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Review Article

Review of the Hydrogeological Controls on Coalbed Methane (CBM) and Development Trends

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Hydrogeological conditions can control the generation, preservation, enrichment, and production of coalbed methane (CBM) in the field; however, research on these impacts is insufficient, resulting in the limitation of the development of coalbed methane. This paper summarizes the current research status and development trends of the effect of hydrogeology on CBM using methods such as mathematical statistics, literature analysis, well logging, and hydrochemical analysis. The results indicate that it is beneficial for the generation of secondary biogenic gases in low-rank coal seams under the situations like active hydrodynamic conditions with a salinity less than 1000 mg/L, a pH range from 5.9 to 8.8, or a range of oxidation-reduction potential from -540 mV to -590 mV. The abnormally high temperature due to the magmatic-hydrothermal fluids accelerates the metamorphism of coal rocks, leading to the promotion of the generation of thermogenic gases. When the coalbed structural conditions of one area are similar to the depositional conditions in that area, the CBM is accumulated if the conditions of that area meet the following criteria: the water type is $NaHCO_3$, the salinity is greater than 1500 mg/L, the desulfurization coefficient is less than 1, and the sodium-chloride coefficient is less than 10. The stable isotope analysis of CBM well-produced water shows that the δD values in the groundwater shift to the left of the global meteoric water line, indicating that the produced water comes from atmospheric precipitation. In the CBM enrichment zone, the area with a relatively high salinity and a low sodium-chloride coefficient is the high-production area. Based on our study, three high CBM-production patterns are summarized: coalbed structure-hydraulic trapping, fold limb-fracture development, and syncline core-water stagnation. Additionally, four development trends of the control of hydrogeology on CBM are proposed: transformation from qualitative evaluation to quantitative evaluation, from a singular evaluation standard to multiple evaluation standards, from static evaluation to dynamic evaluation, and from pure theoretical research to theoretical guidance on production practices.

1. Introduction

Hydrogeological conditions have impacts on the processes of the formation, enrichment, accumulation, and production of CBM in coalbed. Groundwater is not only the medium for the generation of CBM [1, 2] but also the driving force for the migration of CBM and the carrier of the production of CBM [3–5]. After nearly 20 years of explorations and studies on CBM, abundant theoretical findings about the role of hydrogeological conditions in gas controlling are achieved, which effectively guides the selection of CBM enrichment areas. However, few studies on the quantitative evaluation about the hydrogeology in the enrichment areas and its effect on high CBM production are conducted. Therefore, on the basis of reviewing the current research on the gas controlling effect of hydrogeology around the world, this paper analyzes the existing scientific problems and explores the development trends of gas control research with the expectation to guide the efficient extraction of CBM in China.

2. Role of Water in CBM Formation

Coalbed methane forms as either biogenic gas or thermogenic gas [6–9]. The effect of water on the formation of biogenic gas is realized by hydrodynamic conditions, water salinity, and hydrological environments. For the formation of thermogenic gas, the effect of water can be reflected by the heating effect that enhances the coalification process, which further increases the potential of methane generation. The preceding results explain the mechanism of water effect on CBM formation, which is important for selecting the method to extract CBM of different coal ranks.

2.1. Influence of Water on Biogenic Gases. To compare with the secondary biogenic gases, primary biogenic gases are hard to be preserved and accumulated to form reservoirs. Studies around the world indicate that active hydrodynamic conditions with proper salinity, a proper pH value, and oxidation-reduction reactions are beneficial for the formation of secondary biogenic gases in low-rank coals. The hydrodynamic and hydrochemical conditions which are required for producing secondary biogenic gases are as follows: the range of the pH value from 5.9 to 8.8 is suitable for methanogens to survive and grow as well as the most beneficial range for producing methane [10, 11]. Xianbo et al. conducted an experiment in the laboratory and found that, under the same conditions, the low-rank coal has the maximum methane production capability in the water environment with a pH of 8 [12]. In a water environment where the oxidation-reduction reactions are lower than -330 mV, the capability of generating secondary biogenic gases is normal; however, when the oxidation-reduction reactions range is from -540 mV to -590 mV, the methanogens have the highest activity rate and the gas generation capability in low-rank coals reaches the maximum [13]. A temperature range from 36°C to 42°C is most beneficial for the growth of methanogens [14]. When the salinity does not exceed 4000 mg/L, a large amount of secondary biogenic gases is generated. When the salinity is greater than 10000 mg/L, the gas generation capacity of low-rank coals decreases sharply [15–17]. Taking Powder River Basin in the United States as an example, groundwater is quite active in the slope area on the eastern edge. The salinity in that area is less than 1000 mg/L; thereby, the methanogens are very active, which speeds up the generation of secondary biogenic gases [18]. All these theoretical results provide evidence for selecting the best place for extracting CBM in low-rank coals.

2.2. Influence of Water on Thermogenic Gases. Thermogenic gases are generated mostly during the stage where coal undergoes metamorphism. The heat is the main factor that speeds up the metamorphism process while the groundwater plays an additional role during the formation of thermogenic gases. As fluids carrying the heat, the groundwater directly exchanges heat with coal seams, driving the metamorphism of coal seams. There are two ways for hydrothermal fluids to speed up the metamorphism process: one is the direct contact between coal seams and magma. Magma contains volatiles, which emits high-temperature steams. When the temperature reaches a critical point, high-temperature steams become hydrothermal fluids. This process is also called the pneumatolytic hydrothermal process [19]. The other method is that the water in the coal seam and in the neighboring aquifer becomes high-temperature hydrothermal fluids [20] because the water temperature is increased due to influences from the heat source in the depth of the ground.

3. Hydrogeological Controls on CBM Enrichment

3.1. Relationship between Hydrodynamic Zones and CBM Enrichment. Hydrodynamic conditions affect the distribution of methane in coal seams by controlling groundwater movements and changing fluid pressure. To provide evidence for exploring the mechanisms of groundwater movement and finding CBM enrichment zones, this paper carefully divides Qinshui Basin into several hydrodynamic zones.

3.1.1. Classification of Hydrodynamic Fields. At present, representative views on the controlling effect of hydrodynamic zones on the enrichment of CBM in China are as follows: the sealing or plugging of hydraulic flows creates a favorable environment for CBM enrichment. The hydraulic forces cause the methane to migrate and dissipate, resulting in the destruction of CBM reservoirs [21]. Taking the southern Qinshui Basin as an example, domestic scholars divide the basin into three zones based on the geological structure, salinity, and runoff intensity: strong runoff zone, medium runoff zone, and weak runoff zone. The strong runoff zone is located within the belt of 3 km–5 km of the basin margin. Within the zone, the salinity generally ranges from 357 mg/L to 542 mg/L, and the average gas content in main coal seams ranges from 6 to 8 m^3/t. The medium runoff zone is located at the slope zone around the basin with a width range from 3 km to 8 km. In the zone, the runoff condition is relatively strong, and the salinity is generally between 466 mg/L and 1399 mg/L. What is more, the gas content in the coal seam varies greatly, ranging from 3 to 16 m^3/t. The weak runoff zone is located at the internal of the basin, which is abundant in groundwater. The salinity in the zone reaches 1824 mg/L. Due to weak groundwater runoff, the content of CBM in this zone is generally high, reaching 26 m^3/t [22, 23].

