

Article

Comparative Analysis of Coalbed Methane Well Productivity in Eastern Yunnan

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Abstract

The water produced from coalbed methane (CBM) wells contains abundant geochemical information; therefore, analyzing the geochemical information available therein is of great significance for the efficient exploitation of CBM wells. Based on the geochemical characteristics of water from four CBM wells in eastern Yunnan, this paper analyzes the relationship between the geochemical characteristics of the produced water and gas production. The results indicate that the underground environment in which water is produced in the four CBM wells in the study area exists in a closed state. The water sourced from wells L-1 and L-2 is of the Na-Cl-HCO₃ type, whereas the water sourced from wells L-3 and L-4 is of the Na-HCO₃ type. Gas production is approximately positively correlated with high concentrations of HCO₃[−], up to concentrations of 2800 mg/L, beyond which gas production decreases. Both D drift and ¹⁸O isotope drift in the produced water are beneficial for the production of CBM. The trace element content of the well water is influenced by the trace elements found in the coal seams and surrounding rocks, especially at peak trace element contents. The dissolved inorganic carbon isotope (¹³C_{DIC}) in the well water is affected by microbial methanogenesis and carbonate dissolution, and gas production is high when ¹³C_{DIC} is approximately −4‰.

Keywords: coalbed methane; produced water; geochemical characteristics; Eastern Yunnan

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1. Introduction

Coalbed methane (CBM) is a mixed gas composed mainly of methane, an unconventional clean natural gas resource that is found in coal seams mostly in an adsorbed state. Enhancing the development and utilization of CBM not only reduces the gas content in coal seams, thereby helping to prevent coal mine accidents, but also plays an important role in environmental protection. The generation and migration of CBM are influenced by a range of factors. The hydrologic conditions of the coal seam exert a critical influence on the transport of CBM, thereby directly impacting its occurrence [1–7]. The fundamental process of CBM extraction involves discharging groundwater from the coal reservoir, causing the reservoir pressure to continuously decrease to the critical desorption pressure. At this point,

the gas adsorbed in the coal reservoir begins to desorb and migrate to the wellbore through pores and cracks, resulting in CBM production [8–11].

During the process of CBM extraction, a large amount of water needs to be discharged from the coal reservoir to enable CBM to be desorbed and produced, and this water undergoes physical and chemical interactions with the reservoir during the discharge process. As the discharge time increases, the properties of the produced water also change [10,12,13]. Minerals undergo dissolution in aquifers over time, leading to changes in the quality of the produced water [14–18]. The hydraulic fracturing additives introduced during coal seam stimulation significantly alter the chemistry of the produced water, typically elevating sodium ion concentrations and trace element profiles [14,19].

In the initial stage of CBM well drainage, the discharged water is mainly affected by the fracturing fluid. In the middle stage of drainage and extraction, the concentration of fracturing fluid gradually decreases, and the water quality begins to approach that of the water originally found in the formation [15,20,21]. In the stable stage of drainage and production, the geochemical characteristics of the produced water tend to remain stable and continue to approach those of the formation's original water [5,12]. By comparing the produced waters from different CBM extraction wells, it is possible to better understand these changes in water quality [8,22]. Although research has been conducted on the geochemical characteristics of well water [15,16,19,20,22–31], no systematic analysis has been carried out on the relationship between the geochemical characteristics of the produced water and gas production, especially regarding development wells in eastern Yunnan. Based on experimental analyses of conventional ions, trace elements, hydrogen and oxygen isotopes, and dissolved inorganic carbon isotopes ($^{13}\text{C}_{\text{DIC}}$) in water samples from four CBM development wells in eastern Yunnan, this paper systematically assesses the relationship between the geochemical characteristics of well water and gas production, and provides suggestions for future CBM production.

2. Geological Background

The Enhong and Laochang blocks are both located in Fuyuan County, Qujing, Yunnan Province, China, and exhibit climate characteristics typical of strong terrain cutting and plateau mountain topography. The Enhong block is bounded to the west by the Fuyuan–Mile Fault; the remaining boundaries are mainly the bottom boundaries of the Upper Permian coal-bearing strata. The Enhong syncline is a composite syncline composed of the Enhong syncline and the Pingguan–Daping syncline, which have complex geologic structures. The main coal-bearing stratum is the Upper Permian Xuanwei Formation, which has a thickness of 15.99–67.68 m. The minable coal seams are Nos. 7 + 8, 9, 16, 17 + 18, and 21. Petrographically, the coal is mainly composed of bright and dark coal with local scales and flakes. The fault zones within this block are mostly enclosed, with poor water abundance and conductivity.

The Laochang block is to the south and east of the Enhong block. The faults within the Laochang area mainly strike northeast and are predominantly distributed at the edges of the block. Most of the faults with a drop greater than 100 m are boundary faults and are primarily distributed near folds. The main coal-bearing stratum is the Longtan Formation of the Upper Permian, which has a thickness of 415–475 m. The minable coal seams are Nos. 13, 14, 16, 18, and 19. The coal grade is anthracite with high hardness and low brittleness. This block is characterized by its high elevation, steep terrain, and underdeveloped surface water systems.

Hydrogeological conditions significantly influence CBM accumulation, which can be categorized into three types: hydraulic escape, hydraulic sealing, and hydraulic plugging. The first type leads to methane loss, whereas the latter two are beneficial for its preserva-

tion [3,4]. The geological structure of the study area is complex, with the coal-bearing strata and related aquifers composed of detrital sediments. Overlying and underlying strata develop karst aquifers, while aquitards with a thickness of tens to hundreds of meters separate the coal-bearing strata from aquifers. These aquitards are hard and dense, with undeveloped fractures and extremely weak water yield. Groundwater in coal-bearing strata primarily relies on atmospheric precipitation or surface water. Fault zones are mostly closed, exhibiting poor water yield and hydraulic conductivity. Hydrogeochemical characteristics significantly influence daily CBM production, and high-yield well drainage often correlates with high mineralization.

Two CBM development wells, L-1 and L-2, were selected from the Enhong block. The coal seams discharged from well L-1 are Nos. 7 + 8, 9, 16, and 21, and the well's depth is 1182.9 m. The coal seams in well L-2 are Nos. 16 and 17 + 18, with a depth of 1031.0 m. Well L-1 has been producing water since February 2018. As of October 2019, the average water production was 0.71 m³/d, and the average gas production was 63.9 m³/d. Well L-2 has been producing water since January 2018. As of October 2019, the average water production was 0.96 m³/d, and the average gas production was 123.77 m³/d (Figure 1 and Table 1).

