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Understanding the Impact of Cross-Formational Water Flow on Coalbed Methane Production: A Case Study

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Abstract

Cross-formational water flow has the potential to significantly impact the economic feasibility and efficiency of coalbed methane (CBM) production, making it necessary to examine its effects on reservoir parameters such as cleat porosity and gas and water relative permeability curves, as well as total gas and water in place. To assess the extent of hydraulic connectivity and its consequences, well logs or zone isolation tests should be utilized to confirm hydraulic interaction in areas where cross-flow is suspected. This study discovered that high water saturation caused by hydraulic connections delays the peak of gas production. The results further indicate that there are significant differences between the relative permeability plots obtained from simulated production data and the initial relative permeability plots when cross-flow occurs. These findings have crucial implications for methane management in mining. The total water in place ranged from 40227 to 79428 STB, and the total gas in place ranged from 4.5 x 108 to 5.3 x 108 SFC/ton for the cases analyzed. Therefore, this paper's findings could aid in determining the hydraulic connection between coal beds and surrounding formations, as well as the influence of cross-formational flow on reservoir parameters obtained from Production Data Analysis (PDA).

Keywords: *Coalbed methane; Porosity; Relative permeability; Water saturation; Nigeria.*

1. Introduction

The extraction of methane (CH_4) from coal seams through natural gas desorption is a process that raises safety concerns, environmental demands such as global warming and climate change, and the need for additional energy sources [1-4]. As an unconventional natural gas resource, coalbed methane is gaining international attention, and traditional oil and gas industry procedures and equipment are used to produce coal seam gas [3-6].

According to various research studies, there are significant global resources of Coalbed Methane (CBM) estimated at 256.1 x 1012 m^3, primarily located in the Asia Pacific region, North America, and the former Soviet Union [3,7]. Birol [8] reported that global production of coalbed methane exceeded 700 x 108 m^3 in 2011. However, extracting coalbed gas presents challenges due to factors such as low permeability, high capillary pressure, complex pore structure, and high initial water content [3,9]. Hence, it is crucial to understand the gas water permeability curve of a coal seam gas reservoir to predict and evaluate water production and gas well productivity for the cost-effective and efficient development of a coalbed methane reservoir [10,12].

Relative permeability plays a crucial role in understanding multiphase fluid flow through porous media, and it is also significant in coalbed hydrology [4,12-13]. The optimal coal permeability range for achieving economically viable rates of gas flow is between 1-100 mD [[14-15].

Dewatering ultra-high permeability coals can be challenging in the presence of cross-formational flow. Cross-formational flow can occur due to unconformity, leading to hydraulic linkage between surrounding formations and the coalbed, which can influence the reservoir parameters obtained through production data analysis (PDA) approaches [3].

While studying coalbed methane (CBM) reservoirs, production data analysis (PDA) is a useful method for finding relevant reservoir characteristics and stimulation variables [3,13]. Critical CBM reservoir characteristics such as initial gas and water in situ, skin factor, permeability-thickness product (Kh), and peak gas production time may now be determined thanks to recent breakthroughs in production data and rate transient studies [13-19]. Adsorption-driven gas storage mechanisms, estimating relative permeability, and stress/desorption-dependent permeability are just a few of the concerns that can make PDA in CBM reservoirs problematic [13,20]. The rate of fluid output, which is essential for both field and simulation studies, is determined by relative permeability, a complicated component controlling PDA [21-23]. Several writers have used laboratory tests to evaluate the relative permeability of coals [23-27]. Using field data, one may generate water and gas relative permeability curves from CBM wells drilled in water-saturated coals as depletion occurs. Dewatering coal expands the window of water saturation, enabling for more precise calculations of relative permeability [19].

Although currently, the Nigerian government has prioritised the use of coal resources to increase the country's electricity generation capabilities. Nigeria's goal is to revitalise the coal mining industry and increase electricity generation by attracting firms to develop these vast coal reserves and build coal-fired power plants that would connect to the country's electrical distribution grid [12,28]. However, evidence from previous studies shows that the coal present in some parts of the country has been underutilized, especially for energy purposes. Instead, the majority of these studies have focused more on just the characterization of coals for other purposes neglecting the fact that this could be useful in the generation of energy which could tackle the energy crisis the country is facing at the moment. Therefore, the aim of this study is to investigate how the entry of water into a coalbed from an external source impacts production efficiency and reservoir properties, such as cleat porosity and relative permeability plots. The research will utilize a reservoir simulation method based on production data methodology to obtain the desired results.

