INTRODUCTION

Coal reservoirs have special mechanical properties, such as low compressive strength, low tensile strength, low elastic modulus, and strong heterogeneity. Therefore, coal reservoirs are more sensitive to changes in reservoir conditions. The decrease of coal reservoir permeability caused by stress sensitivity has drawn widespread concern in recent decades. Previous studies indicated that the permeability of coal reservoirs changes exponentially with stress (eg, refs. 7-11). Moreover, during drilling and gas production, fluid velocity sensitivity caused by particle migration and pore throat blocking is also a major cause for coal reservoir permeability decrease. Besides stress sensitivity and velocity sensitivity, water sensitivity, alkali sensitivity, and acid sensitivity can also cause damages to coal reservoirs, especially water sensitivity for high-rank coal reservoirs. However, little has been done on the water sensitivity to coal reservoirs during the process of coalbed methane (CBM) development.

Water sensitivity is a phenomenon that the formation permeability decreases due to the blocking of pore throats by the expansion or migration of clay minerals when using fresh water or low salinity water to displace the formation water during the hydraulic fracturing process. For the common clay
minerals, montmorillonite has the strongest swelling ability followed by illite/smectite (I/S) mixed clays and chlorite. The swelling ability of illite is relatively weak. Even though kaolinite has no swelling ability, it can easily disperse and migrate in the low salinity water and then block the pore throats, which also damage the formation permeability. Moreover, as the fluid velocity sensitivity is also caused by the particle migration and blocking in pore throats, this study only takes the expansion of clay minerals into consideration in order to distinguish the velocity sensitivity and water sensitivity.

Currently, China has made great breakthroughs in the exploration and development of CBM from high-rank coal reservoirs, and has established the high-rank CBM demonstration field in the southern Qinshui Basin. Nevertheless, the low gas productivity caused by the damage of coal reservoirs becomes serious after continuous production for 3-5 years. Different types of damage may occur in the CBM blocks. For example, the coal reservoirs will experience the stress sensitivity in the early production stage if the drainage rate is too fast, the velocity sensitivity if the fluid flows too fast, and the water sensitivity if the external fluids are not compatible (improper selection of fracturing fluid, overflow of top and bottom fluids, etc.). So far, studies on the compatibility of reservoir fluids have attracted increasing attention for the gas production from high-rank coal reservoirs in the late production stage.

In this study, coal samples collected from southern Qinshui Basin were used to conduct water sensitivity experiments and to evaluate water sensitivity effects. Considering the production status of CBM wells in this area, the water sensitivity behavior and its relationship with well productivity were discussed, aiming to provide strategies for developing suitable drilling and fracturing liquids which would cause less damage to CBM reservoirs.

**FIGURE 1** Burial depth contour map of No. 3 coal seam and location of samples in the Qinshui Basin (modified from refs. 22,49)
2 | GEOLOGICAL SETTING

The Qinshui Basin is located in the southeast of Shanxi, North China, which covers an area of 23.5 × 10³ km². As shown in Figure 1, the Basin is overall a NNE-trending long axis synclinorium, and the north and south margins warp to form a dustpan slope zone, and the two wings are basically symmetrical. The basin is bounded to the north by the Wutaishan Uplift, to the south by the Zhongtiaoshan Uplift, to the east by the Taihangshan Uplift, and to the west, the basin is adjacent to Linfen Basin divided by Huoshan Uplift. The tectonic condition of the basin is relatively simple with small-scale faults. The strata from bottom to top in the Qinshui Basin include the Cambrian, Ordovician, Upper Carboniferous, Permian, Triassic, Jurassic, Neogene, and Quaternary Systems, and the Silurian, Devonian, Lower Carboniferous, and Cretaceous strata are missing. Among them, the No. 3 coal seam in the Shanxi Formation is the main target zone for CBM development. The burial depth of No. 3 coal seam in southern Qinshui Basin varies from 500 to 1000 m (Figure 1), and most of them are anthracite coals with a vitrinite reflectance (R₀) of 2.2%-4.5%. The No. 3 coal seam has a relatively high gas content, ranging from 10 to 37 m³/t. By the end of 2016, about 9150 CBM wells had been drilled in the southern Qinshui Basin, which has become the first demonstration area for high-rank CBM development in China.