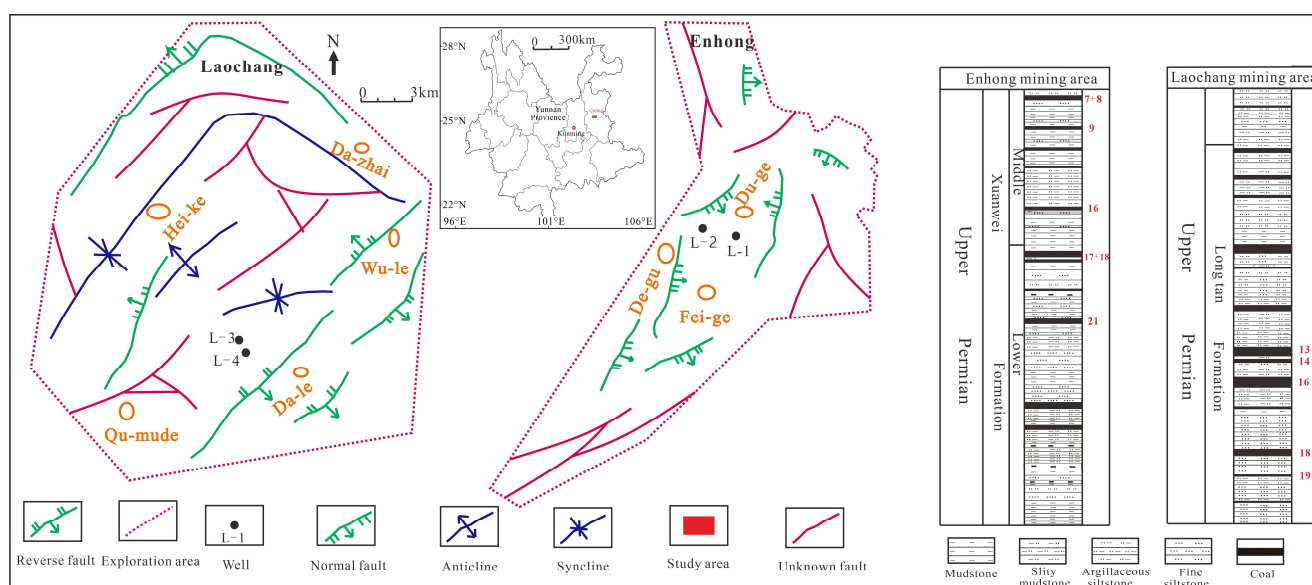


Figure 1. Well locations and structural map of the study area.

Table 1. Data on the development wells in the study area.

CBM Wells	Main Coal Seam	Depth	Average Daily Gas Production	Average Daily Water Production
		m	m ³	m ³
L-1	7 + 8/9/16/21	1182.90	63.90	0.71
L-2	16/17 + 18	1031.00	123.77	0.96
L-3	13/16/18/19	713.20	327.80	1.19
L-4	14/16/18	745.80	398.81	0.94

Two CBM development wells, L-3 and L-4, were selected from the Laochang block. The mining-relevant coal seams in well L-3 are Nos. 13, 16, 18, and 19, and the well's depth is 717.9–780 m. The coal seams fractured by well L-4 are Nos. 16, 18, and 19, with a depth of 713.2 m. Well L-3 has been producing water since May 2018. As of October 2019, its average water production was 1.19 m³/d, and its average gas production was 327.8 m³/d.

Well L-4 has been producing water since May 2018. As of October 2019, its average water production was 0.94 m³/d, and its average gas production was 398.81 m³/d (Figure 1 and Table 1).

3. Test Methods and Results

Water samples have been collected from the four CBM development wells in the Enhong and Laochang blocks since September 2018, and the mass concentrations of conventional anions and cations, along with trace elements in the produced water, stable nuclides of hydrogen and oxygen, and ¹³C_{DIC}, have been determined experimentally. The water samples were collected directly from the outlet of the development well using 0.5 L sampling bottles. Prior to collection, the sampling bottle was flushed more than three times with well water, and the collected water samples were transferred within 72 h to the Institute of Geochemistry of the Chinese Academy of Sciences in Guiyang City for testing.

Routine anion and cation detection in water samples uses an ion chromatograph (DIONEX, USA; Model ICS-90). Trace element analysis employs an inductively coupled plasma optical emission spectrometer (ICP-OES) and an inductively coupled plasma mass spectrometer (ICP-MS) (Thermo Elemental, USA; Models: ICP-OES/ICP-MS). Hydrogen/oxygen isotope measurements utilize a liquid water isotope analyzer (Model 912-0026). For dissolved inorganic carbon (DIC) carbon isotope analysis, CO₂ is extracted via phosphoric acid digestion on a vacuum line, purified, and analyzed with a gas isotope ratio mass spectrometer (Finnigan MAT, Germany; Model MAT 252). As of October 2019, seven well water samples were collected from the four CBM development wells in the study area. The test results are shown in Tables 2–4.

Table 2. Concentrations of conventional ions and ¹³C_{DIC} in well water samples.

CBM Wells	Date	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl [−]	SO ₄ ^{2−}	HCO ₃ [−]	F [−]	δ ¹³ C _{DIC}
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	‰
L-1	Sep.2018	1490.96	11.72	15.46	5.88	1654.14	-	1176.83	0.54	13.31
	Oct.2018	1420.22	11.59	15.25	5.77	1637.03	0.06	1098.58	0.63	14.64
	Nov.2018	1503.94	13.03	13.45	5.95	1559.26	0.04	1148.66	0.64	14.48
	Feb.2019	1498.92	11.29	9.62	4.30	1489.55	0.03	1093.92	0.68	14.23
	Jun.2019	1413.13	9.70	8.46	3.95	1405.09	0.73	1055.94	0.82	13.19
	Aug.2019	1350.10	9.30	8.44	4.00	1336.11	0.47	1109.12	0.77	12.72
	Oct.2019	1305.55	8.47	8.13	3.86	1306.94	0.18	1208.13	0.76	13.06
L-2	Sep.2018	1057.86	4.49	5.65	1.59	841.12	-	1392.79	1.14	16.88
	Oct.2018	1044.70	4.41	5.52	1.52	853.38	-	1383.40	1.31	18.20
	Nov.2018	1067.69	6.38	4.91	1.38	818.44	0.10	1283.24	1.44	19.09
	Feb.2019	1056.26	4.67	4.18	0.91	802.58	-	1207.87	1.67	18.60
	Jun.2019	773.43	3.27	3.14	0.65	719.18	0.03	1109.12	1.95	20.46
	Aug.2019	926.41	4.04	3.67	0.85	699.19	0.03	1071.13	1.82	20.05
	Oct.2019	877.18	3.91	3.88	0.71	656.30	-	1122.94	1.82	20.14
L-3	Sep.2018	2564.84	206.35	17.49	5.46	2454.66	0.46	3170.55	0.66	−4.78
	Oct.2018	2565.69	200.69	17.31	5.60	2358.30	0.42	3233.15	0.61	−4.18
	Nov.2018	2564.53	207.43	16.43	5.96	2255.89	0.30	3358.34	0.64	−4.38
	Feb.2019	2690.99	164.87	11.75	4.68	2076.53	0.93	3441.30	0.76	−4.26
	Jun.2019	2520.73	122.77	5.62	3.70	1766.93	0.62	3578.04	0.77	−4.57
	Aug.2019	2389.69	140.73	7.61	3.77	1658.57	0.27	3441.30	0.83	−4.02
	Oct.2019	2407.07	131.13	8.63	3.80	1621.63	0.34	4271.04	0.72	−4.13

Table 2. Cont.

