Research Article

The Cause of Drop of the Water Level of Underground Quaternary Aquifer of a Mine under Mining Influence

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Received 16 March 2022; Revised 27 April 2022; Accepted 7 June 2022; Published 20 June 2022

Academic Editor: Liang Xin

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Water outburst on the coal mining face will result in the shutdown of the working face, tense mine connection, a sharp increase in mine drainage fee, and serious impact on normal production. In severe cases, it will give rise to mine flooding and endanger state property and life safety. Hydrogeochemical evolution characteristics of groundwater in different aquifers of the test mine were studied using the hydrogeochemical method, especially the source of chemical constituents of groundwater in different aquifers (type of water-rock interaction). Meanwhile, the GMS model was built, and change law of the stratigraphic texture of the gob overlying rock was studied based on site geological conditions. Specific to a sharp drop in Quaternary aquifer of the second west mining area of the test mine, the cause was analyzed based on site geological conditions and using hydrogeochemistry and geologic modeling method to ensure high yield and high efficiency of mine and provide references for production safety of mines of the same kind.

1. Introduction

China is one of countries with the most abundant coal resources and the largest coal output, about 5.57 trillion tons above 2,000 m and 2.8 trillion tons above 1,000 m in depth. However, it is still very difficult to forecast coalmine accidents due to unknown existence state of disasters such as mine water disaster, geological structure, and gas and consequently, coalmine accidents happen frequently [1, 2]. Water disaster tops the list of “five disasters” of coalmine (water, fire, gas, coal dust, and roof fall), especially major downhole water outburst which causes heavy economic losses and casualties [3–5]. In the initial stage when mine water-disaster prevention and control technology lagged behind relatively, more than 100 water bursts occurred every year in China due to unsound local mine water-disaster prevention and control system [6–10].

Conceptually, the mine water disaster refers to geological disaster that surface water, groundwater, and gob ponding enter the mine in different forms and have a negative impact on production safety or economic benefit of mine [11–13]. Under the condition of large-scale mining, the karst water level drops, the water level drops funnel forms, the variation range of water level increases, and the characteristics of water filling and drainage of the water-bearing system change obviously, which are mainly manifested as the increase of karst groundwater recharge, the decrease of groundwater natural excretion, and the change of groundwater runoff conditions. When water burst rushes into a mine quickly or plenty of water burst exceeds the mine drainage capacity, casualties or heavy property losses will be caused and consequently, a mine water burst (water inrush) accident will occur. According to water burst source type, mine water disaster accidents can be classified into surface water, loose bed water, roof and bottom sandstone water, bottom limestone water, and gob water burst accidents. According to water burst channel, mine water disaster accidents can be classified into transmissibility fault, karst collapse pillar, mining, and bed separated fissure water burst accidents. According to statistics, more than 220 mines were flooded in the past two decades, resulting in more than 8,000 deaths and economic losses up to over 30 billion yuan [14, 15]. Since 2000, 2,833 casualties have been caused by water disaster. Especially since July 2005, water accident has been
shocking, and 310 people died in a water accident in 2005, setting a record of annual deaths caused by mine water disaster in this century. 45 water accidents happened in 2006, which had the highest incidence of water accident in this century. Typical accidents such as "7.7" water accident of Yongsheng mine in Shangli County of Jiangxi Province in 2005, "7.14" catastrophic water accident of Fusheng mine in Luogang Town, Xingning City, Mei Zhou City, Guangdong Province in 2011, catastrophic water inrush accident of Inner Mongolia Baotou Chaoyue Mining Company in 2010 caused serious casualties and economic losses. In 2011 alone, 14 major water accidents happened across the country, in which 120 people died and 6 got trapped [16]. Particularly, "6.21" water inrush accident of Wangchong mine in Tongling City of Anhui Province taught a painful lesson. Number of water inrush accidents and deaths from 2004 to 2018 is shown in Figure 1.

Frequent occurrence of water accident and increase of casualty aroused extensive public concern. Mines valued gas accidents and water disasters equally other than valuing gas accidents only. As a result, water accidents were preliminarily contained, and accident frequency and deaths decreased year by year with death rate per million tons decreasing to below 0.1% for the first time in 2018. The National Coal Mine Safety Administration, based on summarizing experiences and lessons and full argumentation, presented a principle for mine water burst prevention and control: “Make forecast, explore in case of doubt, explore before excavation and mine after governance” [17, 18].