On the basis of hydrodynamic zoning at the basin level, domestic scholars worked out a block-level method for identifying hydrodynamic zones according to exploration and practice data. Based on the ground pressure data collected in the field testing, they calculated the converted water table and drew the converted water table map to analyze the groundwater flowing state [14]. Then, they divided the groundwater hydrodynamic fields into three zones according to the following conditions such as the structure, hydrochemical characteristics, and runoff intensity in the basin (see Table 1): strong runoff zone, medium runoff zone, and stagnant zone [22–25].

3.1.2. CBM Reservoir Formation Pattern Based on Hydrodynamic Zones. A hydrodynamic condition is one of the main factors controlling the formation of CBM reservoirs. In general, scholars associate hydrodynamic conditions with structural conditions to figure out the formation pattern of CBM reservoirs. Then, they locate the area which is most favorable for CBM enrichment [26]. Fu et al. were the first to propose a conceptual model that combined hydrodynamic conditions with structural conditions. They divided the seal-capping capability of hydraulic runoffs in Qinshui Basin into three types: stagnant runoffs on the pothole-shaped equipotential surface, slow runoffs on the half-graben equipotential surface, and slow runoffs on the fan-shaped equipotential surface [27]. Qin et al. proposed a CBM reservoir formation pattern in which the CBM reservoir was formed because of the seal-capping of hydraulic flows and the imbricate thrust faults in the Zhuozishan mining area, giving a new way of thinking about how to explain the controlling effect of hydrodynamic conditions under complex compositions [28]. Zhu et al. summarized two CBM reservoir formation patterns according to the hydrochemistry, hydrodynamics, and composition characteristics of the Gujiao mining area in the Xi'shan coalfield: monocline structure with hydraulic sealing and horst with hydraulic sealing [29]. Zeng et al. further put forward three CBM enrichment patterns [30]: monocline hydrodynamics, syncline hydrodynamics, and fault hydrodynamics. All the preceding results are of great significance to be referenced when selecting an area with highly enriched CBM.

In the preceding studies, the reservoir formation patterns are classified based on the relationships between geological structures and hydrodynamic zones, which takes fewer considerations on the capping combination condition under the subsidence control, and the scale of CBM reservoirs formed through these patterns is relatively small.

Based on the coupling between geological structures, hydrodynamics, and sedimentary substances, the author dissected the Qinnan-Xiadian area and set up a configured block-level CBM reservoir formation pattern based on main control elements (see Figure 1). The Qinnan-Xiadian area is mainly a syncline structure. One limb of the syncline is cut off by two faults. Combining the geological structure, hydrodynamics, and sedimentary forces, the author divided the limb into three basic systems: open type, semiopen type, and close type. These three basic systems correspond to the recharge zone, weak runoff zone, and pressure-bearing and stagnant zone, respectively, in the figure. The Qinnan-Xiadian block is a delta sedimentary area with the upper roof made by mudstone which has good sealing and capping performance. The mudstone roof is distributed stably in the whole zone. The lower floor is made of mudstone or silty mudstone which has a relatively good sealing and capping performance. Therefore, the coupling between geological structures and hydrodynamics is the main factor controlling CBM enrichment in this block. The recharge zone is located at the eastern limb of the syncline. The boundaries of the recharge zone are mainly divided into three types: the water-conducting boundary, jacking overflow boundary, and infiltration recharge boundary. The boundaries are closely related to surface hydraulics. Therefore, the hydraulic activity in the recharge zone is strong, thereby dissolving the methane easily and creating a poor CBM preservation condition. The gas content in the coal seam is less than 8 m^3/t. The gas saturation is less than 48%. The weak runoff zone is located on both sides of the eastern fault. The boundaries are mainly divided into three types: the boundary for gas dissipation, the boundary for sealing water and trapping gases, and the boundary for water discharge and gas leakage. This zone is partly supplemented by atmospheric precipitation. The CBM preservation conditions are relatively good. The gas output from CBM wells is stable. Gas content is greater than 16 m^3/t, and gas is evenly distributed. The pressure-bearing and stagnant zone is located at the low-potential area of the syncline. The hydrodynamic runoff conditions in that zone are poor. The boundaries are mainly divided into two types: the boundary for sealing water and trapping gases and the boundary for storing stagnant water. This zone is basically not recharged by atmospheric precipitation. Therefore, it is enriched with CBM. The gas content is greater than 14 m^3/t. The gas saturation is greater than 82%.

3.2. Response Mechanism of Hydrogeochemistry to CBM Enrichment. Hydrogeochemistry features are closely related to CBM. Different groundwater salinity values have varying impacts on CBM enrichment [31]. The isotopic distribution indicates the cause for water produced in coal seams, which further affects the CBM enrichment. Both can indicate the supply source for groundwater, the movement paths of groundwater, and the runoff intensity of groundwater. The groundwater salinity and isotopic distribution can be used to find the CBM enrichment rules under different geological conditions, to figure out the best solution for selecting highly productive and enriched areas of CBM, and to improve the efficiency of extracting and exploring CBM.

3.2.1. Hydrogeochemical Parameter Characterization and Its Relationship with CBM Enrichment. Parameters that mainly characterize hydrogeochemistry features include the water type, salinity, and content of main ions. Currently, the common diagrams for determining the water type mainly include a six-axis diagram (Tickel diagram), three-line diagram, Stiff diagram, and Kurlov diagram [31].

This paper employs the Stiff diagram to visually display the differences in the chemical composition of water which is produced from CBM wells in several typical blocks of Qinshui Basin and Ordos Basin. Figure 2 shows the main findings of the study. From the figure, we can see the specific content of main cations and anions in water which is

Table 1: Conditions for identifying different hydrodynamic zones.

