi-media model capable of describing the changes in multi-flow patterns of concentrated pipeline flow [172,173], which is mainly a porous media–pipeline coupling model. The karst water in northern China is dominated by fissure flow, and atmospheric precipitation recharges the karst aquifer through the fissure part. The runoff characteristics are dominated by the diffusion flow formed by the solution gap or the pipeline flow formed by the local strong runoff zone, which is mainly discharged in the form of springs [174–176]. At present, domestic scholars generally believe that the movement of karst water in the north is dominated by seepage, which generally conforms to Darcy's law. The migration of heavy metals in groundwater in the karst region of North China is mainly characterized by a slow migration rate with a certain lag, and the migration flow is in line with the Darcy flow. In the current study of heavy metal migration in karst groundwater in northern China, it is important to prioritize the coupling of slow seepage in the regionally distributed karst pore-fracture medium with fast flow in the vein-distributed strong runoff zone. When conducting large-scale simulations of the northern karst water system, the Equivalent Continuous Porous Medium Model (EPM) is commonly used. This model aims to depict the anisotropic characteristics of the medium, which are influenced by regional tectonic spreading. Therefore, according to the characteristics of the northern karst area, the model is mainly based on the equivalent continuous pore medium model, which can accurately reflect hydrogeological conditions, focusing on the slow seepage in the karst pore-fracture medium distributed in the coupling area and the rapid flow in the strong runoff zone distributed in the vein. In addition, the study of heavy metal migration in karst groundwater in northern China mainly focuses on the influence of coal mining on heavy metal migration. Huang [31] simulated and predicted the influence of the heavy metals Zn, Cd, and Mn on karst groundwater in the Niangziguan spring area after the outflow of acid old kiln water in Shandi River Basin through Visual Modflow software. Shen [177] used Visual Modflow software to simulate the influence of Pingyao Ermugou coal mining on karst groundwater resources in the Hongshan spring area, mainly aiming at the influence of acid old kiln water discharge caused by coal mining on the migration of heavy metals in karst groundwater [178–181].

Table 9. Comparison of numerical models of heavy metal migration in karst groundwater in southern and northern China.

Region	Application	Model	Parameter	Limitation	Code	Grid Generation
Dawu water source area, Zibo City, Shandong Province (northern) [182]	Numerical study on contaminant transport in fissure karst water	Equivalent porous media (EPM)	Permeability coefficient, effective porosity, hydrodynamic dispersion coefficient, actual average velocity of groundwater, water flux of the aquifer.	The permeability coefficient and effective porosity should be adjusted according to the hydraulic characteristics of the fractured karst aquifer. If the hydraulic characteristics of the fractured karst aquifer are not taken into account, the parameters are also the values of porous media, which may cause significant errors.	MODFLOW-MT3D software package	The numerical simulation of the water head adopts the finite difference method of the central node of the block.
Karst groundwater in the Sangu spring area (northern) [183]	Numerical simulation of pore-fissure groundwater resources	Equivalent porous media model	Water level elevation, precipitation infiltration, leakage recharge, aquifer thickness, permeability coefficient, specific yield.	According to the characteristics of the karst groundwater system, the two-dimensional unsteady flow of groundwater in the heterogeneous anisotropic phreatic-confined aquifer is discretized by triangular elements in the calculation area.	AQUA3D software package	Triangular element discretization

Table 9. *Cont.*

Region	Application	Model	Parameter	Limitation	Code	Grid Generation
Karst water in the east of Weibei, Shaanxi Province (northern) [184]	Fracture–pore dual medium	Three-dimensional groundwater flow model of fracture–pore dual medium	The elevation of the spring mouth, the vertical equivalent permeability coefficient, and the unit water storage coefficient of the water-bearing or weakly permeable layer; gravity yield of the non-pressure aquifer; the mining amount of the mining well and the volume of the working section of the well; the algebraic sum of atmospheric rainfall infiltration recharge intensity and river and reservoir leakage intensity.	To objectively describe the spatial distribution characteristics of water-bearing media, the study area is divided into 20 simulation layers, and each simulation layer has different karst-developed water-bearing media. In this case, how to give the spatial distribution of initial parameter estimates is a difficult problem.	MODFLOW software package	The finite difference method of arbitrary polygon mesh is used to solve the problem
Southwest karst areas [163]	Rock fissures and karst conduits	Equivalent medium coupled distributed pipeline model	Permeability coefficient, flow rate, water storage rate, pipeline flow rate, pipeline diameter, pipeline length, pipeline head loss, hydrodynamic viscosity coefficient, water exchange between pipeline and bedrock, porosity of aquifer medium, hydrodynamic dispersion coefficient, and groundwater seepage velocity.	In the CFP model, only the straight circular pipe is used to generalize the characteristics of the karst pipeline, which is different from the actual karst pipeline morphology. Accurate description of the morphological characteristics of karst pipelines is the goal of further research.	Pipeline flow CFP flow model and MT3DMS solute transport model software package	Finite difference method of element center
Dajing River Basin in Guizhou (southern) [164]	Pipeline-porous medium dual	Porous media–pipeline coupling model	Rainfall infiltration recharge coefficient, permeability coefficient, specific yield, pipe size, pipe curvature, pipe roughness coefficient, exchange coefficient between pipe wall and porous medium, and groundwater temperature.	The equilibrium of the whole model can reflect the overall source-sink term, but it cannot reflect the exchange between the pipeline and the porous medium.	MODFLOW-CFP software package	In the pipeline position, the CFPM2 module in the CFP mode is used for description, and the node still adopts a uniform subdivision format of 100 m × 100 m.
Karst groundwater in the Baixing area of Sanchahe River Basin (southern) [185]	Karst pipeline	Porous media–pipeline coupling model	Horizontal and vertical permeability coefficient of the epikarst zone, precipitation, lateral recharge, pipeline length.	The accuracy of pipeline characterization needs to be improved. The karst pipeline exists underground, and its spatial shape, diameter change, roughness, and curvature of the pipeline are difficult to obtain, so it is difficult to accurately characterize the karst pipeline.	GMS-CFP software package	The whole study area was meshed by GMS at 100 m × 100 m, with a total of 73 rows and 97 columns.