CBM Wells	Date	Na ⁺	K ⁺	Ca ²⁺	Mg ²⁺	Cl [−]	SO ₄ ^{2−}	HCO ₃ [−]	F [−]	δ ¹³ C _{DIC}
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	‰
L-4	Sep.2018	2006.94	197.32	11.07	4.38	1910.23	0.74	2600.91	0.70	−5.46
	Oct.2018	2011.09	207.93	10.51	4.44	1803.25	0.09	2660.38	0.71	−4.36
	Nov.2018	2060.99	181.62	9.48	4.42	1649.12	0.13	2760.54	0.73	−4.43
	Feb.2019	2132.75	139.19	7.70	3.51	1484.26	0.24	2875.35	0.92	−4.23
	Jun.2019	2036.32	104.57	3.07	2.75	1325.50	0.18	2894.34	0.99	−4.39
	Aug.2019	2003.77	116.59	2.94	2.79	1282.47	0.22	2932.32	0.95	−4.41
	Oct.2019	1904.04	114.23	3.02	2.71	1271.20	0.17	3078.40	0.93	−4.37

Table 3. Hydrogen and oxygen isotopes in well water samples.

Isotope	Date	CBM Wells			
		L-1	L-2	L-3	L-4
δ ¹⁸ O	Sep.2018	−11.17	−9.77	−11.69	−12.03
	Oct.2018	−11.14	−9.80	−11.72	−12.06
	Nov.2018	−9.04	−10.29	−11.82	−11.52
	Feb.2019	−11.77	−11.13	−11.96	−12.66
	Jun.2019	−11.58	−10.18	−11.87	−12.12
	Aug.2019	−11.69	−10.15	−11.88	−12.28
	Oct.2019	−11.86	−10.32	−11.87	−12.09
δD	Sep.2018	−71.15	−57.37	−79.46	−83.96
	Oct.2018	−70.89	−58.74	−79.57	−83.23
	Nov.2018	−54.90	−70.41	−83.97	−84.52
	Feb.2019	−75.28	−76.35	−83.77	−86.98
	Jun.2019	−73.23	−57.58	−80.56	−83.28
	Aug.2019	−73.16	−57.26	−78.87	−83.50
	Oct.2019	−73.43	−58.69	−80.17	−83.43

Table 4. Concentrations of trace elements in produced water.

CBM Wells	Date	Ba	Zr	Cr	Cu	Zn	V	Sr	Rb	Li	As
		μg/L	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L	μg/L
L-1	Sep.2018	1343.66	0.13	0.86	19.95	14.18	2.32	1953.35	38.03	84.43	1.36
	Oct.2018	3257.16	1.30	0.24	2.40	13.07	3.14	4619.41	41.08	48.83	0.63
	Nov.2018	3356.30	0.03	0.12	1.32	6.06	2.61	4473.98	38.63	50.16	0.31
	Feb.2019	2887.99	0.05	0.63	1.66	1.52	2.08	3582.61	37.14	47.82	0.57
	Jun.2019	2439.64	-	0.07	5.37	6.01	1.41	-	-	36.78	0.90
	Aug.2019	980.00	0.06	0.19	0.01	4.30	1.10	2601.40	17.87	38.31	0.93
	Oct.2019	1405.60	0.04	0.19	0.07	1.55	1.07	2577.71	17.68	39.99	0.97
L-2	Sep.2018	1279.94	0.10	0.76	12.99	2.33	1.24	612.50	7.93	36.97	1.86
	Oct.2018	1467.17	0.20	0.21	-	-	1.05	1434.71	9.02	22.05	1.01
	Nov.2018	1209.30	0.14	0.04	-	-	0.73	1300.08	8.60	26.27	1.18
	Feb.2019	716.25	0.15	0.15	1.39	2.70	1.65	765.41	6.08	3.65	2.70
	Jun.2019	277.91	-	0.05	2.96	0.59	0.45	-	-	17.62	1.38
	Aug.2019	692.15	0.07	0.20	-	-	0.48	814.57	3.80	18.85	0.73
	Oct.2019	482.14	0.04	0.20	-	-	0.35	740.95	4.01	18.04	0.49
L-3	Sep.2018	2004.51	4.94	1.91	41.54	6.23	2.35	5542.35	62.54	964.92	2.78
	Oct.2018	4546.07	5.86	0.32	1.43	-	4.56	13,423.98	78.17	569.54	1.35
	Nov.2018	5004.39	6.18	0.13	0.77	-	3.64	12,929.26	76.13	751.36	1.38
	Feb.2019	2429.18	6.33	0.58	2.62	2.76	4.79	6691.05	45.61	105.74	5.68
	Jun.2019	3339.49	-	0.30	15.38	1.46	2.01	-	-	554.50	3.27
	Aug.2019	1798.80	6.63	0.88	-	0.19	1.27	6304.88	41.75	609.04	2.52
	Oct.2019	1945.22	7.98	1.11	-	0.74	1.35	7585.86	40.08	632.12	2.11

Table 4. Cont.

CBM Wells	Date	Ba	Zr	Cr	Cu	Zn	V	Sr	Rb	Li	As
		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
L-4	Sep.2018	1941.72	3.02	1.55	28.05	3.34	2.07	4206.15	54.44	1284.98	1.18
	Oct.2018	2742.91	3.52	0.24	3.22	-	2.94	10,779.80	67.70	745.56	0.99
	Nov.2018	3027.71	4.54	0.08	0.62	-	2.19	10,049.76	63.27	1001.60	0.70
	Feb.2019	2236.59	4.55	0.37	3.40	3.54	2.76	6147.19	49.21	129.43	5.28
	Jun.2019	2323.16	-	1.53	0.50	0.93	2.10	-	-	958.55	2.63
	Aug.2019	1221.11	4.67	0.69	-	0.06	0.55	5177.17	31.45	803.72	2.98
	Oct.2019	1248.33	4.73	0.80	-	0.06	0.60	5226.41	31.39	846.56	2.36

4. Analysis and Discussion

4.1. Variation in the Conventional Ion Concentrations and Their Effects on Productivity

The Na⁺ concentration in the produced water from well L-1 ranged from 1305.55 to 1503.94 mg/L with an average of 1426.12 mg/L. The K⁺ concentration ranged from 8.47 to 13.03 mg/L with an average of 10.73 mg/L. The Ca²⁺ concentration ranged from 8.13 to 15.46 mg/L with an average of 11.26 mg/L. The Mg²⁺ concentration ranged from 3.86 to 5.95 mg/L with an average of 4.81 mg/L. The Cl⁻ concentration ranged from 1306.94 to 1654.14 mg/L with an average of 1484.02 mg/L. The concentration of SO₄²⁻ ranged from 0.03 to 0.73 mg/L with an average of 0.25 mg/L. The concentration of HCO₃⁻ ranged from 1055.94 to 1208.13 mg/L with an average of 1127.31 mg/L. The concentration of F⁻ ranged from 0.54 to 0.82 mg/L with an average of 0.69 mg/L (Table 2).