Identification condition	Strong runoff zone	Medium runoff zone	Stagnant zone
Fault development characteristics	Strongly fractured fault with a high hydraulic conductivity	Fractures and faults distributed within the zone with a relatively low hydraulic conductivity	No fractures or fewer fractures within the zone
Connection with surface water	Close relationship between the surface water in the zone and the aquifer	Hydraulic relationships between part of the surface water in the zone and the aquifer	No hydraulic relationship between the surface water and the aquifer
Water type	$SO_4 \cdot Cl^- – Na \cdot K$	$HCO_3 \cdot Cl – Na \cdot K$	$Cl – Na \cdot K$
Converted hydraulic gradient	>0.3 m/m	0.1~0.3 m/m	Less than 0.1 m/m
Salinity	Low	Medium	High

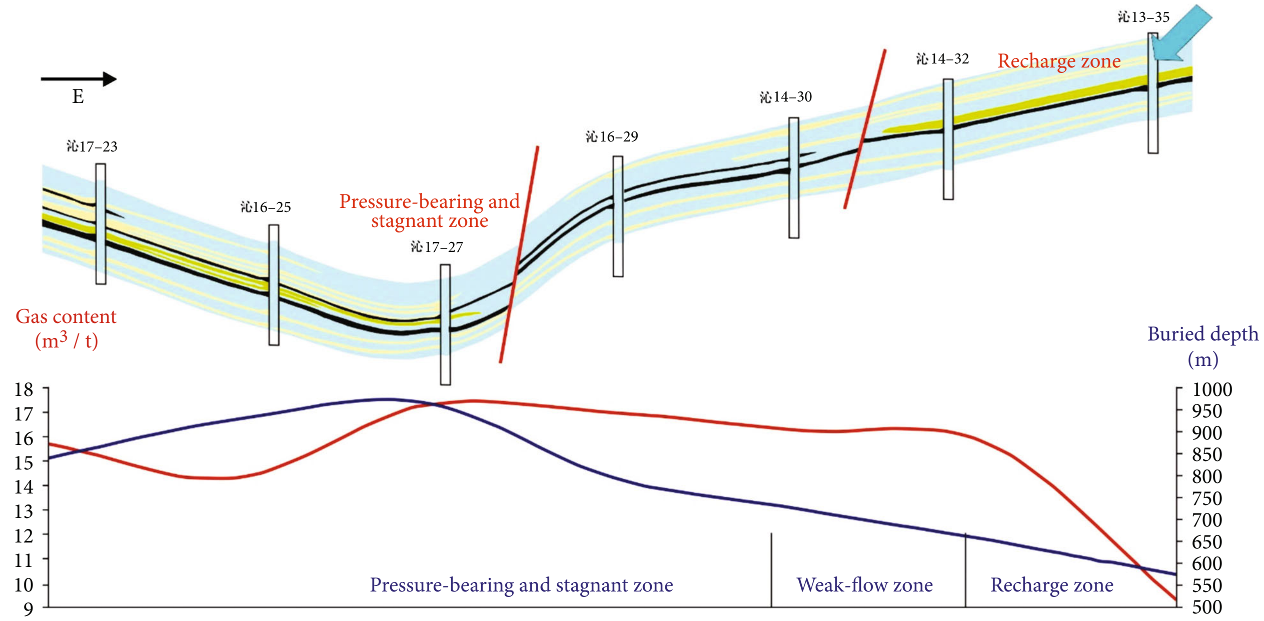


Figure 1: Analysis map of the accumulation model of the Qinnan-Xiadian area.

produced from different blocks and the corresponding Stiff diagrams. It can be concluded from Figure 2 that blocks that were highly developed have similar hydrogeochemical characteristics. Water in the CBM enrichment areas is mainly classified into two types: Na-HCO_3 and Na-Cl-HCO_3. For both water types, the cation characteristics are as follows: Na^+ and K^+ are the dominating cations, accounting for more than 90% of the total amount of cations. The content of Mg^{2+} and Ca^{2+} is very low, which accounts for less than 10% of the total amount of cations. The anion characteristics are as follows: HCO_3^- is the dominating anion, or Cl^- and HCO_3^- are the dominating anions.

Salinity can be used as an important reference to determine the sealing conditions and hydrodynamic conditions of coal reservoirs. Generally speaking, the areas with stagnant groundwater have high salinity; thus, CBM is more likely to be enriched. However, in the areas close to the recharge zone or the areas with intense groundwater runoffs, CBM can be easily dissipated along with groundwater movements. CBM is not easy to be preserved. Domestic scholars have reached similar conclusions through sampling and analyzing the water which is produced from CBM wells in places with relatively simple geological structural conditions such as Fanzhuang, Shijiazhuang, Panzhuang, and Shizhuangnan [32–36] in Qinshui Basin: CBM is more enriched in the areas which have the following conditions: the salinity is greater than 1500 mg/L, the desulfurization coefficient is less than 1, and the coefficient of sodium and chloride is less than 10 (see Table 2).

3.2.2. Response Mechanism of Isotope Geochemistry. The stable isotope compositions of hydrogen and oxygen can provide evidence for the mixture of CBM well-produced water and atmospheric precipitation or groundwater in the surrounding rock aquifers, thus indicating changes in the permeability and water flow rate. In addition, the stable

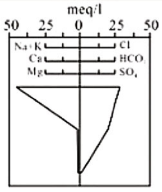
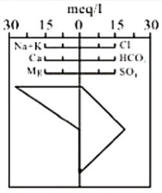
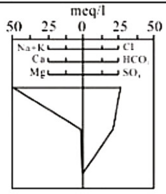
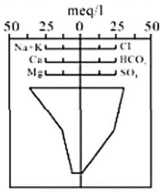
Block Name	main cation (mg·L^{-1})	main anion (mg·L^{-1})	stiff diagram	water type
Fanzhuang block	$Na^{+}+K^{+}$ 262.1～1141 Mg^{2-} 0. 5～38. 2 Ca^{2-} 0. 8～30. 2	SO_4^{2-} 0. 9～763 Cl^- 37. 3～1096 HCO_3^- 200. 8～1689		Na-Cl-HCO_3
Zhengzhuang block	$Na^{+}+K^{+}$ 434.3～861 Mg^{2-} 1. 5～28. 7 Ca^{2-} 3. 1～32. 6	SO_4^{2-} 4. 2～239. 7 Cl^- 42. 7～127. 5 HCO_3^- 740. 3～1507		Na-HCO_3
Hancheng block	$Na^{+}+K^{+}$ 388. 5～1343. 5 Mg^{2-} 1. 1～38. 6 Ca^{2-} 5. 25～44. 4	SO_4^{2-} 0. 5～570 Cl^- 97. 2～1612 HCO_3^- 318～1504		Na-Cl-HCO_3
Baode block	$Na^{+}+K^{+}$ 105～604 Mg^{2-} 24～92.8 Ca^{2-} 22～144	SO_4^{2-} 1～189 Cl^- 114～930 HCO_3^- 180～1073		Na-Cl-HCO_3

Figure 2: Geochemical characteristics of groundwater in typical blocks of North China.