2. Methodology

The study employed modeling techniques to investigate the production of water and gas from both the coalbed and the overlying formation.

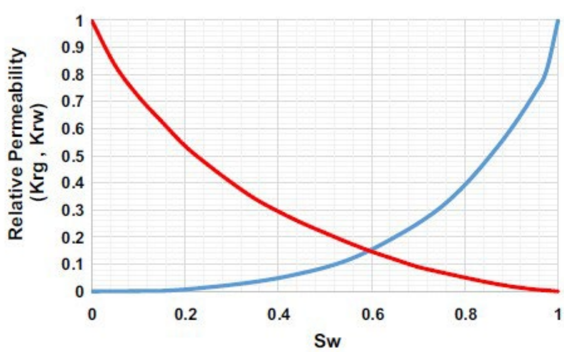

Fig. 1. Input coalbed and overlaying formation relative permeability curves (Gash [24]).

By simulating two-phase flow, relative permeability curves were generated using a tank-type model, and cleat porosity was calculated from water production data. Interestingly, the no-flow boundary assumption was intentionally disregarded when using the tank-type model to examine reservoir engineering parameters in the presence of cross-formational flow. Results indicated that cross-flow may influence reservoir characteristics obtained from PDA. Figure 1 demonstrates how relative permeability plots and cleat porosity were obtained from simulated production data.

2.1. Simulation model

Previous studies have suggested that the behavior of fluids and reservoir performance in Coalbed Methane (CBM) production can be influenced by several pressure-dependent elements. Therefore, numerical reservoir modeling has been recommended as the most suitable approach for investigating this issue [29-30]. In this study, an individual well simulation model was developed using the Computer Modeling Group (CMG) reservoir simulator. To investigate the effects of cross-formational flow, the simulation model was designed to be as simple as possible. Input variables for the model were selected from a wide range of CBM reservoir parameters within and outside of the study region, as the model was not intended to replicate any specific well. Table 1 shows the input parameters used in the simulation model. The simulation model employed the following models and assumptions to simulate water and gas movement in the coalbed:

1. Dual porosity.
2. Sorption under non-equilibrium conditions.
3. Compaction of the Palmer-Mansoori rock type.
4. Sorption isotherm of the Langmuir type.
5. Single gas component (methane).
6. The reservoir's isothermal condition.

Table 1. Reservoir parameters used as inputs in the reservoir simulation model. []

Parameters	Value	References
The thickness of coal (ft)	25	Measured
Depth of coalbed (ft)	1250	Measured
Overlying formation thickness (ft)	11.15	[13]
Overlying formation porosity (%)	9.16 and 2	[13]
Cleat porosity (%)	0.07	[33]
Overlying formation vertical permeability (mD)	100	[13]
Coal horizontal permeability (mD)	100	[33]
Coal vertical permeability (mD)	50	[33]
Drainage area (acres)	81,080	
Coal specific gravity	1.435	[13]
Initial Temperature, (F)	113	[25]
Initial pressure, (psi)	700	[25]
Langmuir pressure (psi)	438	[27]
Critical desorption pressure (psi)	837	[13]
Langmuir volume (SCF/ton)	664	[27]
Wellbore radius (ft)	0.65	[13]
Well skin factor	0	[13]

The representation of fracture and matrix as separate grid blocks was required by the dual porosity model. This model allowed for one porosity to be assigned to the fracture and one porosity to be assigned to the matrix within each grid block. The Langmuir isotherm was used to describe the quantity of gas that can be stored in the adsorbed phase at any pressure that is equal to the pressure of the matrix. The dewatering process leads to a decrease in pressure within the cleat system, which triggers gas to begin desorbing and diffusing within the coal matrix at the desorption pressure. The non-equilibrium sorption model explained the sorption time as the product of a matrix shape factor and a diffusion coefficient, which has a significant impact on the simulation of coalbed methane reservoirs. The relative permeability plots for both gas and water were used to describe the relative flow of water and gas in the cleat system [13,19, 31-32].