3 | ANALYTICAL PROCEDURES

3.1 | Material composition

There are nine coal samples that were collected from No. 3 coal seam in coal mining sites. On the same polished section of each coal sample, mean R₀ measurements and maceral analyses (500 points) were performed using a Leitz MPV-3 photometer microscope in accordance with ISO 7404.3-1994 and ISO 7404.5-1994. Then, they were analyzed for mineral compositions using X-ray diffraction (XRD) spectroscopy at the Beijing Research Institute of Uranium Geology. An X' Pert X-ray diffractometer with Cu-Kα radiation was used for XRD measurements of pulverized samples.

3.2 | Mineral distribution

The form and distribution of minerals were observed using a scanning electron microscope (SEM). Coal blocks were prepared as 3 × 3 × 3 cm³ polished cubes (both the surfaces parallel to the bedding plane and the adjacent surfaces perpendicular to the bedding plane were polished), and each polished slab was observed under Hitachi 3400-X and Hitachi 3400-I (Hitachi, Tokyo, Japan) scanning electron microscopes. The accelerating voltage was 15 kV, and the beam current was within 40-60 mA during SEM operation.

3.3 | Water ion concentration (IC)

A total of 12 water samples were collected from wells WW-1 and WW-2 (each well was sampled every 2 months for a total of six times; Figure 2). Both wells have been put on continuous production for 18 months to ensure that the fracturing fluid was completely flowed back and the representative samples were collected. The distance between wells WW-1 and WW-2 is about 330 m, and the burial depth of the target seam in well WW-1 is only about 30 m deeper than that of well WW-2. Meanwhile, the reservoir parameters of coal seam, such as thickness and gas content, are basically the same. The detailed water sample collection procedure can be found in Li et al. The cation and anion concentrations were measured in accordance to China Petroleum and Natural Gas Industry Standards (SY/T 5523-200). The accuracy and precision of field sampling and analyses were assessed by comparing values with field blanks, deionized water blanks, and duplicate samples.

3.4 | Water sensitivity experiment

3.4.1 | Experimental setup

Figure 3 shows the flowchart of the water sensitivity experimental setup, which is comprised of driving pump
(Gas Pump A for N\textsubscript{2} injection), coal holder, data measurement and acquisition system, and computer calculation system. ISCO 1000D Syringe Pump B can provide the confining pressure around the core holder. In order to measure the injection and outlet pressure at real time, piezometers A and B are installed in the inlet and outlet of the core holder, respectively. Moreover, in order to measure the real-time flow rate during the core flow experiments, the flow meters A and B were also installed in the inlet and outlet of the core holder, respectively. The flow meter B records the gas flow rate at one standard atmosphere pressure.

### 3.4.2 Experimental procedure

1. The coal was prepared in cylindrical cores by wire cutting method\textsuperscript{29} with a length of 3.0-5.0 cm and a diameter of 2.5 cm, with the ends of the cores perpendicular to the axis.

2. The above coal cores were put into the drying chamber under 110°C for 24 hours. For the same sample, under the condition of 2 MPa differential pressure, the permeability of the dry sample ($K_d$) is measured by nitrogen for three times instead of using original coal in order to eliminate the effects of thermally sensitive,\textsuperscript{30} and the error $\Delta K_d$ of tested permeability is determined to be less than 0.01 md.

3. In view of the low permeability of high-rank coal and the long displacement time, combined with the coal permeability value tested in step (2), the coal cores with relatively high permeability are selected for the water sensitivity experiment test (the permeability of the coal core needs to be at least higher than the measurement accuracy of the instrument).

4. An apparatus comprised of two connected vessels was used to saturate these coal cores. The selected dried coal cores were put into one vessel, and the actual formation water was put into the other vessel.\textsuperscript{15} After the