isotope compositions of hydrogen and oxygen are also effective indicators for determining the changes of runoff conditions of CBM well-produced water [36–38]. The stable isotope analysis of CBM well-produced water shows that positive deviations of δ^{18}O and δD values in the groundwater are related to high water yield and low gas yield in CBM wells, while negative deviations of δ^{18}O and δD values in the groundwater are related to low water yield and high gas yield in CBM wells [39]. These conclusions are based on the measured data and theoretical analysis. Some scholars find that shallow strata and areas with more active groundwater are greatly affected by surface water. The hydrogen and oxygen isotope ratios in produced water are high, showing positive deviations of δ^{18}O and δD from the global meteoric water line. However, in the deep strata which have a weak hydraulic connection with surface water, hydrogen and oxygen isotope ratios of produced water are low. It shows negative deviations of δ^{18}O and δD on the global precipitation curve. It means that the measured values of δ^{18}O and δD are lower than the reference values on GMWL. Considering the relationship between hydrodynamics and coalbed methane enrichment and high production, hydrogen and oxygen isotopes are proposed indicators showing coalbed methane enrichment and high production.

Figure 3 shows the H and O isotopes in coal seam-produced water from CBM wells in Qinshui Basin which is located at the central Guizhou uplift area and Bowen Basin in Australia. From Figure 3, we can see that δ^{18}O and δD values in Qinshui Basin are lower, with δD ranging from -80‰ to -75‰ and δ^{18}O ranging from -12‰ to -8‰. CBM wells are distributed on both sides of the global atmospheric precipitation line. Most of the CBM wells are at the right of the curve, indicating that the reason for forming coalbed water is complex. Most of the water is produced by sedimentation; however, the water in some wells is produced by infiltration. For the central Guizhou uplift area, there is a relatively large variation in hydrogen and oxygen isotopes, with δD ranging from -90‰ to -30‰ and δ^{18}O ranging from -11‰ to -4‰. The wells are mainly distributed at the left of the global meteoric water line. The δD has obvious *D* drifting characteristics, indicating that the coalbed water is mainly recharged by atmospheric precipitation as well as a strong interaction between water and rock [40]. The δ^{18}O and δD values in Bowen Basin CBM water are relatively higher, with δD ranging from -50‰ to -30‰ and δ^{18}O ranging from -8‰ to -4‰. The wells are mainly distributed near the global meteoric water line. The δD tends to shift to the right, indicating that the coalbed water is recharged by surface water, and most of the water is produced in sedimentary processes. The hydrogen and oxygen isotopes in atmospheric precipitation are relatively light, while the hydrogen and oxygen isotopes in sedimentary water are relatively heavy due to the influence of fractionation. Therefore, the source of coalbed water can be judged

Table 2: Geochemical characteristics of water produced from CBM wells in Qinshui Basin [4, 32–35].

Block	Well sequence number	Major ion concentration (mg·L^{-1})						Salinity (mg·L^{-1})	Coefficient for sodium-chloride	Desulfurization coefficient
		$Na^+ + K^+$	Mg^{2+}	Ca^{2+}	Cl^-	HCO_3^-	SO_4^{2-}			
Fanzhuang	FZ-1	537.7	4.6	8.65	129	1130.3	1.12	1811.37	6.43	0.32
	FZ-2	703.9	4.65	11.9	308	1341	0.94	2370.39	3.35	0.11
	FZ-3	551.1	1.47	4.13	119	1185.1	0.82	1861.62	7.15	0.25
	FZ-4	640	2.20	4.01	248	1115.9	7.46	2071.57	3.98	1.11
	FZ-5	1061.5	6.55	10.3	981	1019.1	1.62	3080.07	1.67	0.06
	FZ-6	598.07	2.45	4.66	75.5	1366.2	4.47	2051.35	12.23	2.19
North of Shijiazhuang	SJZ-1	476.26	2.36	7.7	37.7	1143	4.95	1718	19.5	4.86
	SJZ-2	391.79	2.50	7.88	42.3	938	0.86	1418	14.3	0.76
	SJZ-3	478.18	3.19	7.38	43.9	1081	1.69	1683	16.81	1.42
	SJZ-4	430.04	2.75	7.06	42.9	978	2.73	1516	15.47	2.35
	SJZ-5	410.09	1.96	6.17	52.3	959	1.68	1469	12.10	1.19
	SJZ-6	402.63	1.87	6.17	5.02	932	4.62	1437	123.79	34.03
	SJZ-7	419.22	2.94	8.12	36.7	953	0.7	1482	17.63	0.71
South of Shijiazhuang	SJZ-8	483.71	2.83	9.08	38.6	1145	2.5	1738	19.34	2.4
	SJZ-9	405.08	2.05	5.81	33.7	968	8.82	1452	18.55	9.68
	SJZ-10	424	1.80	5.60	39.9	1009	2.07	1520	16.40	1.92
	SJZ-11	394.67	2.08	7.44	35.2	906	0.68	1395	17.31	0.71
	SJZ-12	380.05	2.02	7.89	36.2	885	1.57	1358	16.20	1.60
	SJZ-13	401.18	2.50	6.4	36	904	0.33	1409	17.20	0.34
Panzhuang	PZ-1	821.3	7.70	11.3	322.2	1313.7	189.3	2742	3.93	21.73
	PZ-2	610.2	1.05	5.14	60.50	1384	0.59	2130	15.57	0.36
	PZ-3	635.92	4.21	8.09	136	1443	20.9	2258	7.22	5.68
	PZ-4	614.41	5.14	5.02	138	1225	44.9	2112	6.87	12.03
	PZ-5	589.84	7.53	5.89	72.3	1244	57.3	2067	12.59	29.31
	PZ-6	716.63	29.2	41.4	110	997	796	2697	10.06	267.59
South of Sizhuang	SZ-1	419.29	0.43	2.59	93.52	599.86	0.68	4208	6.92	0.27
	SZ-2	278.61	0.17	2.14	86.7	555.04	0.52	5553	4.96	0.22
	SZ-3	318.3	0.3	2.29	81.03	561.94	3.6	2425	6.06	1.64
	SZ-4	747.95	4.24	2.87	336.55	1082.5	0.62	2294	3.43	0.07
	SZ-5	443.03	0.35	2.65	70.35	810.15	0.26	1059	9.72	0.14

Data source from the literature [32–35].

based on the relationship between the hydrogen and oxygen isotopes and the atmospheric precipitation curve.