Mine mining will upset the distribution equilibrium of water resources on the crustal surface and form a cone of depression, and dynamic equilibrium and ecological environment of water in the mining area will also be destroyed [19]. Long-term observational data of Quaternary aquifer in the test mine showed a Quaternary aquifer elevation of -128.036 m to -148.682 m of holes on December 31, 2017, which decreased by at most 131.811 m compared with that before shaft building. The button-hole space of the working face of the first east mining area E3211 was closest to the Quaternary aquifer, but the Quaternary aquifer level declined slightly, while the Quaternary aquifer level declined by more than 100 m when coal was mined to at most -520 m (327 m away from the Quaternary aquifer) in the first and second west mining areas (Table 1), whereas a rapid decline in the Quaternary aquifer level could not be explained by existing geological and hydrogeological data, and a series of problems arose: did Quaternary aquifer enter the pit through the gob? Did land subsidence caused by long-term mining change hydrogeological conditions of the Quaternary aquifer? Would mining at superficial W3.21 and W3.22 working faces be influenced? Under the condition of large-scale exploitation, the recharge and discharge relationship between atmospheric precipitation, surface water, pore groundwater, and karst groundwater is obviously transformed, which is mainly reflected in the increase of precipitation infiltration recharge, pore water overflow recharge and surface water leakage recharge, and the decrease of spring discharge and jacking discharge to pore groundwater [20–23]. Thus, the cause of drop of the Quaternary aquifer in the second west mining area of the test mine was analyzed according to site geological condition, hydrogeochemistry, and geologic modeling method to ensure high yield and high efficiency of mine and provide references for production safety of mines of the same kind [24–27].

2. Engineering Geological Conditions

The test mine is located in the southwest of Suzhou City and about 15 km away from Suzhou City, and it is subordinate to Suzhou City and Suixi County of Huaibei City (Figure 2) according to administrative division. Geographical coordinates were as follows: east longitude: 116°51′00″-117°00′00″; north latitude: 33°27′00″-33°32′30″. The coal-bearing stratum of the test mine is upper Shihezi Formation, lower Shihezi Formation, and Shanxi Formation, and it is covered by the Cenozoic unconsolidated formation. The Quaternary and Neogene unconsolidated formation is 51.65-251.30 m thick and 212.74 m thick on average, which controls by ancient landform, and thickness roughly increases from north to south and from east to west. The unconsolidated formation directly covers the 32 coal bed in unconformable contact. Groundwater of the Quaternary aquifer (group) of the Cenozoic unconsolidated formation is indirect water filling aquifer of the 32 coal bed, and the roof is at the bottom margin of the unconsolidated formation with weak water abundance.

3. Hydrogeochemical Research

3.1. Conventional Hydrochemical Composition.

Conventional hydrochemical composition of 22 groups of water samples was tested, and test results are shown in Table 2.

3.1.1. Quaternary Aquifer.

Statistical result of the Quaternary aquifer is shown in Table 2. It can be seen that Na⁺ + K⁺ has the highest content (97-1,843 mg/l, 953 mg/l on average), followed by Ca²⁺ and Mg²⁺ with a content of 57-334 mg/l (149 mg/l on average) and 18-191 mg/l (87 mg/l on average), respectively. In terms of negative ion, SO₄²⁻ has the highest content of 98-4,160 mg/l (2,184 mg/l on average), followed by HCO₃⁻ and CO₃²⁻ with a content of 87-422 mg/l (217 mg/l on average) and 0-90 mg/l (20 mg/l on average). Besides, the Quaternary aquifer has a high TDS content up to 540-6,819 mg/l (3,725 mg/l on average), which is obviously higher than surface freshwater composition (<1,000 mg/l) and shows a high degree of mineralization. It may be related to high water-rock interaction, and a high SO₄²⁻ content shows oxidability of sulfate (e.g., iron pyrite).

In addition, coefficient of variation CV (also called coefficient of dispersion) is a measure of probability distribution dispersion degree, which is defined as the ratio between standard deviation and mean value. According to relevant researches on environmental sciences, whether pollutant content suffers from obvious man-made influence is often expressed by CV: CV < 0.20 in case of slight man-made influence; on the contrary, CV > 0.80 in case of serious man-made influence. For groundwater, CV shows the complexity of water-rock interaction more (multisource).
Figure 1: Number of water inrush accidents and deaths.

Table 1: Statistical table of water level elevation changes.

<table>
<thead>
<tr>
<th>Item</th>
<th>Hole number</th>
<th>Observation date</th>
<th>Altitude (m)</th>
<th>Observation date</th>
<th>Altitude (m)</th>
<th>Cumulative decline (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water₁ (west first)</td>
<td>mining area</td>
<td>2017.12.31</td>
<td>-148.682</td>
<td>2010.1.15</td>
<td>-38.56</td>
<td>110.122</td>
</tr>
<tr>
<td>Water₃ (west first)</td>
<td></td>
<td>2017.12.31</td>
<td>-128.036</td>
<td>2010.1.15</td>
<td>3.775</td>
<td>131.811</td>
</tr>
<tr>
<td>Water₅ (west first)</td>
<td></td>
<td>2017.12.31</td>
<td>-21.304</td>
<td>2011.6.15</td>
<td>-0.027</td>
<td>21.277</td>
</tr>
</tbody>
</table>

Figure 2: Location of the experimental mine, Anhui, China.
Table 2: Composition of major ions in loose and coal bearing sandstone aquifers.