| TABLE 1 | Results of the proximate and maceral analyses |
|----------|---------------------------------------------|
| Sample  | Coal composition (vol.%, mineral removed basis) | Mineral content (%) | Proximate analysis (wt%, air dry basis) | $R_o$ (%) |
|---------|---------------------------------------------|---------------------|---------------------------------|----------|
| TA      | 78.6 | 21.4 | 9.86 | 1.52 | 15.36 | 8.35 | 74.77 | 3.32 |
| WZ      | 83.4 | 16.6 | 3.5  | 1.74 | 13.2  | 6.98 | 78.08 | 3.96 |
| YCH     | 81.3 | 18.7 | 11.96| 1.22 | 20.84 | 7.12 | 70.82 | 3.83 |
| BF      | 77.2 | 22.8 | 7.41 | 1.98 | 12.62 | 10.14| 75.26 | 2.84 |
| YC      | 84.6 | 15.4 | 11.63| 0.84 | 27.29 | 7.29 | 64.58 | 3.85 |
| TH      | 86.9 | 13.1 | 2.25 | 2.43 | 11.36 | 7.42 | 78.79 | 3.91 |
| YA      | 85.3 | 14.7 | 7.91 | 2.16 | 15.21 | 7.1 | 75.53 | 3.89 |
| HL      | 87.4 | 12.6 | 14.89| 0.92 | 26.68 | 6.51 | 65.89 | 4.03 |
| ZZ      | 77.3 | 22.7 | 5.7  | 2.03 | 14.77 | 12.53| 70.67 | 2.92 |
apparatus being vacuumed for 24 hours, the actual formation water was poured into the vessel with dried coal cores, ensuring that the coal cores were immersed totally. Then the apparatus was vacuumed for another 24 hours.

5. The coal cores were taken out from the vessel and were put into the core holder with the confining pressure being set at 4 MPa that is close to the in situ overlying strata pressure. Before flow tests, the core sample needed to stay at this confining pressure for at least 4 hours to make sure that the stress equilibrium is reached within the sample. N$_2$ was injected until the injection pressure and outlet pressure reached 2 and 1 MPa (slippage effect can be mostly eliminated by adding 1 MPa back pressure)$^{31}$, respectively. After the gas flow rate was stabilized (the gas flow rate does not change significantly within 5 minutes), the outlet gas flow rate $Q_{B1}$ on flow meters B was recorded. Then the permeability $K_1$ can be calculated according to Darcy’s law.

6. Gas pump A and ISCO pump B were closed. When the confining pressure reduced to 0.1 MPa, the coal core was removed from the core holder.

7. Step (2) was repeated and the $K_{d1}$ of the dry coal core was tested. When the difference between the $K_{d1}$ and $K_d$ is within $\pm \Delta K_d$, then steps (4) and (5) were repeated after the actual formation water was replaced by 1/2 salinity formation water (formation water diluted in an equal volume of distilled water). Then we can get the $Q_{B2}$ and $K_2$. When the difference value is too large, indicating the minerals contained in the formation water remain in the sample, this coal core column must be discarded.

8. Step (6) was repeated, and then the steps (4) and (5) were repeated after the 1/2 salinity formation water was replaced by distilled water. After that, the $Q_{B3}$ and $K_3$ can be obtained.

### 3.4.3 Permeability calculation

According to Darcy’s law, gas permeability can be calculated as
where \( k \) is the permeability, \( \mu \text{m}^2 \), \( 1 \mu m^2 = 1 \text{D} = 10^3 \text{mD} \); \( p_0 \) is standard atmospheric pressure, 0.1 MPa; \( \mu \) is the gas viscosity, 0.0176 mPa·s; \( L \) is the length of the coal core, cm; \( A \) is the cross-sectional area of the coal core, cm\(^2\); \( P_A \) is the injection pressure, 2 MPa; \( P_B \) is the outlet pressure, 1 MPa; and \( Q_B \) is the outlet flow rate that is measured by flow meter B, cm\(^3\)/s.

Permeability damage ratio is calculated as

\[
D_{k_i} = \frac{k_0 - k_i}{k_0} \times 100\%
\]

where \( D_{k_i} \) is the damage ratio of the permeability, \%; \( k_0 \) is the permeability of the coal core saturated with actual formation water, mD; and \( k_i \) is the permeability of the coal core saturated with 1/2 salinity formation water or distilled water, mD.