5. Conclusions and Future Perspectives

Investigating the migration process of heavy metals in karst groundwater is crucial for understanding how these metals enter the groundwater system and identifying potential pollution sources and migration paths. This knowledge can aid in risk and vulnerability assessment and serve as a foundation for developing pollution prevention and control strategies. In conclusion, there have been many mature studies on the migration of heavy metals in karst groundwater. This review aims to summarize the impact of environmental factors, including rainfall, vegetation, soil, rock, and aquifers, on the behavior of heavy metal migration. Differences in hydrogeological structures between southern and northern China have resulted in variations in the migration characteristics of heavy metals in groundwater. In southern China, the migration of heavy metals exhibits directional and seasonal patterns. In contrast, in the karst groundwater in the northern region, the migration of heavy metal pollution is characterized by concealment and hysteresis. The mechanism of heavy metal migration also differs between southern and northern China. In the south, heavy rainfall and limestone soils facilitate the migration of heavy metals. In contrast, the migration of heavy metals from karst groundwater due to rainfall in northern China is mainly diffusive, it is while convective in the south. In terms of modeling, the main method of karst groundwater research in southern China is the coupled porous media–pipe model. Conversely, the heavy metals in karst groundwater in northern China are mainly analyzed using the equivalent continuous pore medium model. However, the intricate nature of the migration process and the multitude of influencing factors have significantly hindered the progress of heavy metal migration studies. Therefore, accurately studying the migration of heavy metals in karst aquifers remains a significant challenge. Future research should focus on exploring the following aspects in greater depth:

1. To further analyze the mechanism of heavy metal migration in karst groundwater and then establish research on the microscopic-scale migration of heavy metals. This research focuses on two main aspects: (1) understanding the migration of heavy metals under the influence of various factors, as well as the compound pollution caused by interactions between different heavy metal factors; and (2) conducting an integrated study of the horizontal and vertical migration of heavy metals. This investigation is crucial in assessing the ability of heavy metals to migrate and the associated environmental risks.
2. Combining groundwater simulation software with geographic information systems (GIS) is a significant area of research. The existing groundwater simulation software used globally already offers data interfaces with GIS. As the application of GIS in the field of hydrogeology continues to expand, the integration between groundwater simulation software and GIS will become even more crucial. This seamless integration is essential for effectively visualizing and conducting numerical simulations of groundwater.
3. The investigation of heavy metal migration patterns in evolving karst environments is a crucial focus for future research. Karst groundwater environments have the potential to change over time due to karst action, resulting in the re-migration of heavy metals. Therefore, conducting ongoing indoor and outdoor simulation experiments is essential to enhance our understanding of how karst action influences the migration of heavy metals in groundwater. To accurately estimate the migration of heavy metals in groundwater, a potential area for future research is to include rocks in the design of soil columns during dynamic leaching and static adsorption experiments on the migration of heavy metals in karst areas. The addition of rocks aims to reduce the actual migration of heavy metals in soil. This research will contribute to a deeper understanding of the migration patterns of elements in the entire karst environment and their correlation with karst ecology.
4. In future research, it is recommended to incorporate elemental attenuation, adsorption analysis, and vegetation influence, among other factors, into groundwater pollutant transport modeling. This will provide a more scientific basis for groundwater envi-

ronmental protection. In the solute transport equation, it is important to consider the adsorption of heavy metals from both the upper and lower aquifers. Additionally, the adsorption of the weakly permeable layer plays a crucial role in the transport and distribution of heavy metals. Therefore, it is necessary to couple the vertical one-dimensional solute transport model of the weakly permeable layer with the solute transport model of the upper and lower aquifers to address this issue. The relationship between the characteristics of the adsorption resolution curve and the upper and lower aquifers is still unclear. Thus, it is essential to explore the mechanism of the tracer adsorption curve, study the process of heavy metal ion exchange in karst water systems, and establish a mathematical model for heavy metal solute exchange. These areas should be the primary focus of solute transport studies in karst areas.

5. There is a need for a better understanding of the mechanisms of heavy metal transport in karst groundwater in both the southern and northern regions. This understanding should include changes in precipitation and water table levels, as these variations can influence groundwater flow, which in turn affects the dissolution and transport of heavy metals. Additionally, climate change can impact precipitation and temperature, further influencing the groundwater system and heavy metal migration. It is also important to investigate the timing of extreme precipitation events, as these can lead to flooding. Furthermore, it is crucial to prioritize further research on stabilizing karst groundwater heavy metals during extreme precipitation events.

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