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Evaluation Model of Water Production in Tight Gas Reservoirs Considering Bound Water Saturation

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Abstract

Tight gas is an unconventional resource abundantly found in low-porosity, low-permeability sandstone reservoirs. Production can be significantly reduced due to water production during the development process. Therefore, it is necessary to predict water production during the logging phase to formulate development strategies for tight gas wells. This study analyzes the water production mechanism in tight sandstone reservoirs and identifies that the core of water production evaluation in the Shihezi Formation of the Linxing block is to clarify the pore permeability structure of tight sandstone and the type of intra-layer water. The primary challenge lies in the accurate characterization of bound water saturation. By integrating logging data with core experiments, a bound water saturation evaluation model based on grain size diameter and pore structure index was established, achieving a calculation accuracy of 92% for the multi-parameter-fitted bound water saturation. Then, based on the high-precision bound water saturation, a gas–water ratio prediction model for the first month of production, considering water saturation, grain size diameter, and fluid type, was established, improving the prediction accuracy to 87.7%. The bound water saturation evaluation and water production evaluation models in this study can achieve effective water production prediction in the early stage of production, providing theoretical support for the scientific development of tight gas in the Linxing block.

Keywords: tight gas; Linxing block; grain size diameter; bound water saturation; water production prediction

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1. Introduction

Natural gas is a low-carbon clean energy source. Compared to coal, its combustion reduces carbon emission intensity by more than 50%, giving it an irreplaceable strategic position in the global energy transition. With the increasing depletion of conventional natural gas resources, unconventional natural gas has become the focus of development. Among these, tight gas, as an unconventional resource stored in low-porosity, low-permeability sandstone [1], holds an estimated global reserve of 210 trillion cubic meters, which is 2.1 times that of conventional reserves. In China, technically recoverable tight gas resources amount to 10.92 trillion cubic meters, accounting for more than 25% of the total natural gas production, with the Ordos Basin accounting for more than 60%. Currently, the annual production of the Sulige Gas Field has reached 21 billion cubic meters, providing regional energy security for 50 years [2]. Therefore, tight gas has emerged as a crucial component

in the carbon neutrality transition phase, contributing 30% of clean energy supply with 7% of fossil energy's carbon emissions, giving tight gas the dual energy value of 'efficient development with low-carbon emissions' [3].

During tight gas production and development, formation water is commonly present in gas reservoirs and often hinders development efficiency, leading to a strong challenge in tight gas development that requires solving the gas–water conflict. Through investigation, it is found that there are three main reasons why water production in gas wells leads to a decrease in production capacity: (1) excessive liquid accumulation at the bottom of the well, resulting in insufficient production pressure difference and shutdown; (2) increased water saturation in the near-well matrix, resulting in a decrease in the relative permeability of natural gas: for every 10% increase in water saturation, permeability decreases by 30–50%; (3) the formation of the water lock effect during the development process affects gas migration and reduces the final recovery rate [4,5]. As a typical unconventional tight gas reservoir in the Ordos Basin, the Linxing gas field has early water production and a high water–gas ratio. Free water occupies seepage channels and induces the water lock effect. In addition, the dynamic evolution of the reservoir pore structure further exacerbates the complexity of gas–water seepage, which seriously restricts the efficient development of the gas field [6].

Addressing this challenge, conducting research on reservoir water production mechanisms and control mechanisms is a core scientific issue for breaking through the technological bottleneck of efficient development of tight sandstone gas reservoirs [7,8]. Scholars have conducted systematic research on tight gas reservoirs in the Ordos Basin and have achieved notable progress in the fine characterization of formation water occurrence, quantitative evaluation of water saturation and identification of low-resistivity gas layers [9], and reservoir water content prediction technology based on seismic attributes [10].

Currently, water production analysis mechanisms based on well logging data mainly focus on the evaluation of movable water saturation [11]. For example, Feng Qianghan et al. used well logging data to quantitatively calculate movable water and capillary water saturation and established a prediction model of formation water content using multiple regression techniques [12]. Wang Liying et al. reported a positive correlation between movable water saturation and gas well water production characteristics, and the higher the movable water saturation, the more serious the reservoir water production [13]. Numerous research results indicate that the occurrence mode of water in tight formations is a key factor in water production evaluation. This study focuses on the tight sandstone reservoirs in the Linxing block and investigates the mechanism of water production evaluation and the prediction model of water production.

2. Water Production Overview of the Linxing Block

2.1. Geological Overview of the Linxing Gas Field

The Linxing gas field is located in Shenmu City and Linxian County, Shanxi Province, as shown in Figure 1. It is adjacent to the Shenmu gas field to the west and the Lvliang Mountains to the east. Structurally, it belongs to the northern section of the west Shanxi fold belt, a secondary structural unit of the Ordos Basin [14]. Tectonically, it is significantly influenced by the Lishi strike-slip fault zone and the Zijinshan volcanic thermal activity, leading in a faulting pattern that is strong in the east and weak in the west, and high in the south and low in the north. The gas-bearing strata of the gas field are mainly the Benxi Formation (C2b) of the Upper Paleozoic Carboniferous, the Taiyuan Formation (P1t), the Shanxi Formation (P1s), the Shihezi Formation (P2x), and the Shiqianfeng Formation (P3s) of the Permian, with a total thickness of 500~550 m, which has an excellent source–reservoir–seal assemblage. Among them, the Shihezi Formation is the main development stratum

of the Linxing gas field. Its sand bodies are mainly composed of delta plain distributary channels and barrier sand bar deposits, exhibiting considerable thickness (single layer 0.5~17.7 m) and wide distribution. However, controlled by tectonic and sedimentary facies changes, the lateral connectivity of the sand bodies is poor, showing lenticular or superimposed composite characteristics.