<table>
<thead>
<tr>
<th>Number of sample</th>
<th>Aquifer</th>
<th>Na(^++)/K(^+)</th>
<th>Ca(^{2+})</th>
<th>Mg(^{2+})</th>
<th>Cl(^-)</th>
<th>SO(_4^{2-})</th>
<th>HCO(_3^-)</th>
<th>CO(_3^{2-})</th>
<th>TDS</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>QYZ-01</td>
<td>Quaternary aquifer</td>
<td>904.99</td>
<td>334.33</td>
<td>190.52</td>
<td>106.4</td>
<td>3156.15</td>
<td>136.68</td>
<td>21.61</td>
<td>4782.34</td>
<td>8.38</td>
</tr>
<tr>
<td>QYZ-02</td>
<td>Quaternary aquifer</td>
<td>1842.8</td>
<td>269.88</td>
<td>83.05</td>
<td>312.23</td>
<td>4160.04</td>
<td>248.96</td>
<td>26.41</td>
<td>6818.89</td>
<td>8.4</td>
</tr>
<tr>
<td>QYZ-03</td>
<td>Quaternary aquifer</td>
<td>798.16</td>
<td>181.26</td>
<td>119.68</td>
<td>85.47</td>
<td>2345.71</td>
<td>107.4</td>
<td>16.81</td>
<td>3600.79</td>
<td>8.3</td>
</tr>
<tr>
<td>QYZ-04</td>
<td>Quaternary aquifer</td>
<td>96.99</td>
<td>74.92</td>
<td>17.59</td>
<td>200.59</td>
<td>97.55</td>
<td>104.95</td>
<td>0</td>
<td>540.115</td>
<td>7.76</td>
</tr>
<tr>
<td>QYZ-05</td>
<td>Quaternary aquifer</td>
<td>1057.82</td>
<td>63.64</td>
<td>70.1</td>
<td>279.29</td>
<td>2046.89</td>
<td>86.55</td>
<td>89.86</td>
<td>3650.875</td>
<td>9.68</td>
</tr>
<tr>
<td>QYZ-06</td>
<td>Quaternary aquifer</td>
<td>942.75</td>
<td>104.43</td>
<td>106.37</td>
<td>285.97</td>
<td>1993.38</td>
<td>293.31</td>
<td>16.55</td>
<td>3596.105</td>
<td>8.75</td>
</tr>
<tr>
<td>QYZ-07</td>
<td>Quaternary aquifer</td>
<td>453.19</td>
<td>113.41</td>
<td>94</td>
<td>287.64</td>
<td>928.98</td>
<td>314.95</td>
<td>14.19</td>
<td>2048.885</td>
<td>8.62</td>
</tr>
<tr>
<td>QYZ-08</td>
<td>Quaternary aquifer</td>
<td>832.16</td>
<td>57.11</td>
<td>49.97</td>
<td>335.78</td>
<td>1247.56</td>
<td>422.12</td>
<td>22.93</td>
<td>2756.57</td>
<td>8.69</td>
</tr>
<tr>
<td>QYZ-09</td>
<td>Quaternary aquifer</td>
<td>923.98</td>
<td>108.51</td>
<td>90.04</td>
<td>291.46</td>
<td>1862.08</td>
<td>365.15</td>
<td>0</td>
<td>3458.645</td>
<td>8.15</td>
</tr>
<tr>
<td>QYZ-10</td>
<td>Quaternary aquifer</td>
<td>1780.13</td>
<td>105.21</td>
<td>20.42</td>
<td>173.03</td>
<td>3648.83</td>
<td>194.99</td>
<td>6.93</td>
<td>5832.045</td>
<td>8.3</td>
</tr>
<tr>
<td>QYZ-11</td>
<td>Quaternary aquifer</td>
<td>464.86</td>
<td>225.57</td>
<td>117.39</td>
<td>96.81</td>
<td>2536.69</td>
<td>112.76</td>
<td>9.24</td>
<td>3889.92</td>
<td>8.3</td>
</tr>
<tr>
<td>QYZ-12</td>
<td>Quaternary aquifer</td>
<td>435.41</td>
<td>5.54</td>
<td>2.88</td>
<td>203.85</td>
<td>89.86</td>
<td>65.84</td>
<td>0</td>
<td>1089.645</td>
<td>8.8</td>
</tr>
<tr>
<td>QYZ-13</td>
<td>Quaternary aquifer</td>
<td>281.8</td>
<td>3.96</td>
<td>3.84</td>
<td>186.13</td>
<td>10.29</td>
<td>348.52</td>
<td>47.68</td>
<td>707.96</td>
<td>8.81</td>
</tr>
<tr>
<td>QYZ-14</td>
<td>Quaternary aquifer</td>
<td>871.45</td>
<td>13.49</td>
<td>10.11</td>
<td>172.98</td>
<td>936.8</td>
<td>915.3</td>
<td>0</td>
<td>2462.48</td>
<td>7.54</td>
</tr>
<tr>
<td>QYZ-15</td>
<td>Quaternary aquifer</td>
<td>588.27</td>
<td>7.14</td>
<td>1.92</td>
<td>162.71</td>
<td>329.28</td>
<td>585.79</td>
<td>151.25</td>
<td>1533.465</td>
<td>8.89</td>
</tr>
<tr>
<td>QYZ-16</td>
<td>Quaternary aquifer</td>
<td>450.73</td>
<td>7.25</td>
<td>4.89</td>
<td>176.17</td>
<td>135.83</td>
<td>566.27</td>
<td>98.43</td>
<td>1156.435</td>
<td>9.06</td>
</tr>
<tr>
<td>QYZ-17</td>
<td>Quaternary aquifer</td>
<td>566.77</td>
<td>3.99</td>
<td>2.9</td>
<td>238.63</td>
<td>34.57</td>
<td>954.52</td>
<td>59.57</td>
<td>1383.69</td>
<td>8.34</td>
</tr>
<tr>
<td>QYZ-18</td>
<td>Quaternary aquifer</td>
<td>1160.51</td>
<td>22.99</td>
<td>10.81</td>
<td>131.03</td>
<td>1896.65</td>
<td>480.84</td>
<td>48.02</td>
<td>3510.43</td>
<td>8.8</td>
</tr>
<tr>
<td>QYZ-19</td>
<td>Quaternary aquifer</td>
<td>542.62</td>
<td>10.46</td>
<td>6.05</td>
<td>514.04</td>
<td>24.09</td>
<td>534.54</td>
<td>0</td>
<td>1364.53</td>
<td>7.95</td>
</tr>
<tr>
<td>QYZ-20</td>
<td>Quaternary aquifer</td>
<td>593.08</td>
<td>8.5</td>
<td>3.75</td>
<td>352.74</td>
<td>195.32</td>
<td>718.79</td>
<td>26.88</td>
<td>1539.665</td>
<td>8.8</td>
</tr>
<tr>
<td>QYZ-21</td>
<td>Air way water</td>
<td>612.31</td>
<td>119.58</td>
<td>83.41</td>
<td>104.59</td>
<td>1615.12</td>
<td>149.38</td>
<td>12.24</td>
<td>2621.94</td>
<td>8.31</td>
</tr>
<tr>
<td>QYZ-22</td>
<td>Drainage way water</td>
<td>1214.72</td>
<td>28.92</td>
<td>6.63</td>
<td>212.72</td>
<td>1626.64</td>
<td>910.2</td>
<td>0</td>
<td>3544.73</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Table 2 shows that both positive ions (Na\(^++\)/K\(^+\), Ca\(^{2+}\) and Mg\(^{2+}\)) and negative ions (Cl\(^-\) and HCO\(_3^-\)) represent moderate variation, which indicates source may not be single and may be related to different types of water-rock interactions.