4. Hydrogeological Effects of High CBM Production

4.1. Water Production Features of High CBM-Production Areas. The average water production in the stage of drainage and pressure reduction is used as the basis for dividing CBM wells into three types: high-yield wells, medium-yield wells, and low-yield wells. The low-yield wells are CBM wells with an average daily discharge of less than 2 m^3/d of water during the drainage stage. The medium-yield wells are CBM wells with an average daily discharge of 2~5 m^3/d of water during the drainage stage. The high-yield wells are CBM wells with an average daily discharge of more than 5 m^3/d of water during the drainage stage. Taking the Fanzhuang block as an example, thirty-one high-yield CBM wells (the average daily water production before the entrance of CBM wells into the production decline stage was greater than 1000 m^3/d) are statistically analyzed (see Tables 1–3), and the water production curve is drawn. Among these wells, five wells are wells with a high gas production and high water yield, which are mainly located at the lower part of the local structure. The average daily water production of a single well is between 7.54 m^3/d and 9.74 m^3/d during the stage of drainage and pressure reduction. Ten wells are wells with a high gas production and medium water yield, which are located near the middle and higher parts of the local structure. The average daily water production of a single well is between 2.09 m^3/d and 4.83 m^3/d during the stage of drainage and pressure reduction. Eighteen wells are wells with a high gas production and low water yield, which are mainly located in the higher part of the local structure above the

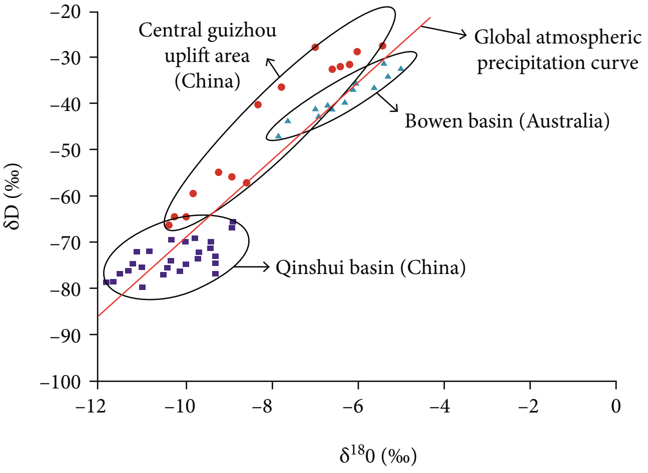


Figure 3: Diagrams of H and O isotopes in coal seam-produced water in different coal basins in China and Australia [38–40].

groundwater level. The average daily water production of a single well is between 0.09 m^3/d and 1.93 m^3/d during the stage of drainage and pressure reduction.

After analyzing the extraction characteristics of selected wells and well structures, the author summarized the following high CBM-production patterns: (1) coalbed structure-hydraulic trapping (see Figure 4(a)), (2) fold limb-fracture development (see Figure 4(b)), and (3) syncline core-water stagnation (see Figure 4(c)).

The area with the first CBM production pattern is located at the higher part of an asymmetric syncline or monocline where the fractures are not developed or water-resistant faults are developed. In Figure 4(a), CBM wells are placed in the higher part of the monocline and far away from the water-resistant fault and recharge source. According to the CBM and the mechanism of water movement, the coalbed water moves from the high-potential zone to the low-potential zone while CBM moves in the opposite direction [41]. However, due to the blocking function of the fault, the hydraulic connection between the hanging wall of the fault and the footwall of the fault is weak. The coalbed water is in a stagnant state in the hanging wall of the fault, which is beneficial for enriching the CBM, resulting in a high CBM content. At the same time, atmospheric precipitation forms hydraulic trapping forces for CBM that moves upwards along the monoclinal structure, preventing CBM in the lower-potential zone from dissipating during the extraction process, which is beneficial for high CBM production in the higher-potential zone. In addition, the coal seam in the higher part of the structure has a better permeability due to the lower pressure and the movements of water and gas. In this pattern, the rules for forming CBM in CBM wells are reflected as follows: a short gas breakthrough time, a low water yield, and a high gas yield. Affected by free gases, the coal seam may have a 100% of gas production.

The area with the second CBM production pattern is located at the limb of a syncline or anticline affected by tensile stress. In Figure 4(b), CBM wells are arranged in the limb of the syncline. Affected by tensile stress, fractures are developed in the coalbed layer and the buried depth of coals is shallow, which is generally about 300 m-800 m. The limb of the syncline is less affected by coalbed water. However, affected by free gases in the core of the syncline, there are more and more CBM formation sources. The fractures generated by the forces of tensile stress are developed on a large scale, leading to the fracturing of reservoirs and further resulting in the desorption of a large amount of CBM [41–43]. In this pattern, the rules for forming CBM in CBM wells are reflected as follows: a short gas breakthrough time in the preliminary stage, an increasing daily yield of gas, and a high peak of gas production.

The area with the third CBM production pattern is located near the core of a synclinore and secondary syncline in a large sedimentary basin. In Figure 4(c), CBM wells are arranged in the core of a broad and gentle syncline where stagnant water stays. No fault is developed, the sealing and capping capability of the roof is good, and the salinity is high. In a situation where the roof has a good water-resistant condition, CBM wells are less affected by external water and the exploitation of CBM wells is not affected. The high effective thickness of the upper layer, the buried depth of the coal seam, and the forces of tensile stress are all beneficial for enriching CBM. In this pattern, the rules for forming CBM in CBM wells are reflected as follows: a high water yield with a long time to enter the stable production phase, a low CBM yield and a high water yield at the beginning, and a long stable production phase with a high peak of gas production and stable gas yield.

4.2. Hydrochemical Features of Areas with a High CBM Yield. The hydrochemical coefficients can better reflect the sealing conditions of groundwater. For example, the coefficient of sodium and chloride can reflect the enrichment degree of sodium salt in groundwater, the metamorphic grade of groundwater, and the hydrogeochemical environment of the reservoir. The desulfurization coefficient is an important index to reflect the openness of groundwater. In general, a better formation closure has the following characteristics: a more thorough desulfurization, a lower SO_4^{2-} content, a smaller desulfurization coefficient, and a more intense reducing action [14].

A comprehensive analysis of hydrochemical characteristics and gas content in the southern part of the Fanzhuang block reveals that the salinity in the southern part of the block gradually increases from north to south, and the sodium-chloride coefficient gradually decreases from northwest to southeast. Two CBM enrichment centers are formed in the area with a high salinity (shown in Figure 5). The area with salinity greater than 2000 mg/L is the CBM stagnation area, and the coalbed gas content is above 26 m^3/t. The above information shows that the area with high salinity and the area with high CBM are positively correlated. However, CBM wells in the area with the highest salinity are not highly productive. The areas with high CBM production in the south of the Fanzhuang block are the intersecting areas with a medium salinity of 2000-3500 mg/L and rNa/rCl less than 6.