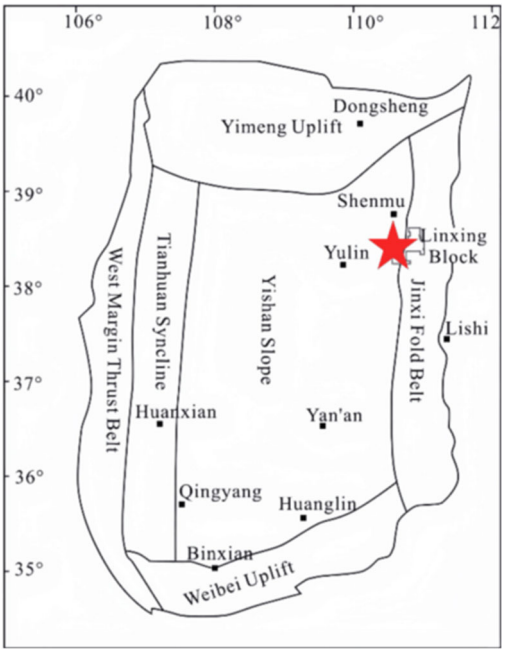


Figure 1. The tight sandstone reservoir is located in the Linxing block (red star) of the Ordos Basin.

The reservoir type is a typical tight sandstone gas reservoir, with porosity ranging from 5% to 16% and permeability ranging from 0.1 to 11 mD. Most reservoirs have characteristics such as low porosity, low permeability, low formation pressure, low natural production, high water saturation, high development cost, and strong heterogeneity. Pore types are mainly intergranular dissolved pores and residual intergranular pores, and secondary dissolution plays a significant role in the contribution of reservoir space. The complexity of the pore structure of tight sandstone leads to significant differences in gas–water mobility. The distribution of high-yield gas wells in the Linxing gas field has no obvious pattern, which limits the exploration and development of tight gas reservoirs. Therefore, it is necessary to reveal the relationship between the pore permeability structure and water production potential of tight formations to achieve water and gas production prediction in the Linxing block.

2.2. Gas Reservoir Characteristics and Water Production Characteristics

The Linxing reservoir lies at depths of 1300–2200 m, with a pressure coefficient ranging from 0.85 to 1.01. It is a layered, constant-volume gas reservoir driven by elasticity, lacking a distinct edge or bottom water interface. Natural gas is mainly transported vertically, and the accumulation pattern is controlled by the coupling of three factors: "source rock–structure–sedimentation". The hydrocarbon generation intensity of coal-measure source rocks (CH4 content 95%) is high in the south and low in the north (4~24 $\times$ 10^8 m^3/km^2), with a maximum residual pressure of 20 MPa. However, due to the reservoir's tight nature, some primary formation water remains trapped, forming a complex gas–water system characterized by interlocking or locally continuous distribution. Overall, the distribution of gas–water layers is affected by multiple factors. First, it is affected by the heterogeneity of the reservoir. High-porosity and high-permeability reservoirs are preferentially filled

with natural gas, while primary water remains in low-porosity and low-permeability areas, resulting in gas–water spatial differentiation. Second, it is affected by the structural amplitude. Structurally low positions are prone to enrichment of free water, while high positions are dominated by bound water. Third, it is affected by sedimentary facies. Distributary channel sand bodies have good physical properties due to strong hydrodynamics, and gas layers are continuously developed. Inter-channel bays and mudstone interlayers have a higher risk of water content, which greatly reduces the accuracy of gas production prediction. Therefore, in addition to the formation's porosity factors directly affecting water and gas production capacity, the water saturation of the reservoir section is also a core parameter that needs to be considered in the prediction of complex continental tight sandstone gas–water layers.

The Linxing gas field is affected by complex geological conditions and reservoir characteristics and generally has water production problems such as "early water production, high water–gas ratio, and large differences between wells". The impact of formation water on productivity is mainly manifested in two core mechanisms. One is the gas–water interlocking effect. The hydrocarbon generation pressure fails to completely displace the formation water to form a gas–water coexistence system [15]. During the development process, the water phase occupies the seepage channel, inducing the Jamin effect and water lock phenomenon, which significantly reduces the gas phase permeability. The second is the water production mode dominated by large pores. Nuclear magnetic resonance experiments confirm that movable water in mesopores with a pore size greater than 1 μm is the main source of water production, which is produced with gas expansion when the pressure drops. Under the disturbance of the fracturing development process, it is more likely to cause water encirclement or bottom-hole liquid accumulation. Traditional water control technologies (such as drainage gas production and diversion fracturing) are not sufficiently adaptable to unconventional gas reservoirs with complex gas–water relationships. It is worth noting that the eastern part of the Linxing block is affected by fault activity, and the aquifer develops deep into the gas–water mixing zone of the Upper Shihezi Formation, which further exacerbates the trend of productivity decline.

The gas–water distribution in the Linxing gas field is controlled by multiple factors, including reservoir properties, structural amplitude, and source rocks. The post-fracturing water production mechanism is even more unclear, and the large differences between wells pose deeper challenges for development: the spatial difference in gas content of the formations is significant, and the relationship between productivity and drilled thickness is non-linear; the fracturing effect of the reservoir varies significantly, and water production seriously restricts economic development. Specifically, it manifests as four major seepage deterioration mechanisms: ① The starting pressure gradient increases, the gas slippage effect weakens, and the Jamin effect occurs. ② The water phase of the pressure-sensitive effect occupies the gas seepage channel, increasing the gas seepage resistance. ③ Water film water swelling leads to water film blockage of pore throats. ④ Gas phase trapping and water locking effects. Therefore, severe water production in tight gas wells seriously affects productivity and drainage radius, shortening the production cycle of gas wells. These mechanisms change the dynamic characteristics of the seepage field, significantly compressing the drainage radius of gas wells [16]. Especially in areas with developed water–gas mixing zones, the multiphase flow coupling effect accelerates the water invasion rate, forming a vicious cycle of "increased water production and permeability damage, and permeability damage accelerating water invasion", which greatly increases the difficulty of stable production. A systematic analysis of the complex water production problems in tight gas reservoirs is of great guiding significance for formulating differentiated water control and stable production technical strategies.