The Na⁺ concentration in the produced water from the L-2 well ranged from 773.43 to 1067.69 mg/L with an average of 971.93 mg/L. The K⁺ concentration ranged from 3.27 to 6.38 mg/L with an average of 4.45 mg/L. The Ca²⁺ concentration ranged from 3.14 to 5.65 mg/L with an average of 4.42 mg/L. The Mg²⁺ concentration ranged from 0.65 to 1.59 mg/L with an average of 1.09 mg/L. The Cl⁻ concentration ranged from 656.30 to 853.38 mg/L with an average of 770.03 mg/L. The SO₄²⁻ concentration ranged from 0.03 to 0.10 mg/L with an average of 0.05 mg/L. The HCO₃⁻ concentration ranged from 1071.13 to 1392.79 mg/L with an average of 1224.36 mg/L. The F⁻ concentration ranged from 1.14 to 1.95 mg/L with an average of 1.60 mg/L (Table 2).

The Na⁺ concentration in the produced water from the L-3 well ranged from 2389.69 to 2690.99 mg/L with an average of 2529.08 mg/L. The K⁺ concentration ranged from 122.77 to 207.43 mg/L with an average of 167.71 mg/L. The Ca²⁺ concentration ranged from 5.62 to 17.49 mg/L with an average of 12.12 mg/L. The Mg²⁺ concentration ranged from 3.70 to 5.96 mg/L with an average of 4.71 mg/L. The Cl⁻ concentration ranged from 1621.63 to 2454.66 mg/L with an average of 2027.50 mg/L. The concentration of SO₄²⁻ ranged from 0.27 to 0.93 mg/L with an average of 0.48 mg/L. The concentration of HCO₃⁻ ranged from 3170.55 to 4271.04 mg/L with an average of 3499.10 mg/L. The concentration of F⁻ ranged from 0.61 to 0.83 mg/L with an average of 0.71 mg/L (Table 2).

The Na⁺ concentration in the produced water from well L-4 ranged from 1904.04 to 2132.75 mg/L with an average of 2022.27 mg/L. The K⁺ concentration ranged from 104.57 to 207.93 mg/L with an average of 151.64 mg/L. The Ca²⁺ concentration ranged from 2.94 to 11.07 mg/L with an average of 6.83 mg/L. The Mg²⁺ concentration ranged from 2.71 to 4.44 mg/L with an average of 3.57 mg/L. The Cl⁻ concentration ranged from 1271.20 to 1910.23 mg/L with an average of 1532.29 mg/L. The concentration of SO₄²⁻ ranged from 0.09 to 0.74 mg/L with an average of 0.25 mg/L. The concentration of HCO₃⁻ ranged from 2600.91 to 3078.40 mg/L with an average of 2828.89 mg/L. The concentration of F⁻ ranged from 0.70 to 0.99 mg/L with an average of 0.85 mg/L (Table 2).

As shown in Figure 2, as the drainage time increased, it became clear that the water produced from wells L-1 and L-2 was of the Na-Cl-HCO₃ type, whereas the water produced from wells L-3 and L-4 was of the Na-HCO₃ type. The concentrations of Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻, and SO₄²⁻ fluctuated and exhibited a decreasing trend over time, while the concentrations of HCO₃⁻ and F⁻ fluctuated but tended to increase over time. As the fracturing fluid, which contains Na⁺, K⁺, and Cl⁻, is gradually discharged during the drainage process of the CBM wells, the concentrations of Na⁺, K⁺, and Cl⁻ in the produced water decrease.

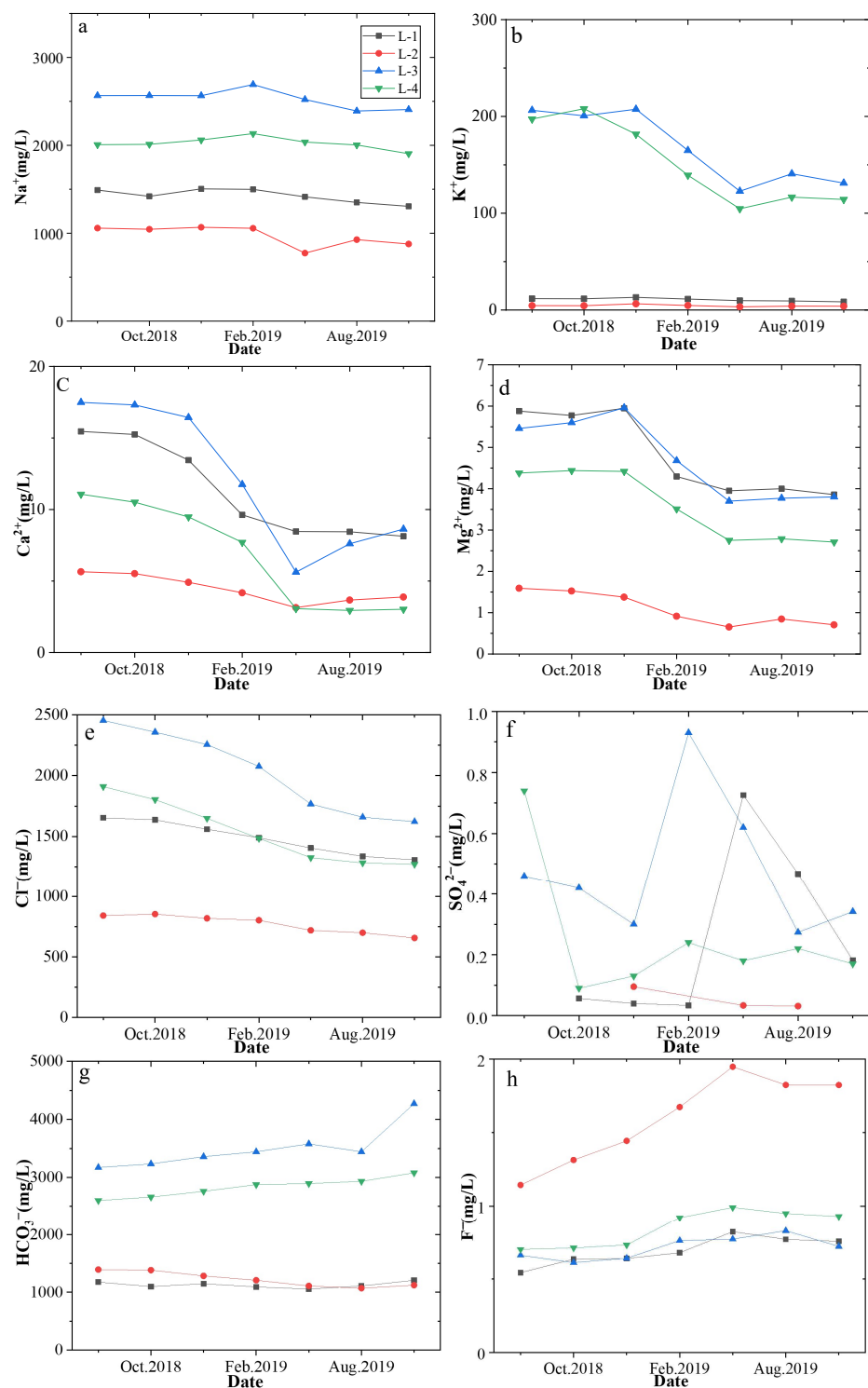


Figure 2. Concentrations of conventional ions in well water over time.