Taking the Fanzhuang block in Qinshui Basin as an example, we discussed the controlling effects of the

Table 3: CBM well gas and water productivity in the Fanzhuang block.

No.	Gas production		Total water production (m^3)	Gas-water ratio	Drainage and pressure reduction stage		
	Average (m^3/d)	Total (m^3)			Number of days (d)	Total discharged water (m^3)	Average daily discharged water (m^3/d)
FZ-1	1238	1770555	967.4	1830.2	210	468.00	2.23
FZ-2	1627	2241711	496.8	4512.3	240	440.30	1.83
FZ-3	1233	1541258	556.1	2771.5	193	403.70	2.09
FZ-4	2238	2715371	899.1	3020.1	233	595.90	2.56
FZ-5	1942	2832225	600.3	4718	258	499.20	1.93
FZ-6	1107	1877232	563.3	3332.6	279	446.30	1.60
FZ-7	1236	1436079	817.2	1757.3	393	549.30	1.40
FZ-8	1029	1099688	648.0	1697.1	366	320.70	0.88
FZ-9	2116	1410890	62.6	22538.1	48	14.60	0.30
FZ-10	2799	964503	57.1	16891.5	83	15.80	0.19
FZ-11	1141	4330482	3897.9	1111	1451	3276.40	2.26
FZ-12	1344	5896287	2404.1	2452.6	1144	1707.00	1.49
FZ-13	1008	3627541	5223.2	694.5	936	2971.20	3.17
FZ-14	1544	6624604	6084.1	1088.8	991	4634.20	4.68
FZ-15	1858	7349913	3661.6	2007.3	1935	3288.00	1.70
FZ-16	1064	3740135	10178	367.5	1896	9162.50	4.83
FZ-17	1346	2349283	2982.9	787.6	456	1174.70	2.58
FZ-18	5399	583072	138.3	4216.0	176	107.90	0.61
FZ-19	4938	2114079	349.9	6042.0	151	13.70	0.09
FZ-20	8249	3089116	30.0	102970.5	55	11.20	0.20
FZ-21	1025	7871921	348.6	22581.5	421	233.50	0.55
FZ-22	1250	9834482	2261.8	4348.1	1087	1825.60	1.68
FZ-23	1020	6859558	793.4	8645.8	356	478.70	1.34
FZ-24	1224	9335585	876.3	10653.4	540	427.80	0.79
FZ-25	8284	4076042	101.4	40197.7	124	29.80	0.24
FZ-26	3855	2070627	437.5	4732.9	183	253.30	1.38

Table 3: Continued.

No.	Gas production		Total water production (m^3)	Gas-water ratio	Drainage and pressure reduction stage		
	Average (m^3/d)	Total (m^3)			Number of days (d)	Total discharged water (m^3)	Average daily discharged water (m^3/d)
FZ-27	10362	3348692	938.1	3569.7	251	610.80	2.43
FZ-28	8365	2751742	2394.3	1149.3	217	2034.90	9.38
FZ-29	10682	1131285	2073.9	545.5	259	1953.10	7.54
FZ-30	8063	807480	3473.9	232.4	356	3467.00	9.74
FZ-31	6519	81626883	3621.8	22537.7	410	1754.31	4.28

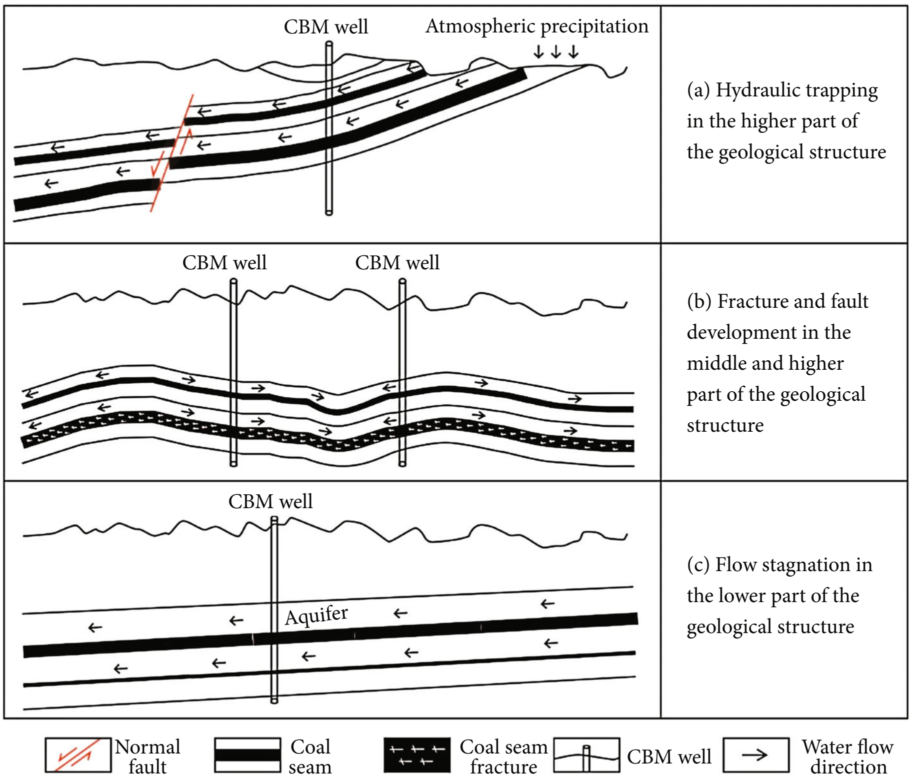


Figure 4: Schematic diagram of high-yield patterns of CBM wells.

coefficient of sodium and chloride, the desulfurization coefficient, and the H and O isotopes on the high CBM production in the CBM enrichment area in the southern part of the block. By studying the distribution of these coefficients in the Fanzhuang block, it is found that CBM wells with a high daily gas production are mainly distributed in the area with the coefficient of sodium and chloride ranging from 3.5 to 8. Besides, the distribution of CBM wells with a high daily gas production has a negative correlation with the sodium-chloride coefficient within a certain range. The lower the sodium-chloride coefficient, the more frequent the high-production wells appear in the area. The desulfurization coefficient can reflect how enclosed the groundwater environment is. The Fanzhuang block is located at the area with a desulfurization coefficient between 4 and 10 and a high distribution of high-yield wells. The desulfurization coefficient is also positively related to the daily gas production of a single well. The distribution of hydrogen and oxygen isotopes can reflect the cause for coalbed water generation and its permeability. In general, the densities of hydrogen and oxygen isotopes in coalbed water from different origins are different. The order of the densities should be as follows: the density of water from atmospheric precipitation>the density of surface water>the density of sedimentary water. Among the water from different origins, the permeability of water from atmospheric precipitation is preferred. The