In summary, water production in the Linxing block is primarily affected by the formation's porosity and permeability structure and the type of water within the formation, which will seriously affect the stability of production capacity during fracturing development. In order to realize the water production evaluation of tight gas, it is essential to focus on the influence law of bound water saturation in complex continental strata, and it is urgent to construct a new water production evaluation model considering various logging data and bound water saturation, so as to reveal the gas–water two-phase seepage law under engineering disturbance and provide data support for the full life-cycle development optimization of tight sandstone gas reservoirs.

3. Bound Water Saturation Evaluation Model Based on Grain Size and Reservoir Quality Index

To establish a water production evaluation model for tight gas reservoirs, this study focuses on irreducible water saturation as a critical parameter, conducting experiments on the response mechanism of irreducible water saturation and establishing a high-precision characterization model for irreducible water saturation in tight gas reservoirs based on conventional well logging data.

First, gas testing data of 165 wells in the Linxing block were classified. Based on the stable decline of the water production curves and the consistent ionic composition characteristics of formation water among the wells in the Linxing block, it was preliminarily determined that intra-layer water is the main source of water production in the Linxing block. Therefore, in the subsequent water production evaluations, upper and lower fluid influence could be reasonably excluded. Continuing to statistically analyze the microscopic pore throat radius distribution of core samples from nuclear magnetic resonance experiments in the Linxing block, it was found that the matrix porosity of the main reservoirs in the Linxing block is between 8% and 15% [17]. Within this porosity range, samples with an average pore radius of less than 1 μm, the fluid seepage channels are mainly capillary throats. At this point, the irreducible water saturation of the reservoir is relatively high, and the effective water saturation is generally less than 6%. The effective water saturation is less than the critical value for effective water production, and the water production is mainly due to the conversion of irreducible water into effective water. For samples with a pore radius greater than 1 μm, the fluid seepage channels are mainly super-capillary throats and large throats. At this point, the irreducible water saturation of the reservoir is relatively low, and the effective water saturation is greater than 6%. The water production type is mainly effective water production. Therefore, through the nuclear magnetic resonance experimental analysis of the core, it is considered that the pore radius is a key indicator for distinguishing whether the water production comes from effective water or irreducible water.

As for how bound water transforms into mobile water, scanning electron microscopy was used to analyze the pore throat structure of the core. Previous studies in the Linxing block have demonstrated that the combination of pore types and their structure has a significant controlling effect on the occurrence form of formation water: residual intergranular pores and dissolved intergranular pores, due to their large pore throat size and good connectivity, store a large amount of mobile free water under uncharged conditions, whereas dissolved particle pores and intercrystalline pores, due to their poor connectivity, mainly retain capillary water and bound water.

In Figure 2a,b, secondary quartz forms an enveloping shell on the surface of particles, isolating the primary pores into isolated pores, thereby aggravating the entrapment of bound water. However, as the production pressure difference increases, the secondary quartz enveloping shell may rupture, allowing the isolated pores to connect and forming

new seepage channels in the originally unconnected pores, resulting in a large release of bound water.