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**FIGURE 4** Distribution of clay minerals observed by SEM. (A) Kaolinite with a well-ordered structure; (B) leave-like chlorite and worm-like kaolinite; (C) Illite with a filiform shape; (D) cotton-like I/S mixed clays; (E, F) fissures filled with clay minerals.
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TABLE 4 Initial gas-phase permeability of selected dry coal cores

| Sample | L (cm) | D (cm) | Three \( K_d \) values (mD) | \( \Delta K_d \) (mD) | Average \( K_d \) (mD) |
|--------|--------|--------|----------------------------|------------------|------------------------|
| TA     | 4.919  | 2.5    | 0.491                      | 0.486            | 0.483                  |
| WZ     | 3.576  |        | 0.732                      | 0.738            | 0.736                  |
| YCH    | 3.256  |        | 1.881                      | 1.879            | 1.875                  |
| BF     | 4.1    |        | 0.773                      | 0.776            | 0.769                  |
| YC     | 4.288  |        | 0.778                      | 0.781            | 0.772                  |
| TH     | 3.827  |        | 1.45                        | 1.449            | 1.455                  |
| YA     | 3.468  |        | 0.431                      | 0.429            | 0.435                  |
| HL     | 3.904  |        | 0.115                      | 0.118            | 0.123                  |
| ZZ     | 3.69   |        | 0.579                      | 0.581            | 0.584                  |

L, length; D, diameter.

4 | RESULTS

4.1 | Material composition and distribution

As shown in Table 1, the collected coals are very high in metamorphic grade with \( R_o \) ranging from 3.83% to 4.03%. The coals have a high vitrinite content (77.2%-87.4%, mean 82.6%), followed by inertinite (12.6%-22.8%, mean 17.4%). These high-rank coal samples have low volatile yields (6.51%-12.53%) and moisture content (0.84%-2.43%), whereas they contain relatively high ash yields (11.36%-27.29%) and fixed carbon content (64.58%-78.79%).

The mineral content varies from 2.25% to 14.89%, which is mainly composed of clay minerals (7.19% on average) and calcite (2.92% on average) (Table 2). The clay minerals are mainly composed of kaolinite (36% on average) and I/S mixed clays (32% on average), followed by illite (17% on average) and chlorite (15% on average; Table 3). Clay minerals are mainly distributed in coal pores with various shapes, such as well-ordered and worm-like kaolinite (Figure 4A,B), leave-like chlorite (Figure 4B), filiform illite (Figure 4C), and Cotton-like I/S mixed clays (Figure 4D). Moreover, clay minerals can also be found in coal fissures (Figure 4E,F).

4.2 | Water sensitivity damage to coal permeability

Table 4 shows that the initial gas-phase permeability of selected coal cores varies from 0.119 to 1.878 mD (average 0.804 mD), which is slightly higher than the values described by Li et al\(^{32}\) (average 0.49 mD) and Chen et al\(^{33}\) (average 0.35 mD), due to the different measuring conditions such as gas used and gas pressure. The average error \( \Delta K_d \) is 0.0065 mD, which meets the accuracy requirement of the instrument (0.01 mD).

As can be seen in Table 5, the \( K_{d1} \) is close to \( K_d \), indicating that there is no residual mineral in the coal cores after being saturated with formation water or the residual mineral has less influence on the later experiment. The permeability damage ratio caused by water sensitivity varies from 1.6% to 50% when the coal cores were saturated by 1/2 salinity formation water, and the damage ratio varies between 5.21% and 66.67% under distilled water condition.

The water sensitivity damage ratio shows a negative exponential relationship with the flow rate (Figure 5A), indicating that the damage ratio is not caused by the increase of flow velocity. In other words, flow velocity sensitivity did not occur during the experiments. The positive correlation between water sensitivity damage ratio and clay content also suggests that the damage is mainly caused by swelling of clay minerals (Figure 5B). The strong correlation of water sensitivity damage ratio with I/S and I/S+Chlorite (Figure 5C,D) indicates that the damage ratio depends on the content of I/S and chlorite in clay minerals, but not on the kaolinite and illite content (Figure 5E,F).

4.3 | Source of water and change of water IC

A Piper diagram (Figure 6) was created for the wells WW-1 and WW-2 using the analytical data obtained from the hydrochemical analysis. It can be seen that the water from well WW-1 is a kind of mixed water from both coal seam and sandstone layer, while the water from well WW-2 is mainly from the coal seam. To analyze the impact of water sensitivity on gas productivity, the water samples from well WW-1 were further analyzed.