3.1.2. Sandstone Water. Statistical result of sandstone water is shown in Table 3. It can be seen that the Na\(^++\)/K\(^+\) content of sandstone water is 282-1,160 mg/l (610 mg/l on average), which is obviously lower than that of the Quaternary aquifer. Then, the content of Ca\(^{2+}\) and Mg\(^{2+}\) is 4-23 mg/l (9 mg/l on average) and 2-11 mg/l (5 mg/l on average), respectively, which are also lower than those of the Quaternary aquifer.

In terms of negative ion, sandstone water is distinctly different from the Quaternary aquifer. HCO\(_3^-\) has the highest negative ion content (389-955 mg/l, 635 mg/l on average), followed by SO\(_4^{2-}\) and CO\(_3^{2-}\) with a negative ion content of 10-1,897 mg/l (404 mg/l on average) and 0-151 mg/l (55 mg/l on average). Moreover, TDS content of sandstone water is 708-3,510 mg/l (1,639 mg/l on average), which is also obviously lower than that of the Quaternary aquifer. It indicates obviously different water-rock interactions of sandstone water and Quaternary aquifer, and the highest negative ion content of HCO\(_3^-\) indicates that silicate minerals are probably weathered more obviously than the Quaternary aquifer.

As shown in Table 3, CV of SO\(_4^{2-}\) of sandstone water reaches up to 1.56 and is obviously higher than that of the Quaternary aquifer, indicating that oxidation of sulfide in sandstone water is probably more uneven. A big regional difference shows uneven distribution of sulfide or a big
difference in the degree of oxidation of different areas (related to degree of opening). It should be noted that CV of HCO$_3^-$ of sandstone water is less than that of the Quaternary aquifer, indicating that its source is simpler than that of the Quaternary aquifer.