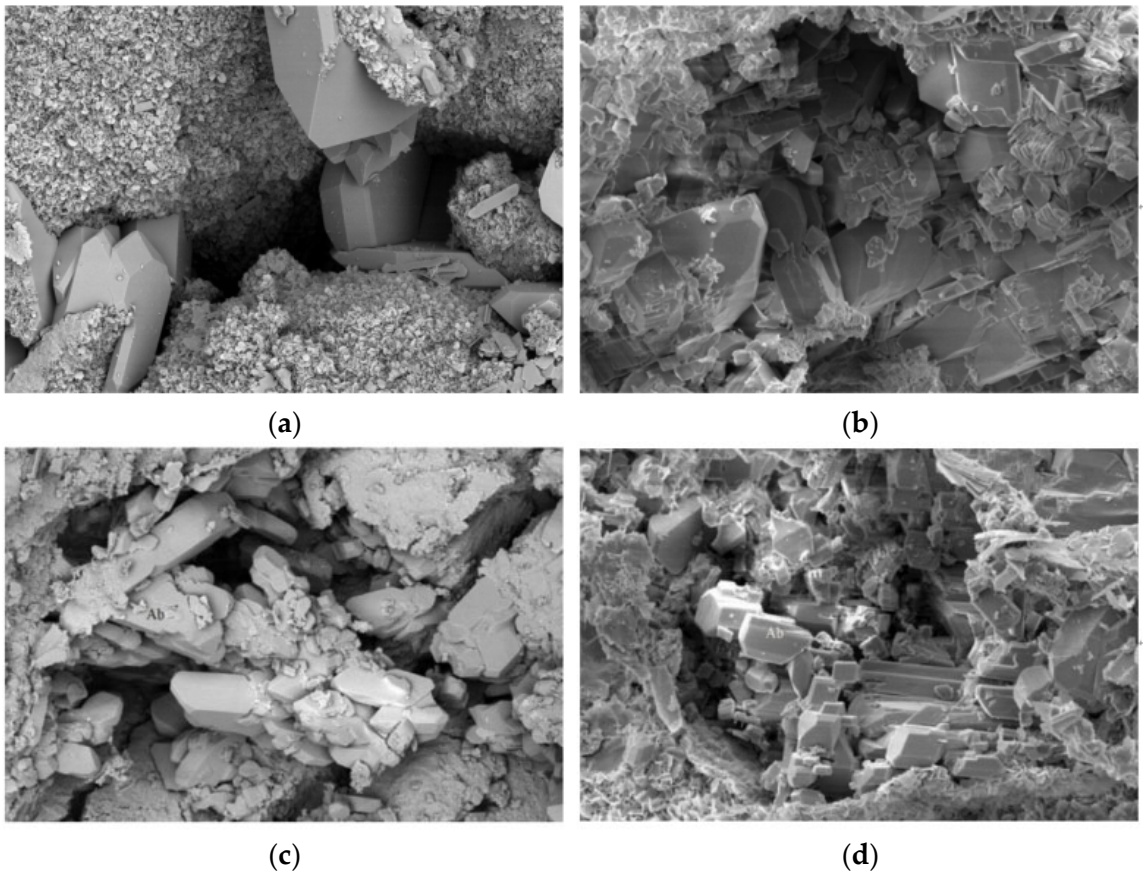


Figure 2. SEM images of pore throat structures in the Linxing block tight sandstone. (**a**) Secondary quartz blocks pores; (**b**) secondary quartz fills the dissolution pores of feldspar; (**c**) feldspar fills the pores in grains; (**d**) feldspar-filled intergranular pores.

In addition, the unstable microporous network formed by feldspar dissolution residues in Figure 2c,d inhibits the flow of free water by increasing the tortuosity of the pores, and pressure changes may trigger the migration of feldspar fragments, thereby relieving pore blockage, which can also lead to the production of bound water.

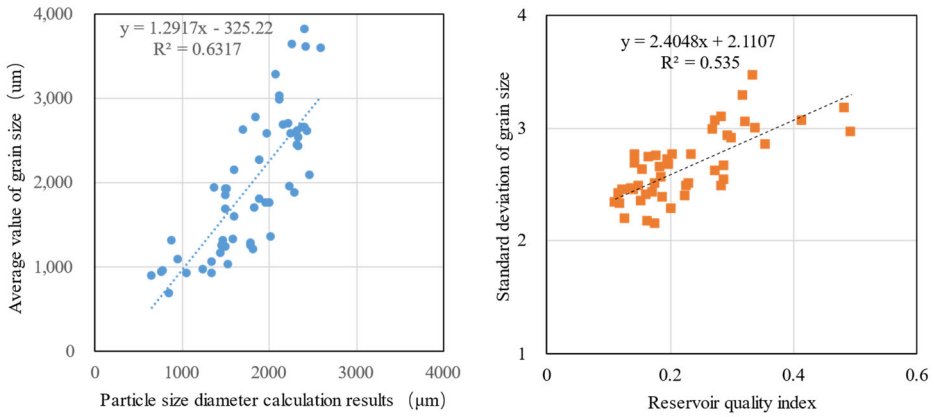
Therefore, it is believed that the bound water in the tight reservoirs of the Linxing block is all converted from bound water in larger pores to free water and discharged in large quantities due to changes in the original pore structure under increased production pressure difference. Pore structure is a key factor affecting the production of bound water and free water. Based on the hypothetical understanding of rock physics experiments, this paper focuses on exploring high-precision characterization methods for complex bound water saturation in tight reservoirs, starting from the pore structure analysis.

Pore structure parameters that affect irreducible water saturation in tight sandstone include the following: ① Characteristics of the bedrock framework, such as smaller grain diameters, which increase the specific surface area of the rock and the contact area between the rock and water, leading to an increase in the content of film-bound water. ② Pore diameter characteristics, such as a decrease in porosity, which will cause an increase in capillary-bound water retained in small capillary tubes or at the curved areas of pore throats. ③ Microscopic pore characteristics, such as a decrease in permeability and pore structure index, which will significantly limit reservoir productivity, cause deterioration in pore throat connectivity and microscopic pore structure, and increase the overall irreducible

water saturation. ④ Clay content, such as an increase in hydrophilic components like clay minerals, which will also increase the film thickness of pore-bound water. Therefore, an evaluation model for irreducible water saturation that considers pore structure parameters must incorporate grain diameter, porosity, permeability, pore structure index, and clay content [18].

The characterization model of grain size diameter can be obtained through regression of cuttings grain size test results in the Linxing block. Through correlation analysis of multiple logging curves, it is found that grain size diameter has certain correlation with mud content V_{sh}, porosity ϕ, and permeability K. The characterization Formula (1) of grain size diameter D_p established through multiple regression shows that the variation law of particle size diameter calculation results D_p is consistent with that of average value of grain size (as shown in Figure 3a), and the average calculation error is less than 22%.

$$D_p = -28V_{sh} + 243\phi - 495 \ln K - 275 \quad (1)$$



(**a**) (**b**)

Figure 3. (**a**) Relationship between grain size diameter and mean sandstone cutting grain size; (**b**) relationship between reservoir quality index and standard deviation of cutting grain size.

Using the classical Formula (2) for calculating reservoir quality index RQI, it is found that RQI has a good correlation with standard deviation of grain size (as shown in Figure 3b), indicating that the reservoir quality index can effectively characterize the sorting property of tight sandstone and further reflect the hydrodynamic environment during sedimentation.

$$RQI = \sqrt{\frac{K}{\phi}} \quad (2)$$

The grain size formula and reservoir quality index formula can characterize the C value and standard deviation σ of the grain size of tight sandstone cuttings, respectively. Based on the effective characterization of grain size and reservoir quality index, the evaluation method of bound water saturation can be further studied. Referring to the bound water saturation calculated by NMR core analysis, it is considered that shale content, porosity, permeability, grain size, and reservoir quality index can be used as key logging evaluation parameters to effectively evaluate bound water saturation. Therefore, combining the core nuclear magnetic resonance bound water saturation experimental results and key logging evaluation parameters of the Linxing block, as shown in Figure 4, it is found that in the two main productive layers of He2 and He8, the shale content is proportional to the tested bound water saturation, and the porosity, permeability, grain size, and reservoir quality index are inversely proportional to the tested bound water saturation, and there is a large

correlation coefficient between these five logging evaluation parameters and the core-tested bound water saturation.