The coalbed was sandwiched between an extremely porous top layer and an impervious bottom layer. It had an ultra-high permeability of 100 mD, similar to coal found in the center of a field [15,33]. At a depth of 1,250 ft, the reservoir had an initial pressure of 942 psi and a gas concentration of 430 SCF/ton, resulting in a desorption pressure of 837 psi. Prior to gas production, the water in the coalbed had to be removed. The stratum above the coalbed was filled with water, which was connected to the coalbed through vertical permeability. This connectivity could be attributed to fractures (vertical) or permeable faults that extended from coal into adjacent strata. The methane gas and water data for the coalbed and the stratum above it were generated using the water and gas relative permeability plots (Fig. 2). As the wellbore was finished and perforated within the coal zone, only fluid flow from the coal interval was allowed into the wellbore.

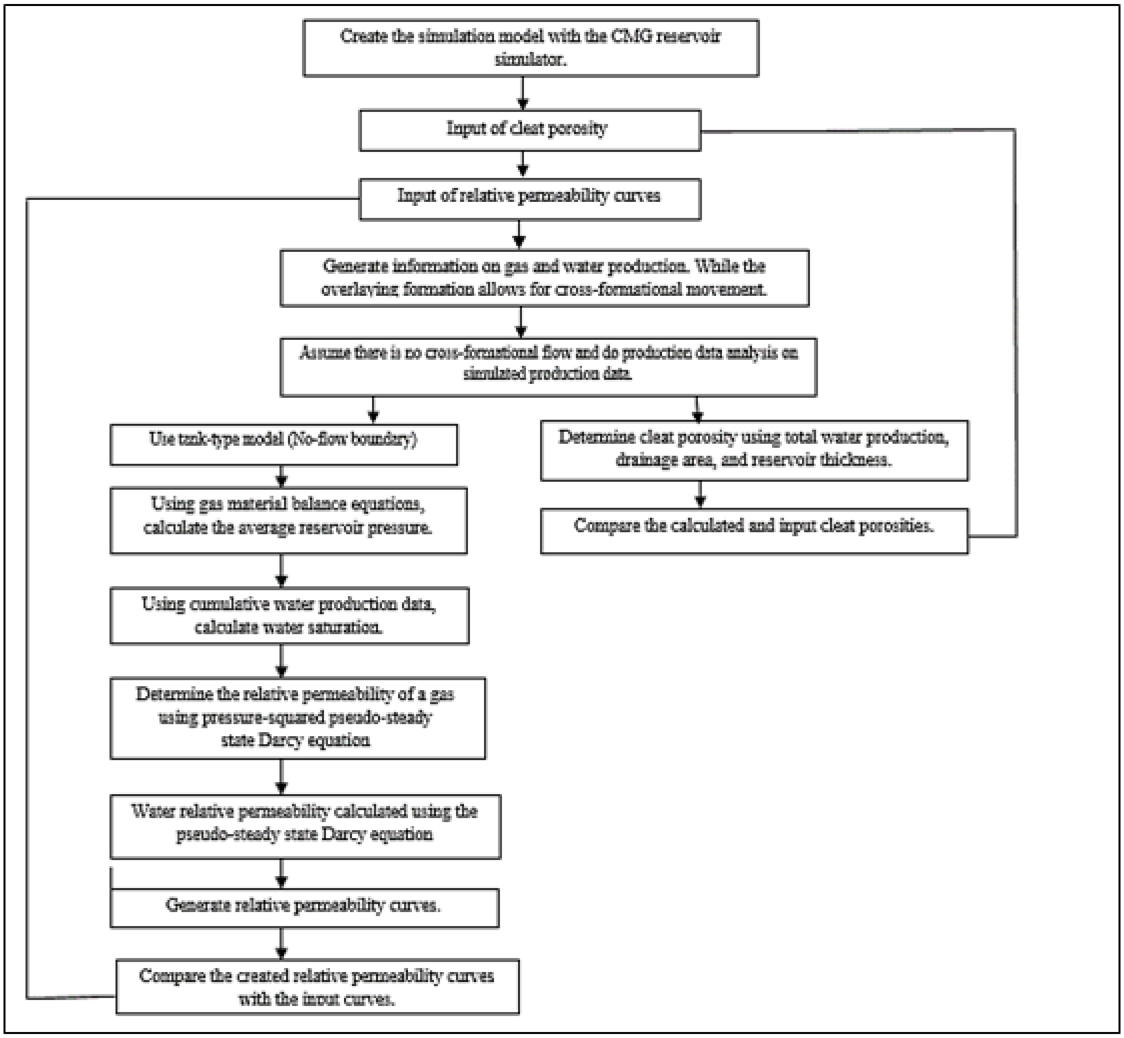

Fig. 2. A generalised approach to estimate cleat porosity and relative permeability plots from simulated production data (modified from Salmachi & Karacan [13]).

Starting in 2023, the reservoir was simulated to predict how gas and water will move through the coalbed and the overlaying formation for the next 30 years (10950 days). By adjusting the porosity of the layer above the coalbed, we were able to establish two simulated scenarios with varying amounts of water storage. While the hydraulic connectivity/permeability stayed the same in all scenarios, scenario one allowed for more water to enter the coalbed. In the third case, we looked at how increasing permeability and vertical conductivity affected cross-formational flow.

2.2. Production data

Water and gas depletion in a closed CBM well was studied with the use of the tank-type model, a popular technique [34]. Using production data in the field or through simulation, this model may produce relative permeability plots. Clarkson *et al.* [21] described a five-step process for generating relative permeability curves for both gas and water, which was followed hereunder in Table 1.

Using King's [35] material balance equations (Eqs. 1-3), average reservoir pressure and water saturation in coal beds were determined. For this investigation, we computed gas relative permeability using the pressure-squared formulation (Eq. 4), and water relative permeability was determined using a pseudo-steady-state equation (Eq. 5).