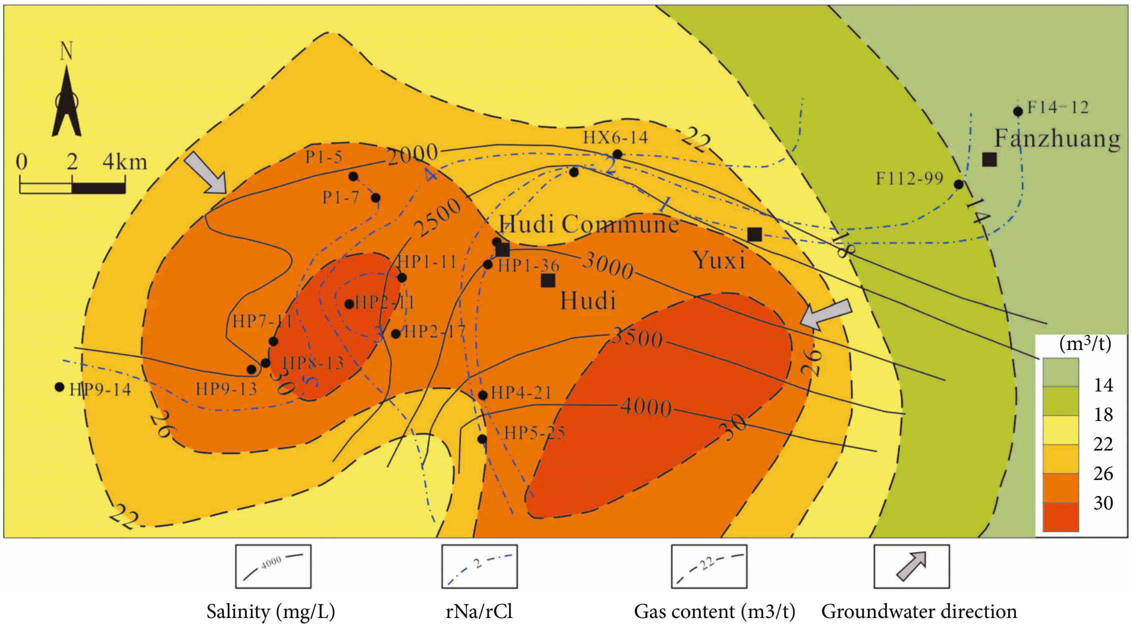


Figure 5: Relationship between the salinity of produced water (constant ratio) and the CBM in the south of the Fanzhuang block.

reason is that water from atmospheric precipitation is most conducive to the high production of CBM wells. The higher the permeability in areas with a lighter hydrogen isotope, the higher the CBM production is. The δD value of the Fanzhuang block ranges from -75‰ to -77‰, which is beneficial for CBM production [14].

In summary, in CBM enrichment areas, it is prone to produce high yields of CBM for the CBM wells with a relatively low sodium-chlorine coefficient, a relatively high desulfurization coefficient, and a good permeability due to water from atmospheric precipitation.

5. Typical Case Analysis

5.1. Fanzhuang Block in Qinshui Basin. In the Fanzhuang block of Qinshui Basin, fifty-eight CBM wells with a relatively rich concentration of CBM and permeability greater than 0.1 mD are selected for statistical analysis. Data in the initial stage of the two-phase flow of CBM wells is used for comparison. According to the daily gas production, the wells are divided into three types: high-yield wells (17 wells with daily gas production > 2000 m^3), medium-yield wells (16 wells with daily gas production between 1000 and 2000 m^3), and low-yield wells (25 wells with daily gas production < 1000 m^3).

The gas-water ratio of high-yield wells in the Fanzhuang block is between 212 and 6113 with an average value of 1988. These wells are mainly located at slopes and the higher part of the geological structure. The gas-water ratio of medium-yield wells is between 91 and 1944, with an average of 625. These wells are mainly located at slopes and the higher part of the geological structure. The gas-water ratio of low-yield wells is between 40 and 2035, with an average value of 373. These wells are distributed at slopes and higher parts and lower parts of the geological structure (see Table 4).

By analyzing the statistical results, it is found that the high-yield wells are mainly located at the slope zone and the higher part of the geological structure with a gas-water ratio higher than 500. Low-yield wells are mainly distributed at the lower part of the geological structure with a gas-water ratio of less than 500. One of the main reasons that cause the difference in gas production of medium-yield and high-yield wells is the dynamic effect of groundwater. The higher part of the geological structure and the slope zone are both conducive to draining away water and lowering the pressure of CBM wells. However, at the higher part of the geological structure, the good hydrodynamic conditions may cause the CBM to disperse along with water flows. In the slope zone, the poor hydrodynamic conditions are beneficial for CBM preservation and high production of wells.

5.2. Hancheng Mining Area in Ordos Basin. According to the research by Li et al. [25], the gas content and gas production of the No. 11 coal seam in the Hancheng mining area on the southeastern margin of Ordos Basin are highly correlated with the chemical composition of its coal seam water. Table 5 describes the relationships between hydrochemical zones and gas content (data from 25 samples). In their study, 249 samples that were used for the statistical study revealed the relationships among hydrochemical characteristics, gas content, and water content (see Table 6) [44].

In the Hancheng mining area, the CBM wells are mainly distributed in the HCO_3^-–Cl^-–Na^+ zone. The wells with the highest gas production are in the Cl^-–Na^+ zone, and the wells with the second-highest gas production are in the SO_4^{2-}–Cl^-–Ca^{2+}–Na^+ zone. On the contrary, the wells with the highest water production are in the HCO_3^-–Na^+ zone, and the wells with the second-highest water production are in the HCO_3^-–Cl^-–Na^+ zone. An obvious negative correlation exists between CBM production and water production

Table 4: The produced gas-water volume ratio of typical CBM wells and distribution of structural parts in the Fanzhuang block.

Gas production scale		High-yield wells	Medium-yield wells	Low-yield wells
Structural parts	Higher part	3	6	9
	Slope	14	9	10
	Lower part	0	1	6
Gas-water ratio		212~6113	91~1944	42~2035
Average value		1988	625	373

Table 5: Distribution of gas content in different hydrochemical zones of the No. 11 coal seam in the Hancheng mining area [44].

Hydrochemical zone	HCO_3^-–Na^+ zone	HCO_3^-–Cl^-–Na^+ zone	SO_4^{2-}–Cl^-–Ca^{2+}–Na^+ zone	Cl^-–Na^+ zone
Number of samples	5	10	5	5
Current gas content (m^3/t)	4~6	6~9	8~13	12~15
Current average gas content (m^3/t)	5.5	8.3	11.6	14.1
Original gas content (m^3/t)	11~15	10~15	9~16	10~16
Original average gas content (m^3/t)	13.9	14	14.1	14.3

Table 6: Water production and gas production of CBM wells in different hydrochemical zones of the No. 11 coal seam in the Hancheng mining area [44].