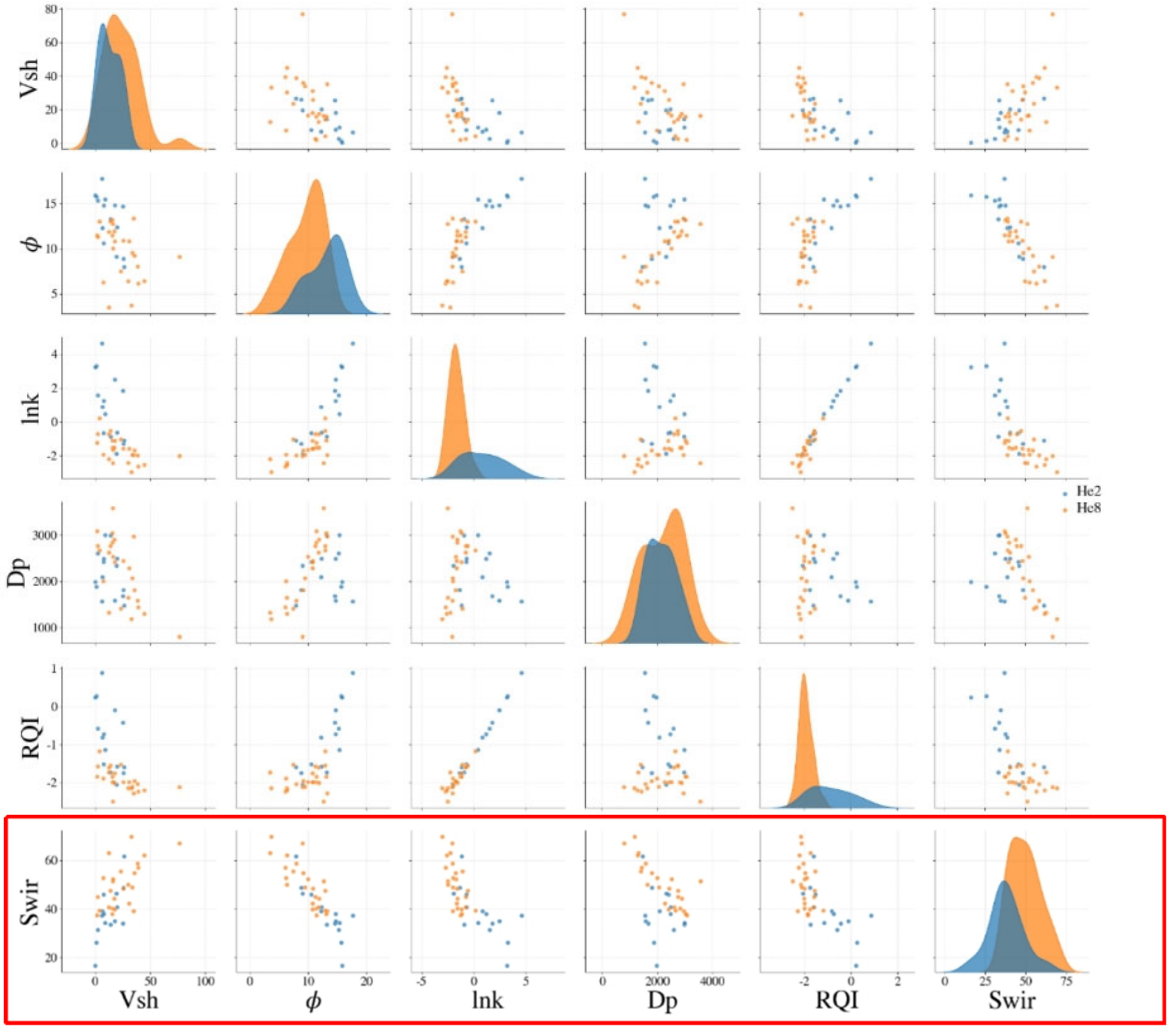


Figure 4. Multiparameter scatter matrix diagram of the Shihezi Formation 2 section and 8 section in the Linxing block.

Considering that bound water saturation is affected by the coupling of multiple factors, the evaluation Formula (3) for bound water saturation S_{wi} in the tight sandstone reservoir of the Linxing block can be obtained through multiple linear fitting.

$$S_{wi} = -0.025V_{sh} - 0.91\phi - 0.45\ln K - 0.0072D_p - 6.26RQI + 61.64 \quad (3)$$

where V_{sh} is the mud content, ϕ is the porosity, K is the permeability, D_p is the particle size diameter, and RQI is the reservoir quality index.

The calculation results of the bound water saturation evaluation formula for the Linxing block are shown in Figure 5. The maximum error between the predicted bound water saturation of each well and the core test results does not exceed 15%, and the average error is less than 8.4%. Compared with the 29% average error of the traditional bound water saturation model from porosity and permeability [19], the fitting Formula (3) based on conventional logging data has very high accuracy in predicting bound water saturation. Moreover, this evaluation formula comprehensively covers the numerical range of bound water saturation. Therefore, this formula can be effectively applied to reservoir evaluation of bound water saturation in the Linxing block.