### 3.1.3. Air Way and Drainage Way Samples.

Through comparison with Quaternary aquifer and sandstone water (Table 4), the Na$^+$+K$^+$ content of complementary air way water sample is similar to that of sandstone water, but the Ca$^{2+}$ and Mg$^{2+}$ content of complementary air way water sample is very similar to those of the Quaternary aquifer. For negative ion, it is similar to the Quaternary aquifer with a relatively high SO$_4^{2-}$ content and a relatively low HCO$_3^-$ content. Nevertheless, complementary drainage way sample has Na$^+$+K$^+$ content approximate to that of the Quaternary aquifer, but it has Ca$^{2+}$ and Mg$^{2+}$ content similar to those of sandstone water. For negative ion, drainage way sample

### Table 4: Statistical characteristics of coal bearing sandstone aquifer in experimental coal mine.

<table>
<thead>
<tr>
<th>Component</th>
<th>Na$^+$+K$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>Cl$^-$</th>
<th>SO$_4^{2-}$</th>
<th>HCO$_3^-$</th>
<th>CO$_3^{2-}$</th>
<th>TDS</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of samples</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Minimum value</td>
<td>281.8</td>
<td>3.96</td>
<td>1.92</td>
<td>131.03</td>
<td>10.29</td>
<td>348.52</td>
<td>0</td>
<td>707.96</td>
<td>7.54</td>
</tr>
<tr>
<td>Maximum value</td>
<td>1,160.51</td>
<td>22.99</td>
<td>10.81</td>
<td>514.04</td>
<td>1,896.65</td>
<td>954.52</td>
<td>151.25</td>
<td>3,510.43</td>
<td>9.06</td>
</tr>
<tr>
<td>Average value</td>
<td>610.071</td>
<td>9.258</td>
<td>5.239</td>
<td>237.587</td>
<td>403.55</td>
<td>635.391</td>
<td>55.297</td>
<td>1,638.70</td>
<td>8.554</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>260.324</td>
<td>5.986</td>
<td>3.197</td>
<td>121.645</td>
<td>630.56</td>
<td>197.23</td>
<td>47.737</td>
<td>847.30</td>
<td>0.507</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.427</td>
<td>0.647</td>
<td>0.61</td>
<td>0.512</td>
<td>1.563</td>
<td>0.31</td>
<td>0.863</td>
<td>0.517</td>
<td>0.059</td>
</tr>
<tr>
<td>p value</td>
<td>0.102</td>
<td>0.067</td>
<td>0.063</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>&gt;0.15</td>
<td>&gt;0.15</td>
<td>0.035</td>
<td>0.016</td>
</tr>
</tbody>
</table>

**Figure 3:** Piper diagram (group 1 and group 2 are, respectively, fourth aquifer and sandstone water, and group 3 is the water of air way and drainage way).

<table>
<thead>
<tr>
<th>Component</th>
<th>Na$^+$+K$^+$</th>
<th>Ca$^{2+}$</th>
<th>Mg$^{2+}$</th>
<th>Cl$^-$</th>
<th>SO$_4^{2-}$</th>
<th>HCO$_3^-$</th>
<th>CO$_3^{2-}$</th>
<th>TDS</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of samples</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Minimum value</td>
<td>281.8</td>
<td>3.96</td>
<td>1.92</td>
<td>131.03</td>
<td>10.29</td>
<td>348.52</td>
<td>0</td>
<td>707.96</td>
<td>7.54</td>
</tr>
<tr>
<td>Maximum value</td>
<td>1,160.51</td>
<td>22.99</td>
<td>10.81</td>
<td>514.04</td>
<td>1,896.65</td>
<td>954.52</td>
<td>151.25</td>
<td>3,510.43</td>
<td>9.06</td>
</tr>
<tr>
<td>Average value</td>
<td>610.071</td>
<td>9.258</td>
<td>5.239</td>
<td>237.587</td>
<td>403.55</td>
<td>635.391</td>
<td>55.297</td>
<td>1,638.70</td>
<td>8.554</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>260.324</td>
<td>5.986</td>
<td>3.197</td>
<td>121.645</td>
<td>630.56</td>
<td>197.23</td>
<td>47.737</td>
<td>847.30</td>
<td>0.507</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>0.427</td>
<td>0.647</td>
<td>0.61</td>
<td>0.512</td>
<td>1.563</td>
<td>0.31</td>
<td>0.863</td>
<td>0.517</td>
<td>0.059</td>
</tr>
<tr>
<td>p value</td>
<td>0.102</td>
<td>0.067</td>
<td>0.063</td>
<td>0.01</td>
<td>&lt;0.01</td>
<td>&gt;0.15</td>
<td>&gt;0.15</td>
<td>0.035</td>
<td>0.016</td>
</tr>
</tbody>
</table>
is more approximate to sandstone water with a relatively high HCO$_3^-$ content. It indicates that chemical composition of air way and drainage way samples may be between Quaternary aquifer and sandstone water. It also indirectly indicates a certain hydraulic connection between two aquifers.