Water produced by CBM wells is generally considered to come from two types of groundwater environments: open and closed. Open groundwater environments are close to the source of water recharge and have relatively high concentrations of Ca^{2+} and Mg^{2+} . Closed groundwater environments are far from the water recharge source and exhibit relatively high concentrations of Na^+ , Cl^- , and HCO_3^- [8,9,12,32].

The water samples produced by the four selected CBM wells all exhibited similar conventional ion concentrations (Figure 2 and Table 2); specifically, high concentrations of Na^+ , Cl^- , and HCO_3^- , and low concentrations of Ca^{2+} and Mg^{2+} . Therefore, the water produced by the four selected CBM wells comes from a closed environment. The observed decreases in the concentrations of Ca^{2+} and Mg^{2+} indicate weakened water–rock interactions. In August, due to the influence of the rainy season, the water–rock interactions were strengthened, and the concentrations of Ca^{2+} and Mg^{2+} increased. The dissolution rate of calcite in the water is far greater than that of dolomite; thus, the concentration of Ca^{2+} in the water increased significantly. The presence of SO_4^{2-} is related to desulfurization [33]; in a reducing environment, the sulfate in the coal seam water can act on the organic matter to generate bicarbonate, which reduces the concentration of SO_4^{2-} and increases the concentration of HCO_3^- .

From the above analysis, it can be seen that the underground environment of the four selected CBM wells is in a closed state with high concentrations of Na^+ , Cl^- , and HCO_3^- . Due to the presence of Na^+ and Cl^- in the fracturing fluid, HCO_3^- was selected as the ion most likely to correspond to production capacity. Figure 3 shows that the concentration of HCO_3^- was roughly positively correlated with gas production; however, when the concentration of HCO_3^- exceeded 2800 mg/L, gas production decreased. The relationship between the characteristics of the well water and gas production can be divided into two stages: when gas production is low, gas production is roughly positively correlated with water production; when the gas production exceeds approximately 330 m^3/d , the production levels of water and gas are negatively correlated.

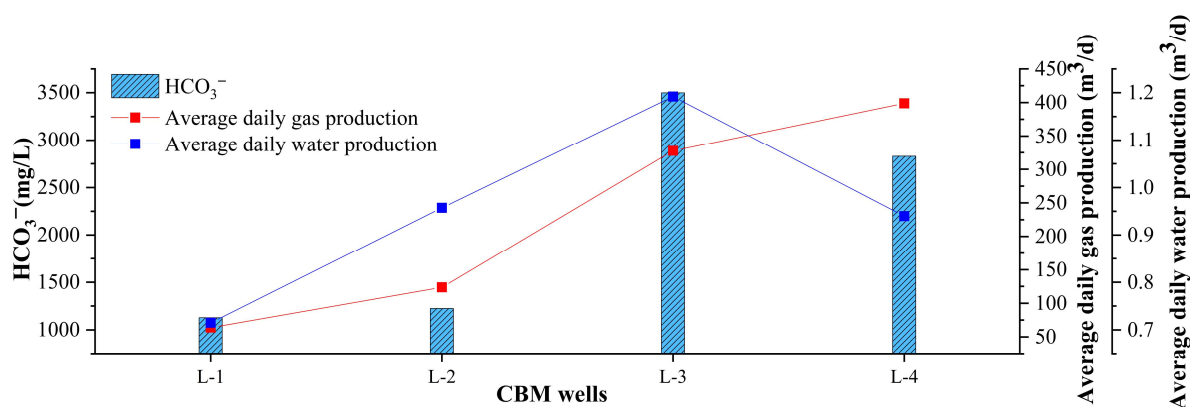


Figure 3. Relationships between HCO_3^- , average daily gas production, and average daily water production in the water produced from the four CBM wells in the study area.

4.2. Variation in Hydrogen and Oxygen Isotopes and Their Effects on Productivity

The δD value in the water produced by well L-1 ranged from -75.28‰ to -54.90‰ , with an average of -70.29‰ . The $\delta^{18}\text{O}$ value in water from this well ranged from -11.86‰ to -9.04‰ with an average of -11.18‰ . For the water produced by well L-2, the δD value ranged from -76.35‰ to -57.26‰ , with an average of -62.34‰ , and the $\delta^{18}\text{O}$ value ranged from -11.13‰ to -9.77‰ , with an average of -10.24‰ . The δD value in the water produced by well L-3 ranged from -83.97‰ to -78.87‰ , with an average of -80.91‰ . The $\delta^{18}\text{O}$ value in water from this well ranged from -11.96‰ to -11.69‰ , with an average of -11.83‰ . In the water produced from well L-4, the δD value ranged from -86.98‰ to

−83.23‰, with an average of −84.13‰. Here, the $\delta^{18}\text{O}$ value ranged from −12.66‰ to −11.52‰, with an average of −12.11‰ (Table 3).

The δD and $\delta^{18}\text{O}$ values of the water produced from wells L-1 and L-2 changed significantly with time (The δD value in the water produced ranged from −76.35‰ to −54.90‰, with an average of −66.32‰; The $\delta^{18}\text{O}$ value ranged from −11.86‰ to −9.04‰ with an average of −10.71‰), whereas the δD and $\delta^{18}\text{O}$ values of the water produced from wells L-3 and L-4 exhibited relatively small changes over time (The δD value in the water produced ranged from −86.98‰ to −78.87‰, with an average of −82.52‰; The $\delta^{18}\text{O}$ value ranged from −12.66‰ to −11.52‰ with an average of −11.97‰) (Figure 4).

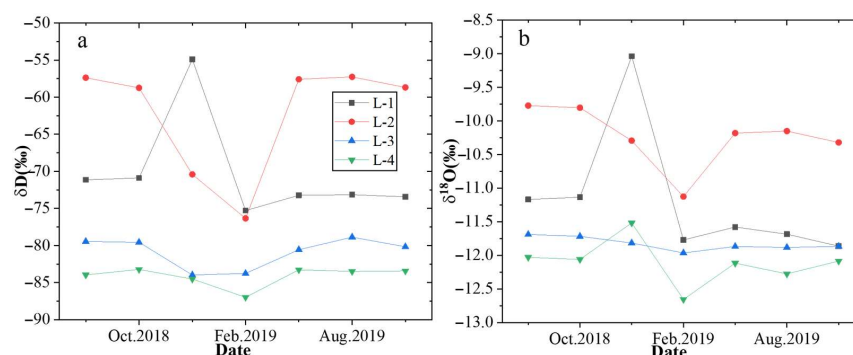


Figure 4. Variations in the δD and $\delta^{18}\text{O}$ isotopes in water produced from the four selected CBM wells over time.