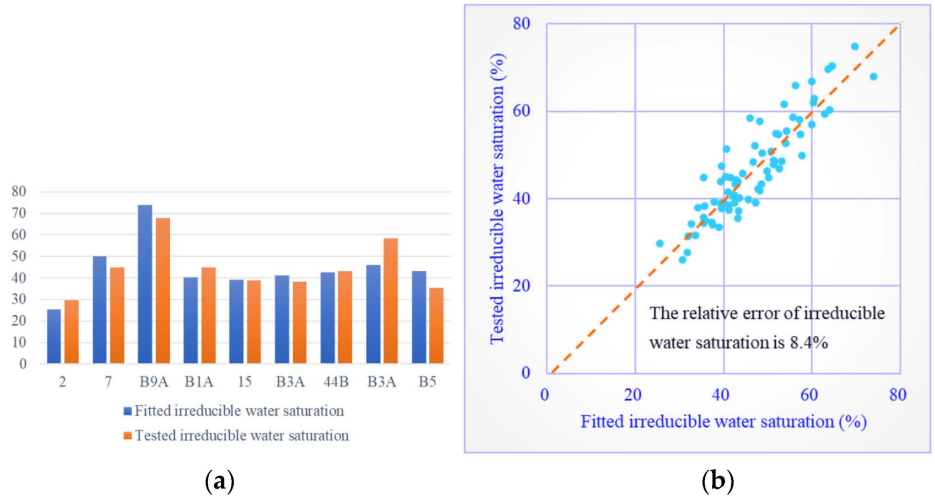


Figure 5. Calculation accuracy of bound water saturation in the Linxing block. (**a**) Calculation results of bound water saturation for key samples from the Shihezi Formation; (**b**) accuracy statistics of predicted bound water saturation versus test results.

Based on the experimental analysis results of bound water saturation in the Linxing block, a bound water saturation evaluation model based on grain size diameter and reservoir quality index was established, which enabled the calculation accuracy of bound water saturation to reach 92%, providing solid data support for the subsequent water production prediction based on bound water saturation.

4. Water Production Evaluation Model for Tight Gas Reservoirs

The observed geological, logging, and development data in the Linxing block currently do not exhibit effective correlations with water production due to the combined influence of multiple factors, namely the difficulty in evaluating mobile water content, the unclear water production mechanism of bound water, complex three-dimensional spatial variations of tight formations, and multiple well shutdowns during development. This has resulted in the absence of a high-precision water production evaluation model for tight reservoirs.

This study argues that in different water production stages of the Linxing block, the product of porosity and water saturation represents the upper limit of producible water volume in the formation around the wellbore during the initial water production stage. Bound water saturation reflects the potential for water production potential in the middle and late stages. Grain size and permeability are theoretically directly related to the fluid production rates. Fluid classification provides a rough division of water production types from a production statistics perspective [19,20]. Therefore, in the absence of strong single-parameter correlations with water production, the above parameters can be used to conduct in-depth research on water production prediction methods.

Statistical parameters related to the above theory, as shown in Figure 6a, show that the correlation between water production and the above parameters is still not significant. Meanwhile, as shown in Figure 6b, there is a good negative correlation between the tested gas water ratio W_g/W_w and water saturation S_w, particle size diameter D_p, and irreducible water saturation S_{wi}. Furthermore, the fluid identification type has a clear distinction in the evaluation of the gas–water ratio. Considering that the gas production prediction accuracy of tight reservoirs is high and the method is mature, in the water production prediction of complex tight reservoirs, the fluid identification model of tight gas can be combined to establish a high-precision prediction formula for the gas–water ratio to achieve accurate prediction of water production types. Based on the mechanistic analysis of the key parameters and their contribution to water production, this paper proposes that a

multiplicative model of the key parameters can be constructed to characterize the gas–water ratio. This approach has also been validated through actual data calculations in the subsequent water production prediction model. Since the variation range of the gas–water ratio is large, the gas–water ratio predicted in this paper is logarithmically processed, and the gas–water ratio prediction formula considering irreducible water saturation in the first month of production (4) is finally obtained.

$$\ln\left(\frac{W_g}{W_w}\right) = 5.25 \times \ln\left[\frac{10^7}{(S_w \cdot D_p \cdot S_{wi} \cdot T)}\right] + 7.98 \quad (4)$$

where W_g is the daily gas production statistically obtained in the first month, W_w is the daily water production statistically obtained in the first month, S_w is the water saturation, S_{wi} is the bound water saturation, D_p is the particle size diameter, and T is the fluid identification type (gas layer is marked as 1, water-bearing gas layer is marked as 2, gas–water coexisting layer is marked as 3, and water layer is marked as 4) from the deep-learning-based fluid identification with residual vision transformer network [21].

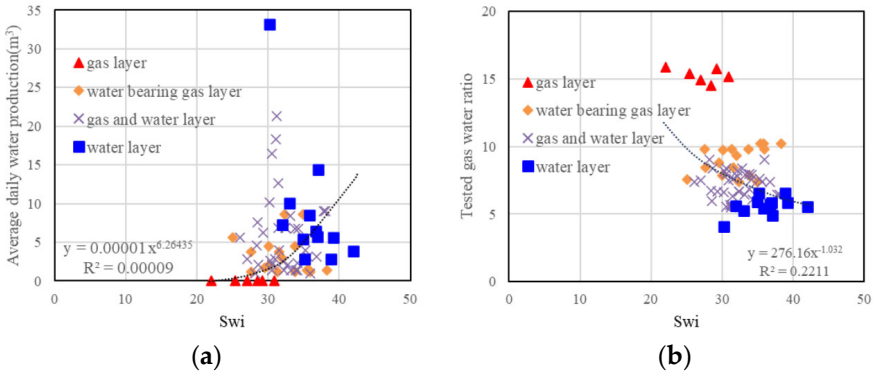


Figure 6. (**a**) The correlation between bound water saturation and daily water production is poor; (**b**) the correlation between bound water saturation and gas–water ratio is better.