Hydrochemical zone	HCO_3^-–Na^+ zone	HCO_3^-–Cl^-–Na^+ zone	SO_4^{2-}–Cl^-–Ca^{2+}–Na^+ zone	Cl^-–Na^+ zone
Number of samples	10	212	10	17
Average water production (m^3/d)	9.92	5.64	3.62	1.61
Average gas production (m^3/d)	235	598	1056	1983

in the coalfield: the lower the water production, the higher the CBM production is.

By comparing the current gas content of coal seams in different hydrochemical zones, it is found that the Cl^-–Na^+ zone has the highest gas content, then followed by the SO_4^{2-}–Cl^-–Ca^{2+}–Na^+ zone and HCO_3^-–Cl^-–Na^+ zone, and the HCO_3^-–Na^+ zone has the least gas content. According to the calculation of the Lanchester equation, the gas content of original coal seams in different zones has no significant difference. Therefore, it can be deduced that Cl^-–Na^+ and HCO_3^-–Cl^-–Na^+ zones are more favorable for CBM preservation.

6. Existing Problems and Development Trends

6.1. Existing Problems. By reviewing the literature in China and other counties, we can find that predecessors have already made significant progress in studying the mechanisms for controlling the enrichment and high yield of CBM from the aspects of coalbed hydrodynamics, coalbed hydrogeochemistry, and hydrogeological conditions. All the research achievements provide solid theoretical bases and practices for selecting the CBM enrichment area and effectively extracting CBM. However, there are still some existing problems that need to be discussed and further studied:

(1) The distribution and migration of coalbed water determine the enrichment and dissipation of CBM. Due to the complexity of geological structures, the difference in reservoir permeability, and the interaction between water and rock, more finely and three-dimensional hydrogeological units are needed to make the CBM exploitation more economically beneficial. However, the current distribution rule of coalbed water is only at the stage of qualitative description, and it is urgent to establish a quantitative method to evaluate the heterogeneous distribution of coalbed water in both the longitudinal and lateral directions

(2) If the selection of favorable CBM zones and sweet spots involves hydrogeological conditions, hydrodynamic conditions are considered to a large extent. However, hydrogeochemistry, especially the isotope characteristics of coalbed water, is less considered. In addition, most of the previous studies mainly focus on the enrichment of CBM. Therefore, it is urgent to establish a comprehensive system to evaluate CBM enrichment and high production based on hydrogeological indicators

(3) The studies on the relationships among hydrodynamic conditions, hydrogeochemical characteristics, and the extraction efficiency of CBM wells are not enough. Various hydrodynamic models based on different hydrodynamic fields and dynamic changes of hydrochemistry are needed to guide highly efficient CBM extraction from CBM wells

6.2. Development Trends

6.2.1. Transform from Qualitative Evaluation to Quantitative Evaluation. Due to the differences in the hydrogeological conditions of groundwater, most of the predecessors defined boundaries of coalbed water distribution and divided the hydrogeological zones based on conditions such as the geomorphology, geological structure, and surface water system. However, the gas production of CBM wells in the same hydrogeological zone varies greatly. The reason is that the coalbed water has a strong vertical and horizontal heterogeneity in hydrogeological units. Therefore, it is necessary to establish a quantitative method to evaluate the heterogeneous distribution of coalbed water vertically and horizontally to accurately describe the heterogeneous distribution characteristics of hydrogeological units.

6.2.2. Transform from a Single Evaluation Standard to Multiple Evaluation Standards. The relationship between CBM enrichment and high yields shows that the area with high-yield CBM must be located at the CBM enrichment area. The coal seam water content, hydrodynamic zoning, and different hydrochemical conditions that are summarized by the predecessors obviously have controlling effects on CBM enrichment, especially on the coalbed gas content. However, the standard for evaluating the enrichment is more of a singular indicator. It is urgent to transform the singular way to evaluate CBM enrichment (gas content) to multiple ways to evaluate CBM enrichment (gas content and water content) and high production (gas production and water production) and establish an evaluation system with multiple evaluation indicators including the dynamic zones, flow intensity, water ion characterization, and water isotope.

6.2.3. Transform from Static Evaluation to Dynamic Evaluation. The hydrogeological conditions underground are accompanied by the production of CBM wells, and they are in a process of dynamic change. The content of coalbed water, hydrodynamic conditions, and hydrochemical characteristics will change with the production process of CBM. Therefore, analyzing static data to find the CBM controlling mechanism cannot meet the requirements of efficient development of CBM. On the basis of quantitatively characterizing the CBM controlling parameters of coalbed water, it is urgent to analyze the changing rules of hydrogeological parameters in the CBM production process and transform the static evaluation on the gas controlling mechanism of hydrogeological conditions to dynamic evaluation.

6.2.4. Transform Theoretical Studies to Practices Guided by Theoretical Results. The theoretical research of CBM in China starts in the 1970s and 1980s. Many theoretical breakthroughs and innovations have been made around the gas controlling effects of hydrogeological conditions. However, the hydrogeological conditions of coal seams in the CBM basin in China are of great variety. The aquifers are heterogeneously distributed. The relationships between hydrogeology and geological structures are complex. The research results are not closely related to the actual CBM extraction and production. Therefore, it is urgent to combine theoretical research studies with field practices to deepen the research studies on the gas controlling mechanism of hydrogeology, to construct a comprehensive hydrogeological evaluation system and a customized and efficient drainage system that serve the exploration and development of CBM and guide the selection and efficient development of CBM enrichment areas and high-yield zones.

7. Conclusion

(1) From the perspective of hydrogeology, this paper summarizes the fruitful research results achieved by domestic and foreign researchers on the gas controlling effect of hydrogeology under similar structural and deposition conditions in recent years. Among them, the water conditions suitable for biogenic gas formation are identified; the division of hydrodynamic zones and its index are summarized; the response mechanism of water geochemical characteristics to CBM is analyzed; and the high production model of CBM based on different water production characteristics is established

(2) According to the research progress and existing problems, this paper proposes the following trends about research on the controlling mechanism of hydrogeological conditions: transform from qualitative evaluation to quantitative evaluation, from a singular evaluation standard to multiple evaluation standards, from static evaluation to dynamic evaluation, and from pure theoretical research to practices under theoretical guidance

Data Availability

The data that support the findings and conclusions of this study are available on request from the corresponding author, Wang Dangliang (wangdangliang@cumt.edu.cn). The data are not publicly available due to the restrictions from the Natural Science Foundation of China (No. 41872179).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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