The hydrogen and oxygen isotope composition was studied using the Yunnan atmospheric precipitation line equation: $\delta\text{D} = 6.56\delta^{18}\text{O} - 2.96$ [34]. Previous studies found that water from coal-bearing formations undergoes isotopic exchange with organic matter and rocks during production, resulting in D or ^{18}O isotope drift [12,22,24,35–38].

As shown in Figures 4 and 5, the isotope values of the water produced from wells L-1 and L-2 fall roughly above the atmospheric precipitation line, which is indicative of D drift, presumably due to the influence of the coal seam on the water it produces. The isotope values of the water produced from wells L-3 and L-4 are located on both sides of the precipitation line, indicating both D drift and ^{18}O drift. Figure 6 shows that the values of isotopes δD and $\delta^{18}\text{O}$ in the water produced from wells L-3 and L-4 are more indicative of long-term CBM production than those of water from wells L-3 and L-4. Based on the above analysis, when the water produced from a CBM well shows both D drift and ^{18}O drift, this is indicative of good CBM production prospects.

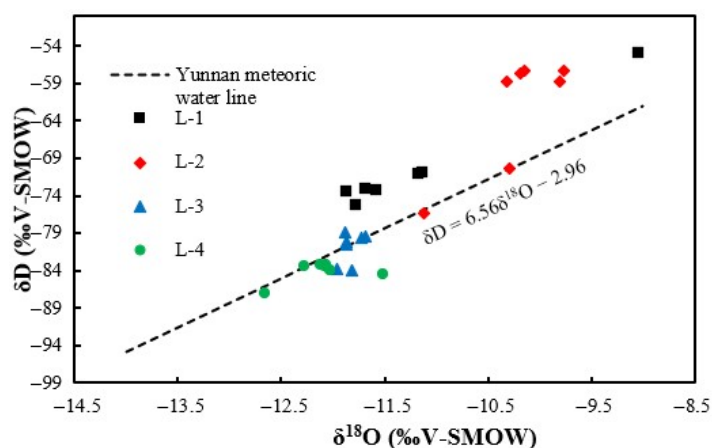


Figure 5. Relationship between the δD and $\delta^{18}\text{O}$ values of water produced from the four CBM wells in the study area.

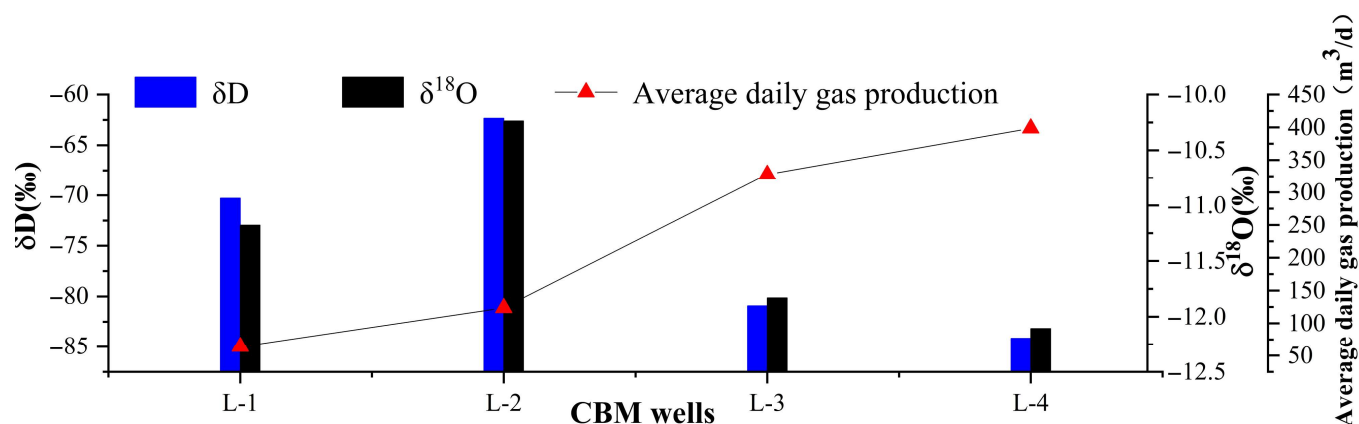


Figure 6. Relationships between gas production and isotopes δD and $\delta^{18}O$ in water produced from the four selected CBM wells.

4.3. Variation in the Concentrations of Trace Elements and Their Effects on Productivity

The concentrations of 10 trace elements (Ba, Zr, Cr, Cu, Zn, V, Sr, Rb, Li, and As) were analyzed in the main coal seams of the CBM wells and their surrounding rocks, and the effects of the coal seams and their surrounding rocks on the trace element concentrations in the produced water were assessed.

The content of trace elements differs between well water that has been in contact with coal seams and well water that has been in contact with the surrounding rocks. Water that has been in contact with the surrounding rocks is mainly enriched with elements such as Ba, Cr, Rb, and Sr, whereas water that is mainly enriched with As has been in contact with coal seams [39–43].

The contents of Ba, Zr, Cr, Cu, Zn, V, Sr, and Rb were much higher in water that had been in contact with the surrounding rock than that which had been in contact with the coal seam, whereas the contents of Li and As (As was not detected in the evaluated water samples) were much higher in the water that had been in contact with the coal seams (Figure 7). Therefore, the presence of trace elements Ba, Zr, Cr, Cu, Zn, V, Sr, and Rb was used as an indicator of the influence of the coal seam roof and floor on the corresponding trace elements in the produced water.

The contents of the trace elements fluctuated with depth (Figure 7). In the surrounding rock, the trace element concentrations exhibited a “double peak” with increasing depth, while the trace element contents in the coal seams showed a “single peak” (the As content reached its highest value at a depth of 720 m). The maximum trace element contents in both the coal seams and surrounding rocks appeared at a depth of approximately 700 m.

The contents of trace elements in the produced water also fluctuated with increasing drainage time (Figure 8). The contents of Ba, Zn, V, Sr, and Rb tended to decrease with increasing drainage time, whereas the Zr content showed an increasing trend. The contents of trace elements in the water produced from wells L-1 and L-2 were generally lower than those in the water produced from wells L-3 and L-4.

The above analysis shows that the trace element contents in the coal seams and surrounding rocks reach their maximum values at a depth of approximately 700 m. The corresponding coal seams at this depth are coal seam No. 16 in wells L-3 and L-4 (in wells L-1 and L-2, the depth of coal seam No. 16 is approximately 1000 m). Therefore, the contents of trace elements in the coal seams and surrounding rocks affect the composition of the water produced, especially at the peak trace element contents.