The reason W_w predicts water production for the first month is that the well logging data used in this study can effectively characterize formation information within 100 m around the well in the Linxing block. Therefore, it enables reliable water production prediction within the first month, whereas production beyond this period is more influenced by development factors. Additionally, irreversible production declines in many gas–water layers often occur within the first month. Thus, W_w is crucial for the rational development of tight gas wells.

The water production evaluation model of Formula (4) was applied to 212 formations with production test data (90 of which were evaluated using blind wells) to predict reservoir fluid types and gas production, respectively, to provide the W_g and T required for Formula (4) and ultimately achieve gas–water ratio prediction and water production evaluation results.

As shown in Figure 7, comparing the L1 tight sandstone formation of the Shiqianfeng Formation in the X1 well of the Linxing block with the L2 tight sandstone formation of the Shihezi Formation in the X2 well, it is found that in the logging curve, the L2 formation only has a natural gamma smaller than the L1 formation by 20API, while the values of resistivity, acoustic waves, density, and neutrons are basically the same. From the perspective of porosity and electrical properties, it is impossible to effectively distinguish the differences in water and gas production between the two formations. Therefore, the conventional pore permeability saturation evaluation model interprets these two formations as gas layers. However, production testing data show that the daily gas production of the L1

formation is 3373 m^3/d, and the daily water production is 1.6 m^3/d; meanwhile, the daily gas production of the L2 formation is 3786 m^3/d, and the daily water production is 5.8 m^3/d. Due to the different water production rates, the production capacity of the L2 formation deteriorates rapidly in the later stages of production.

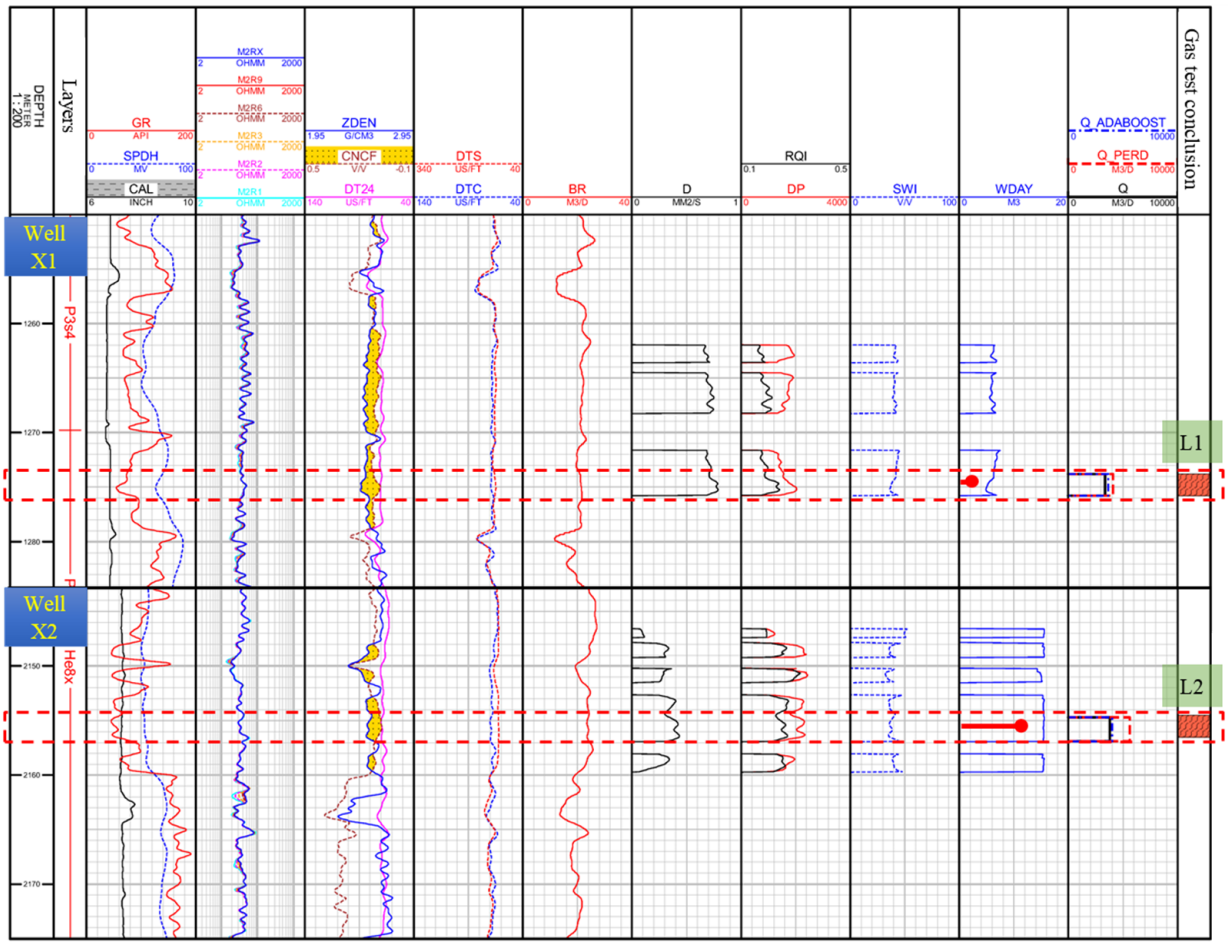
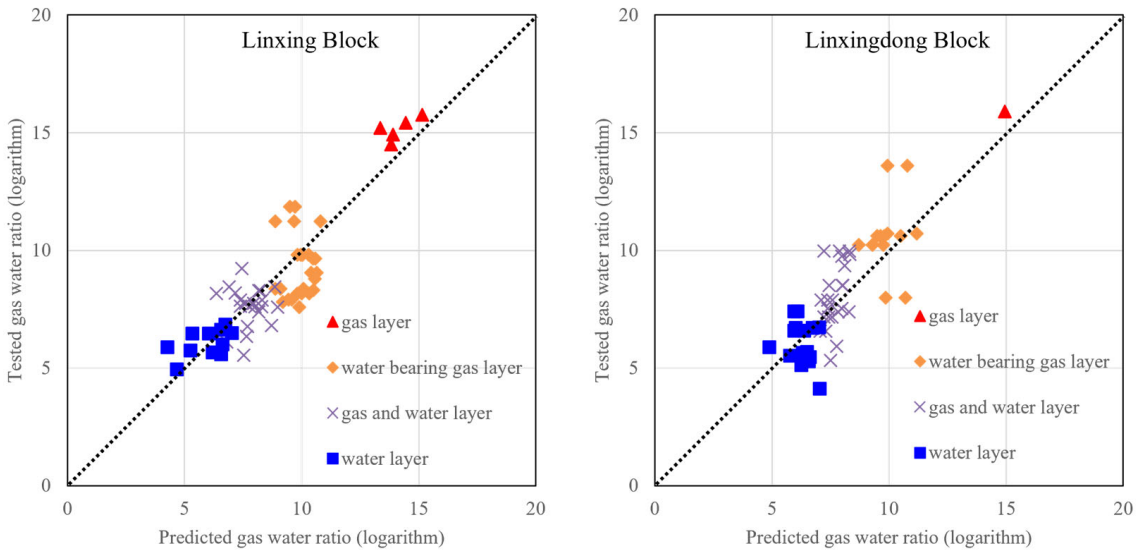