The change of water IC in well WW-1 is shown in Table 6. From 2014.9.23 to 2015.1.23, the concentration of Mg\(^2+\) and CO\(_3^{2-}\) decreased abnormally, but the concentration of Na\(^+\) increased rapidly (Figure 7).
DISCUSSION

5.1 Mechanism of permeability change caused by the water sensitivity

Figure 4 shows that the clay minerals in coals mainly exist in two forms, filling the matrix pores in granular form and filling the fractures in layered or banded form. Under the water sensitivity effect, the clay minerals in pores will enlarge the matrix volume, while those in fractures will directly narrow the fractures. The above two mechanisms can both lead to the decrease in coal permeability. Figure 5 presents that the major clay minerals of water sensitivity in southern Qinshui Basin are I/S mixed clays and chlorite, especially the smectite in I/S mixed clays. On the one hand, the crystal layer charge and edge broken bond of smectite give it a strong electrostatic attraction, which can absorb polar water molecules into the crystal layers to expand the crystals. When the smectite is in contact with water, its electrostatic attraction will cause water molecules to enter the crystal layer and contact with exchangeable cations to cause a hydration reaction. Each cation is surrounded by a plurality of water molecules, making the diameter of cation increased after hydration, which results in an increase in the interlayer spacing (interlayer zone) of smectite. Especially the sodium smectite, because of the high hydrability of Na\(^+\), it is easily swelled when it contacts with water.

On the other hand, the structure of smectite is like a sandwich, whose displaceable cations are mainly Na\(^+\) and interlayer gravitation is weak. Typically, the higher the ionic price is, the easier the ion can be adsorbed by rock particles. Therefore, the adsorption ability of Mg\(^{2+}\) and Ca\(^{2+}\) in out-injection water is stronger than that of Na\(^+\). As the clay minerals are characterized in small particle size, large surface area and strong adsorption ability enables them to adsorb large amounts of Mg\(^{2+}\) and Ca\(^{2+}\) and displace Na\(^+\) into the water, leading to the loss of Mg\(^{2+}\) and Ca\(^{2+}\) in coal seam water and abnormal high content of Na\(^+\) (Figure 8). The volume of smectite increases correspondingly due to the adsorption of Mg\(^{2+}\) and Ca\(^{2+}\) whose diameters are larger than that of Na\(^+\).

Therefore, the swelling of smectite after contacting with water is directly caused by the entry of free polar water molecules on the one hand, and on the other hand, it is produced by the hydration of cation.

5.2 Water sensitivity and gas productivity response

Figure 9 displays the gas and water production for wells DP-1, DP-2, and DP-3 near the well WW-1. It can be seen that the water sensitivity damage of coal reservoirs of wells DP-1, DP-2, and DP-3 occurred on September or October, 2014.

### Table 5

| Sample | L (cm) | D (cm) | Permeability and permeability damage under different fluids |
|--------|--------|--------|-----------------------------------------------------------|
| TA     | 4.919  | 2.5    |                                                             |
| WZ     | 3.576  | 0.89   |                                                             |
| YCH    | 3.256  | 1.874  |                                                             |
| BF     | 4.1    | 0.7    |                                                             |
| YC     | 4.288  | 0.774  |                                                             |
| TH     | 3.827  | 1.453  |                                                             |
| YA     | 3.468  | 0.82   |                                                             |
| HL     | 3.904  | 0.43   |                                                             |
| ZZ     | 3.69   | 0.686  |                                                             |

L, length; D, diameter.
which is caused by the leakage of low salinity water from sandstone layer sandwiched in coal seams and leads to the decrease of coal permeability and gas production rate, especially for wells DP-2 and DP-3. During this period, the water production rate suddenly increased significantly due to the replenishment of sandstone water (Figure 9), and the gas production rate was also decreased after 1-year gas production (Table 7). However, these thin sandstone layers sandwiched in coal seams are not aquifers which have little effort on the overall average water production rate (Table 7). Since the damage to the coal permeability is irreversible, the gas production can hardly recover to the peak level even though the secondary hydraulic fracturing has been implemented on the three wells in the late production stage (Figure 9; Table 7). The water sensitivity damage of coal reservoirs in wells DW-1, DW-2, and DW-3 near well WW-2 did not occur, so the gas production of the three wells maintains high, stable, and continuous (Figure 10; Table 7).