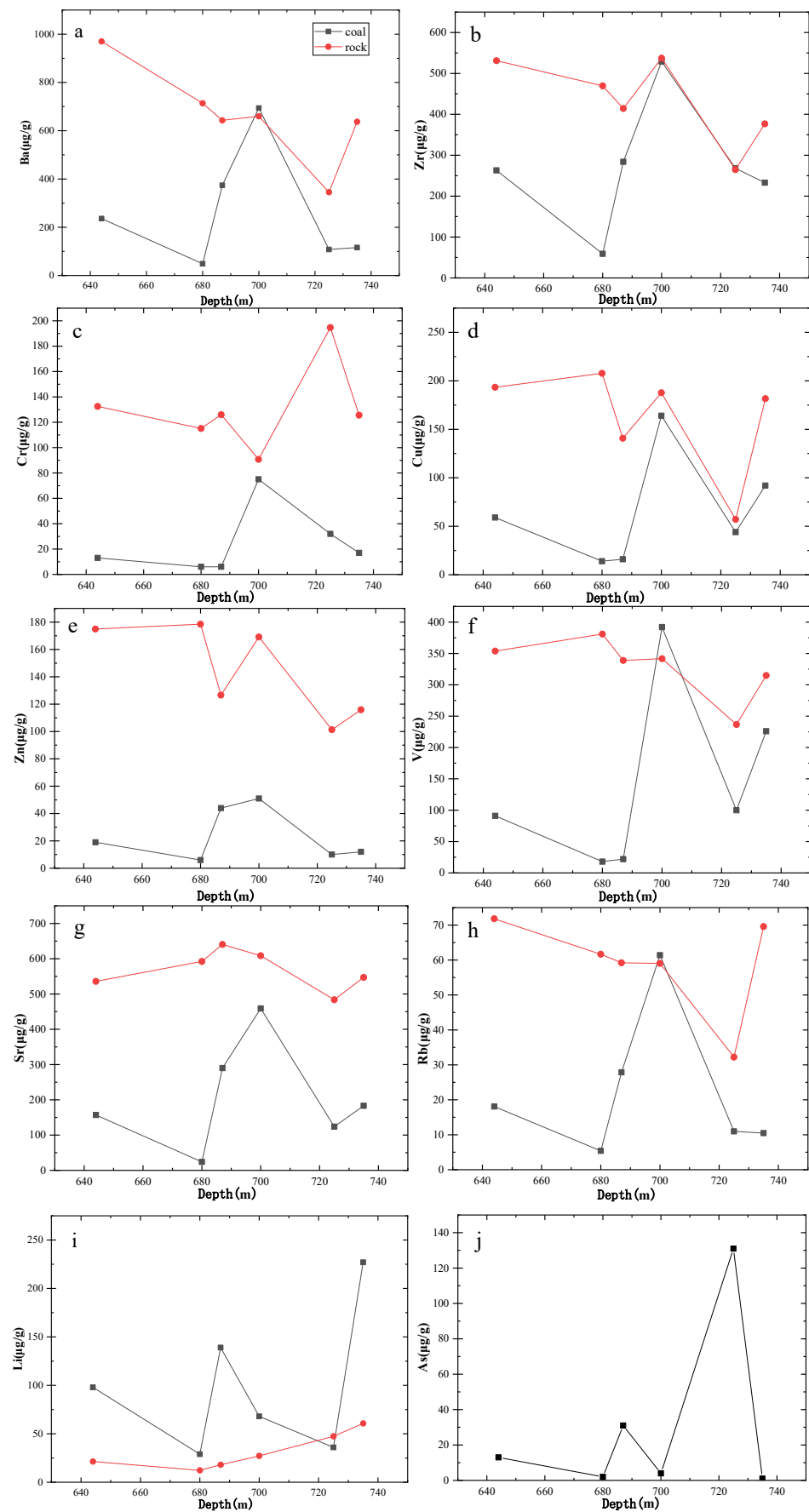


Figure 7. Variations in the concentrations of trace elements in the coal seams and surrounding rocks with depth.