Figure 7. Blind well calculation results for the Linxing block.

Based on the water production prediction model developed in this study, the predicted daily gas production of the L1 formation is 3660 m^3/d, and the predicted daily water production is 3.6 m^3/d; meanwhile, the predicted daily gas production of the L2 formation is 4000 m^3/d, and the predicted daily water production is 7.9 m^3/d. Overall, the results of blind well evaluation demonstrate that the prediction accuracy of gas production accuracy reached 94%, and the water production error was within 2 m^3/d. When using water production grading evaluation, the accuracy of water production evaluation can meet the needs of development and production.

Compared with the gas–water ratio of production testing, the gas–water ratio prediction results of 212 calculated strata were sorted out in Figure 8 and Table 1. In the Linxing block (Figure 8a), the prediction accuracy reached 87.70%, the R^2 is 0.76, the mean square error of gas–water ratio is 1.53, and the final prediction accuracy of water production classification reached 94%. Therefore, in the case of high accuracy in gas production prediction, the water production prediction model adopted in this article can effectively predict the water production in the first month of development, and its accuracy far exceeds other fitted water production prediction models in the Linxing block. At the same time, as shown in Table 1 and Figure 8b, the gas–water ratio prediction accuracy saw only a slight decline when tested on another block in Linxingdong that was not used in model

building, confirming the model's strong external applicability in tight sandstone reservoirs. As this model is developed based on the water production mechanism specific to tight sandstone reservoirs, it is particularly applicable to tight sandstone formations where bound water effects are pronounced. Therefore, Formula (4) provides important guidance for water production prediction and water injection development strategy formulation in the Linxing block.



(**a**) (**b**)

Figure 8. Comparison between gas–water ratio prediction results and test results in (**a**) the Linxing block and (**b**) the Linxingdong block.

Table 1. The gas–water ratio prediction accuracy in the Linxing block and the Linxingdong block.

Block	R^2	RMSE	Prediction Accuracy	Classification Accuracy
Linxing	0.76	1.52	87.70%	94%
Linxingdong	0.69	1.83	86.18%	91%

Overall, the water production prediction model in this study is constructed based on the water production mechanism. It is proposed that the water production in the Linxing block originates from free water and partially from bound water within the formation, with the water production rate being controlled by grain size diameter and reservoir quality index (RQI). Therefore, water production prediction requires comprehensive consideration of these factors.

Due to cost constraints, the completeness of actual production well data varies.

① When NMR (nuclear magnetic resonance) test data on bound water saturation are available, water production can be directly predicted using Formula (4).

② When only cuttings grain size data are available, water production prediction can be derived from Formula (3).

③ When only conventional well logging data are available, grain size diameter and bound water saturation can still be calculated step-by-step starting from Formula (1), ultimately enabling water production prediction.

The model in this study makes full use of available data—the more core experiments conducted, the more stable the water production evaluation results for tight sandstone reservoirs.

5. Conclusions and Recommendations

Addressing the common issue of increased water production leading to decreased gas output during the development of tight gas, this paper establishes a water production prediction model considering irreducible water saturation, achieving high-precision prediction of water production types.

(1) To tackle the gas–water conflict that severely restricts development efficiency in the Linxing block, this paper analyzed the water production mechanisms in tight sandstone reservoirs. It concludes that the Shihezi Formation in the Linxing block is characterized by low porosity and permeability, as well as complex formation factors. Water production evaluation needs to consider the influence of the formation's pore permeability structure and the type of water within the layers. Crucially, it is necessary to clarify the influence law of bound water saturation in complex continental strata.

(2) A model for evaluating bound water saturation based on particle size diameter and pore structure index was established. Through experimental data analysis such as nuclear magnetic resonance, it was found that mud content, porosity, permeability, particle size diameter, and pore structure index can be used as key logging evaluation parameters to effectively evaluate bound water saturation. The calculation accuracy of the multi-parameter fitting model achieved a prediction accuracy of 92%.

(3) From the perspective of well logging evaluation, a gas–water ratio prediction model based on bound water saturation, water saturation, particle size, and fluid type was established, with a prediction accuracy of 87.7%. The final water production classification prediction accuracy reached 94%, providing effective guidance for the rational development of tight gas reservoirs in the Linxing block.

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