3.1.4. Hydrochemical Type. Analysis result of Piper chart (Figure 3) shows 3 hydrochemical types of 22 samples, among which hydrochemical type of the Quaternary aquifer is mainly Na-SO$_4^-$ type, and that of 1 sample is Na-Cl type. It indicates that two problems might exist: first, the Quaternary aquifer has poor runoff condition and supply shortage results in increase in SO$_4^{2-}$ and Cl$. Second, oxidation of sulfide in the Quaternary aquifer may play an important role. Conversely, hydrochemical type of sandstone water is mainly Na-HCO$_3^-$ type, that of 2 samples is Na-SO$_4^-$, and that of 1 sample is Na-Cl type, indicating that weathering of silicate minerals in sandstone water may play a leading role. However, hydrochemical type of a few samples similar to the Quaternary aquifer may indicate a hydraulic connection with the Quaternary aquifer. This inference is consistent with hydrochemical type of air way water and drainage way water because these 2 samples have hydrochemical type identical to that of the Quaternary aquifer (Na-SO$_4^-$ type), which indicates the possibility of hydraulic connection.

3.2. Traditional Hydrogeochemical Evolution Analysis. The variation range of Gibbs I value of the Quaternary aquifer is 0.57-0.85 (0.64 on average), and that of Gibbs II value is 0.53-0.94 (0.82 on average). As shown in Figure 4, almost all water samples are located where evaporation and water-rock interaction occur, indicating that dissolution of evaporating salt and water-rock interaction plays an important role in chemical composition of groundwater in the mine. For sandstone water, Gibbs I value is relatively lower than the Quaternary aquifer, and the variation range is 0.25-0.62
Gibbs II value is relatively higher than the Quaternary aquifer, and the variation range is 0.98-0.99 (0.98 on average). The difference indicates that sandstone water has more obvious water-rock interaction than the Quaternary aquifer, and evaporating salt in the Quaternary aquifer makes a bigger contribution.

The Ca/Na variation range of the Quaternary aquifer is 0.07-0.89 (0.26 on average), and the MG/Na variation range is 0.02-0.40 (0.22 on average). As shown in Figure 5, weathering of silicate and dissolution of evaporating minerals are the main types of water-rock interaction of the Quaternary aquifer system, which is further demonstrated by the relationship between Ca/Na and HCO₃⁻/Na. It is consistent for sandstone water, but there are some differences. The main differences are that sandstone water obviously has a relatively lower Ca/Na and Mg/Na value, indicating that dissolution of evaporating salt is a main type of water-rock interaction of sandstone water. Figure 5 also shows that air way water is similar to the Quaternary aquifer, but drainage way water is similar to sandstone water.

### 3.3. Multitechnological Hydrogeochemical Evolution Analysis

#### 3.3.1. Correlation Analysis

Correlation analysis result is shown in Table 5. Suppose the confidence coefficient of 22 samples is 95%, the critical value of the correlation coefficient \( r_{0.05} = 0.42 \). In this case, there is a significant positive correlation between \( \text{Na}^{+}+\text{K}^{+} \) and \( \text{SO}_{4}^{2-} \), \( \text{Ca}^{2+} \) and \( \text{Mg}^{2+} \), \( \text{Ca}^{2+} \) and \( \text{SO}_{4}^{2-} \), and \( \text{Mg}^{2+} \) and \( \text{SO}_{4}^{2-} \), indicating that source of \( \text{Na}^{+}+\text{K}^{+} \), \( \text{Ca}^{2+} \), and \( \text{Mg}^{2+} \) in groundwater may be related to sulfate. On the contrary, there is a significant negative correlation between \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \), and \( \text{SO}_{4}^{2-} \), and \( \text{HCO}_3^- \), indicating that dissolution of carbonate minerals makes limited contributions to \( \text{Ca}^{2+} \) and \( \text{Mg}^{2+} \), and it decreases with increase in dissolution of sulfate minerals. Furthermore, ion exchange does not play a significant role in the aquifer of the test mine since there is no significant negative correlation between \( \text{Na}^{+}+\text{K}^{+} \) and \( \text{Ca}^{2+} \) and \( \text{Mg}^{2+} \).

#### 3.3.2. Factor Analysis

Factor analysis result is shown in Table 6. Two factors are obtained when the characteristic value is greater than 1: \( \text{Ca}^{2+}, \text{Mg}^{2+}, \text{and \( \text{SO}_4^{2-} \)} \) in factor 1 have a relatively high positive load, and \( \text{HCO}_3^- \) has a relatively high negative load, indicating that factor 1 may be dissolution factor of sulfate minerals and it has a restrictive relation with weathering of carbonate minerals. \( \text{Na}^{+}+\text{K}^{+} \) in factor 2 has a relatively high positive load, followed by \( \text{SO}_4^{2-} \). It also indicates an important contribution of dissolution of sulfate minerals to \( \text{Na}^{+}+\text{K}^{+} \). Besides, dissolution of sulfate minerals has a restrictive relation with dissolution of chlorine salt and silicate and carbonate minerals.

Factor score (Figure 6) shows a significant difference between Quaternary aquifer and sandstone water, while air way and drainage way samples are between the two: the former approaches Quaternary aquifer, and the latter approaches sandstone water.