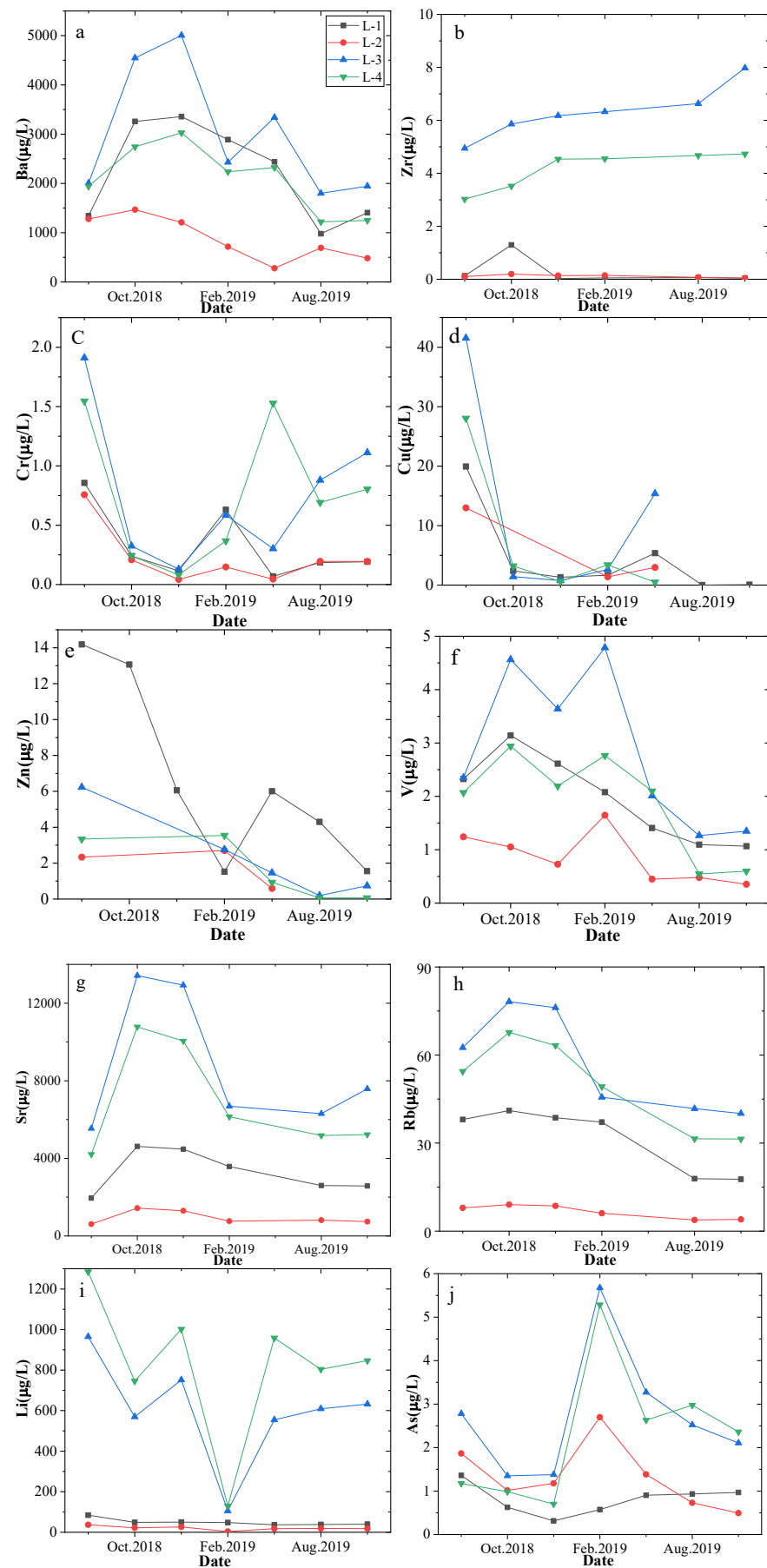


Figure 8. Variation in trace element concentrations in the produced water over time.

4.4. Variation in $\delta^{13}\text{C}_{\text{DIC}}$ and Its Effect on Productivity

The $\delta^{13}\text{C}_{\text{DIC}}$ value in the water produced from well L-1 ranged from 12.72‰ to 14.64‰, with an average of 13.66‰. The $\delta^{13}\text{C}_{\text{DIC}}$ value in the water produced from well L-2 ranged from 16.88‰ to 20.46‰, with an average of 19.06‰. The $\delta^{13}\text{C}_{\text{DIC}}$ value in the water produced from well L-3 ranged from −4.78‰ to −4.02‰, with an average of −4.33‰. The $\delta^{13}\text{C}_{\text{DIC}}$ value in the water produced from well L-4 ranged from −5.46‰ to −4.23‰, with an average of −4.52‰ (Table 2).

Different sources of $\delta^{13}\text{C}_{\text{DIC}}$ result in different compositions of this isotope. Generally, a $\delta^{13}\text{C}_{\text{DIC}}$ value of less than −8‰ is thought to indicate an organic origin, while a $\delta^{13}\text{C}_{\text{DIC}}$ value of approximately 0‰ suggests an inorganic origin. The $\delta^{13}\text{C}_{\text{DIC}}$ value in the coal seam was between −7‰ and 0‰, which can be attributed to methane production by microorganisms and carbonate dissolution. When the depth reached approximately 1000 m, the $\delta^{13}\text{C}_{\text{DIC}}$ value was between 10‰ and 30‰ due to the action of methanogens [25,44–50].

As shown in Figure 9, the $\delta^{13}\text{C}_{\text{DIC}}$ values in the water samples produced from wells L-1 and L-2 were between 12‰ and 21‰, indicating that these values were mainly affected by methanogens. The depth of coal seam No. 16, the main coal seam of wells L-1 and L-2, is approximately 1000 m. The $\delta^{13}\text{C}_{\text{DIC}}$ values in the water produced from wells L-3 and L-4 were between −6‰ and −4‰, which can be attributed mainly to microbial methanogenesis and carbonate dissolution.

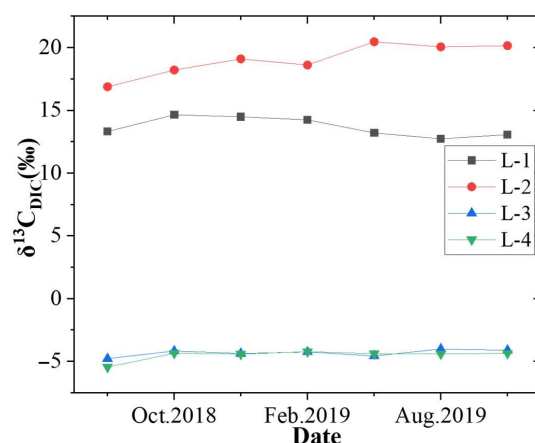


Figure 9. Variation in $\delta^{13}\text{C}_{\text{DIC}}$ in the produced water over time.

As shown in Figure 10, the $\delta^{13}\text{C}_{\text{DIC}}$ value in the water produced from wells L-1 and L-2 was positively correlated with gas production, but the gas production in these wells was lower than in wells L-3 and L-4. It can be seen that the factors affecting gas production are approximately the same within the same block. According to Figures 9 and 10, it can be broadly concluded that when $\delta^{13}\text{C}_{\text{DIC}}$ in the produced water is affected by methane production by microorganisms and carbonate dissolution, and its value is approximately −4‰, the gas production is relatively high, which is beneficial for the production of CBM.

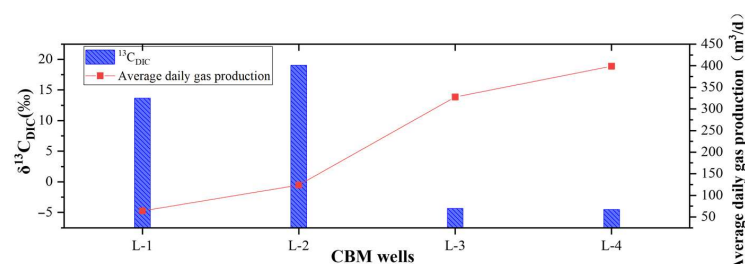


Figure 10. Relationship between $\delta^{13}\text{C}_{\text{DIC}}$ in the produced water and gas production.

5. Conclusions

Based on a comparative analysis of the characteristics of conventional ions, hydrogen and oxygen isotopes, trace elements, and $\delta^{13}\text{C}_{\text{DIC}}$ in the water produced from the four selected CBM wells, we obtained the following conclusions:

- (1) The water from the selected four CBM wells is produced in a closed environment. The water produced from wells L-1 and L-2 is of the Na-Cl- HCO_3 type, whereas the water produced from wells L-3 and L-4 is of the Na- HCO_3 type. The concentration of HCO_3^- is positively correlated with gas production; however, when the concentration of HCO_3^- exceeds 2800 mg/L, the gas production decreases.
- (2) The isotope values of the water produced from wells L-1 and L-2 exhibit the characteristics of D drift, and the isotope values of the water produced from well L-3 and L-4 exhibit the characteristics of both D drift and ^{18}O drift, which are indicative of good CBM production.
- (3) The contents of trace elements in the produced water are affected by the contents of trace elements in the coal seams and surrounding rocks, especially at the peak trace element concentrations in the rocks and coal seams.
- (4) The $^{13}\text{C}_{\text{DIC}}$ in the produced water is influenced by microbial methanogenesis and carbonate dissolution; when its value is approximately -4‰ , gas production is high, which is beneficial for the production of CBM.

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Conflicts of Interest: Author Xiongfei Xia was employed by the company China United Coalbed Methane Corp., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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