Combining the water source, changing of water ion concentration, and features of output gas and water in well block WW-1, it can be analyzed that the relatively strong water-rock interaction occurs between the clay minerals of coal reservoirs and the mixed water (coal seam water + sandstone layer water) due to the injection of sandstone layer water. On the one hand, the Mg$^{2+}$ and Ca$^{2+}$ with a high concentration in the mixed water displace the Na$^{+}$ in the clay minerals and

FIGURE 5   Relationships between water sensitivity damage ratio and flow rate and some of discussed minerals. The diamond represents under distilled water condition and the triangle represents under 1/2 salinity formation water condition
FIGURE 6  Piper plot shows hydrochemical character of wells WW-1 and WW-2 in different periods

TABLE 6  Water IC of well WW-1 in different periods (unit in mg/L)

| Date    | Cl⁻   | NO₃⁻ | SO₄²⁻ | HCO₃⁻ | CO₃²⁻ | Fe³⁺ | K⁺    | Na⁺   | Mg²⁺ |
|---------|-------|------|-------|-------|-------|------|-------|-------|-------|
| 2014.7.23 | 392.82 | 11.11 | 4.18  | 1085.19 | 114.76 | 0.2  | 4.19  | 370.97 | 1.73  |
| 2014.9.23 | 396.62 | 11.33 | 1.99  | 1088.82 | 109.32 | 0.15 | 5.89  | 448.26 | 1.99  |
| 2014.11.23 | 410.91 | 9.75  | 8.27  | 1001.02 | 134.8  | 0.12 | 7.55  | 288.54 | 1.87  |
| 2015.1.23  | 335.19 | 10.11 | 4.29  | 1085.9  | 84.7   | 0.13 | 4.68  | 1545.72 | 1.44  |
| 2015.3.23  | 260.57 | 8.34  | 3.61  | 1064.21 | 83.61  | 0.17 | 3.58  | 157.35 | 1.39  |
| 2015.5.23  | 350.95 | 8.63  | 34.69 | 1025.2  | 89.09  | 0.3  | 5.3   | 156.79 | 1.65  |

FIGURE 7  Relative change trend of water IC in well WW-1. IC/Max IC = single IC in different periods/Maximum IC (eg, the ratio of Cl⁻ on 2014.7.23 is 392.82/410.91)

FIGURE 8  A schematic diagram indicates the displacement mechanism of ions in smectite and coal seam water
FIGURE 9  Features of output gas and water in well block WW-1 and water sensitivity effect

TABLE 7  Average gas and water production of wells at different stage

| Well  | Average water production rate (m³/d) | Average gas production rate (m³/d) |
|-------|-------------------------------------|-----------------------------------|
|       | 0.5 a  | 1 a  | 1.5 a | 2 a  | 2.5 a |
| DP-1  | 3.45   | 420  | 550   | 367  | 352   | 375   |
| DP-2  | 0.68   | 775  | 1014  | 772  | 682   | 691   |
| DP-3  | 1.25   | 305  | 502   | 316  | 305   | 282   |
| DW-1  | 0.84   | 2972 | 3040  | 3025 | 2997  | 2985  |
| DW-2  | 0.45   | 1382 | 1714  | 2167 | 2355  | 2350  |
| DW-3  | 2.28   | 1072 | 2128  | 2363 | 2428  | 2459  |

The average gas production rate is calculated after the gas breakthrough time, and the average water production rate is calculated from the beginning of drainage.
result in the abnormal high content of sodium ion in the output water (Figure 7; Table 6). On the other hand, the water sensitivity effect makes the overall permeability of coal reservoirs decrease. The production ability of gas wells declines in the late drainage stage.

6 | CONCLUSIONS

1. The mineral contained in the coal samples collected from southern Qinshui Basin is mainly composed of clay minerals and calcite, followed by ankerite and aragonite. The clay minerals mainly consist of kaolinite and I/S mixed clays, followed by illite and chlorite.

2. The permeability damage ratio caused by water sensitivity varies from 1.6% to 66.67% under different saturation fluids, and the water sensitivity effect is mainly caused by I/S mixed clays and chlorite.

3. The water-rock interaction occurs between the clay minerals of coal reservoirs and the mixed water due to the injection of sandstone layer water. On the one hand, the Mg$^{2+}$ and Ca$^{2+}$ with a high concentration in the mixed water

**FIGURE 10** Features of output gas and water in well block WW-2 and water sensitivity effect
displace the Na$^+$ in the clay minerals and result in the abnormal high content of Na$^+$ in the output water. On the other hand, the water sensitivity effect reduces the overall permeability of coal reservoirs, which in turn reduces the gas and water production.

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