#### 3.3.3. Unmix Model Analysis

In this research, conventional water chemistry of 22 water samples was analyzed, and the analysis result is shown in Table 7. Min Rsq obtained is 0.91, which is greater than the required value 0.80 of the model; while Min Sig/noise is 2.65, which is also greater than the required value 2.00 of model. Through comparison between the fitted content and the measured content, other ions have a good fitting effect except \( \text{HCO}_3^- \).

---

**Table 5: Result of correlation analysis.**

<table>
<thead>
<tr>
<th>Component</th>
<th>( \text{Na}^{+}+\text{K}^{+} )</th>
<th>( \text{Ca}^{2+} )</th>
<th>( \text{Mg}^{2+} )</th>
<th>( \text{Cl}^- )</th>
<th>( \text{SO}_4^{2-} )</th>
<th>( \text{HCO}_3^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Na}^{+}+\text{K}^{+} )</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Ca}^{2+} )</td>
<td>0.418</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Mg}^{2+} )</td>
<td>0.221</td>
<td>0.890</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{Cl}^- )</td>
<td>-0.015</td>
<td>-0.287</td>
<td>-0.249</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{SO}_4^{2-} )</td>
<td>0.859</td>
<td>0.792</td>
<td>0.646</td>
<td>-0.253</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>( \text{HCO}_3^- )</td>
<td>-0.127</td>
<td>-0.657</td>
<td>-0.664</td>
<td>0.232</td>
<td>-0.529</td>
<td>1.000</td>
</tr>
</tbody>
</table>

**Table 6: Result of factor analysis.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Na}^{+}+\text{K}^{+} )</td>
<td>-0.056</td>
<td>0.976</td>
</tr>
<tr>
<td>( \text{Ca}^{2+} )</td>
<td>0.785</td>
<td>0.523</td>
</tr>
<tr>
<td>( \text{Mg}^{2+} )</td>
<td>0.843</td>
<td>0.338</td>
</tr>
<tr>
<td>( \text{Cl}^- )</td>
<td>-0.568</td>
<td>0.110</td>
</tr>
<tr>
<td>( \text{SO}_4^{2-} )</td>
<td>0.457</td>
<td>0.881</td>
</tr>
<tr>
<td>( \text{HCO}_3^- )</td>
<td>-0.811</td>
<td>-0.185</td>
</tr>
<tr>
<td>Character value</td>
<td>2.519</td>
<td>2.162</td>
</tr>
<tr>
<td>Variance explained rate</td>
<td>42.0%</td>
<td>36.0%</td>
</tr>
</tbody>
</table>

**Figure 6:** Diagram of factor scores (1, 2, and 3 are the samples of quaternary aquifer, sandstone, and air way-drainage way, respectively).
As shown in Table 7, source 1 accounts for a large proportion in $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, and $\text{SO}_4^{2-}$, source 2 accounts for a large proportion in $\text{Na}^{+}$+$\text{K}^{+}$ and $\text{SO}_4^{2-}$, and source 3 mainly includes $\text{HCO}_3^-$ and $\text{Cl}^-$, followed by $\text{Na}^{+}$+$\text{K}^{+}$. Based on the aforesaid research results, source 1 is related to sulfate containing Ca and Mg, and it may be dissolution of gypsum. Source 2 is related to sulfate containing Na and K, and it may be Epsom salt. Considering that this source makes the biggest contribution to TDS, it may be related to gob water and oxidation of sulfide (e.g., iron pyrite). Source 3 may represent dissolution of chlorine salt and silicate minerals.

The contribution rate of the above inferences from different sources can also be further demonstrated. As shown in Figure 7, source 1 makes a big contribution to the Quaternary aquifer, indicating that plenty of gypsum may exist in sediments of the unconsolidated formation, but it makes a small contribution to sandstone water, indicating a few gypsum minerals in surrounding rocks of the sandstone aquifer. Source 2 shows no significant difference in two aquifers. Source 3 is just opposite to source 1 due to a high content of silicate minerals in the sandstone aquifer.

The difference in the contribution ratio reflects the difference in aquifer composition, and it also can be used to identify water source. Figure 7 shows consistency between air way water and Quaternary aquifer and between drainage way water and sandstone water. The above analysis data (significant difference) does not show a significant hydraulic connection between two aquifers.

### 4. GMS Simulation (GMS Modeling)

Groundwater Modeling System, or GMS, in the American Brigham Young of The Environmental Modelling Research Laboratory at University and the U.S. Army Drainage Engineering Test Station developed a comprehensive groundwater model based on existing MODFLOW, FEMWATER, MT3DMS, RT3D, SEAM3D, MODPATH, SEEP2D, NUFT, UTCHEM, and so on. There is a graphic interface software for groundwater simulation [28–31]. GMS is the most advanced software system for groundwater simulation in 3D environment. Water source identification result of the first mining area based on hydrogeochemistry shows no strong hydraulic connection between Quaternary aquifer and sandstone water and weak connection with downhole water points [32–36]. Therefore, fall of the Quaternary

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**Table 7: Results of Unmix model analysis.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Source 1</th>
<th>Source 2</th>
<th>Source 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Na}^{+}$+$\text{K}^{+}$</td>
<td>-154.000</td>
<td>659.000</td>
<td>302.000</td>
</tr>
<tr>
<td>$\text{Ca}^{2+}$</td>
<td>77.300</td>
<td>22.000</td>
<td>-14.100</td>
</tr>
<tr>
<td>$\text{Mg}^{2+}$</td>
<td>53.700</td>
<td>-6.490</td>
<td>2.560</td>
</tr>
<tr>
<td>$\text{Cl}^-$</td>
<td>-29.600</td>
<td>23.400</td>
<td>229.000</td>
</tr>
<tr>
<td>$\text{SO}_4^{2-}$</td>
<td>304.000</td>
<td>1300.000</td>
<td>-195.000</td>
</tr>
<tr>
<td>$\text{HCO}_3^-$</td>
<td>-216.000</td>
<td>81.900</td>
<td>552.000</td>
</tr>
<tr>
<td>TDS</td>
<td>133.000</td>
<td>2040.000</td>
<td>633.000</td>
</tr>
</tbody>
</table>
aquifer level should not be attributed to hydraulic connection, and it may be related to extra water storage space formed by land subsidence arising from mining after shaft building [37–41]. Based on this, change law of the unconsolidated formation was studied through GMS modeling after 32 coal bed was mined [42]. Data of 75 drill holes
(Figure 8) of the test mine was collected to study the relationship among the unconsolidated formation, 32 coal bed and 7, 8, and 10 coal beds.

As a primary mineable coal bed of the test mine, after 32 coal bed is mined, the upper unconsolidated formation will be instable, and sand and mudstone on the 32 coal roof will start to collapse and gradually develop upwards and expand in all directions. The range will increase, and the incidence will decrease. At a certain extent, fractures on the 32 coal roof will stop developing, and the area from the top of these fractures to the surface of the unconsolidated formation is called bending sinking zone, in which the rock stratum deforms and moves under stress and has poor water conductivity. The mined unconsolidated formation was simulated according to this rule and the result is shown in Figure 9.

To be specific, gob is formed after 32 coal bed is mined, and the upper unconsolidated formation will form water-conductive fissure zone, bending sinking zone, and ground fracture zone vertically and a cone of depression with a radius of $R$ horizontally with stress change. As shown in Figure 9, the bending sinking zone will affect change in the upper aquifer level in two different ways when it becomes stable:

1. When the Quaternary aquifer of the upper aquifer has high water abundance and good supply condition, high-head groundwater outside the bending sinking zone will be supplemented to the mobile zone timely and consequently, the water level of the observation point in the second west mining area will restore to the initial position before mining within a short time. Obviously, it is not consistent with water abundance of the Quaternary aquifer displayed in the geophysical exploration result.

2. Bending sinking arising from coal mining is a time-continuing process. However, when the Quaternary aquifer has weak water abundance and poor supply condition and groundwater of the bending sinking zone is supplemented by high-head Quaternary aquifer (observation well) on the cone edge, groundwater on the cone edge is not fully supplemented and consequently, the observed water level decreases.

5. Conclusion

1. Groundwater of the Cenozoic Quaternary aquifer (group) is an indirect water filling aquifer for water filing of mine with weak water abundance. While entering a mine in the superficial part along weathered fracture zone and caving fracture zone in the gob or coal bed and sand-controlled (water-controlled) coal pillar is reserved, Quaternary aquifer is main supplementary water for water filling of mine when the superficial coal seam group is mined.

2. Hydrogeochemistry shows obvious differences between Quaternary aquifer and sandstone water in chemical composition, which is mainly caused by different types of water-rock interactions. Dissolution of sulfate minerals in the Quaternary aquifer and weathering of silicate minerals in sandstone water contribute a lot. Discriminant analysis, clustering analysis, and Unmix model analysis results show no obvious hydraulic connection between Quaternary aquifer and sandstone water except air way and 4# samples.

3. According to GMS simulation, gob will be formed when 32 coal bed is mined. The upper unconsolidated formation of the gob will form water-conductive fissure zone, bending sinking zone, and ground fracture zone vertically and a cone of depression horizontally with stress change. When the Quaternary aquifer in the second west mining area has weak water abundance and poor supply condition, high-head groundwater of the bending sinking zone will be supplemented to the mobile zone slowly. In a certain period of time, change in the water level of the observation point will be affected, and the water level will decline.

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The author declares no conflicts of interest.

Acknowledgments

This work is supported by the Natural Science Research Projects of Colleges and Universities in Anhui Province in 2020 (No. KJ2020A0740). The author sincerely acknowledges the former researchers for their excellent works, which greatly assisted his/her academic study.

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