$$\frac{P}{Z^*} = \frac{Pi}{Zi^*}\left(1 - \frac{G_p}{G_i}\right) \tag{1}$$

$$Z^* = \frac{\text{Z}}{\frac{PB^V Ldaf^{(1-a-w)P_{sc}TZ}}{32.037\emptyset Z_{sc}T_{sc}(P+PL)} + (1 - S_w)} \tag{2}$$

$$S_w = S_{wi} - \frac{B_w\,(W_{in} - W_p}{7758.4An\emptyset} \tag{3}$$

$$K_{rg} = \frac{a_g\left[1422\text{TZ}\mu_g\left(\text{In}\left(\frac{r_e}{r_w}\right) - 0.75 + s\right)\right]}{K_{abs}\,h\,(P^2{}_R - P^2{}_{wf})} \tag{4}$$

$$K_{rw} = \frac{q_w\left[141.2B_w\mu_w\left(\text{In}\left(\frac{r_e}{r_w}\right) - 0.75 + s\right)\right]}{K_{abs}\,h\,(P_R - P_{wf})} \tag{5}$$

3. Results and discussion

The aim of this study was to investigate the effects of cross-formational flow on the production performance of CBM wells by simulating three different scenarios. In all three scenarios, water was introduced into the coalbed by extending the contact zone across the entire drainage area during production. The first scenario involved a high water storage capacity in the overlying formation, which allowed for a substantial flow of water into the coalbed. The second scenario was similar to the first, but the overlying formation had a reduced water storage capacity due to lower porosity. Lastly, the third scenario examined the simultaneous occurrence of cross-formational flow and permeability enhancement, which allowed for the investigation of the role of permeability variation on cross-flow.

3.1. Case 1 (ONY)

The study utilized a reservoir simulator to analyze the water and gas production statistics for a specific scenario where the coalbed had a constant absolute permeability. The simulation results, as presented in Figure 3, illustrate the production history of the well, which can be divided into two phases. The initial phase of single-phase water flow lasted for almost a year, followed by a subsequent phase of two-phase gas and water flow. Water production continued to rise until it peaked in 2053. The average water and gas saturation in the coal seam and the overlying formation were displayed in Figure 4. The average water saturation in the coal section remained almost constant throughout the simulation period, as water from the underlying formation replenished the water produced by the coal section. However, the average water saturation in the overlying deposit declined rapidly over time. The efficiency of the dewatering process was limited due to the cross-flow of water between the coal and the neighboring formation, which restricted gas production.

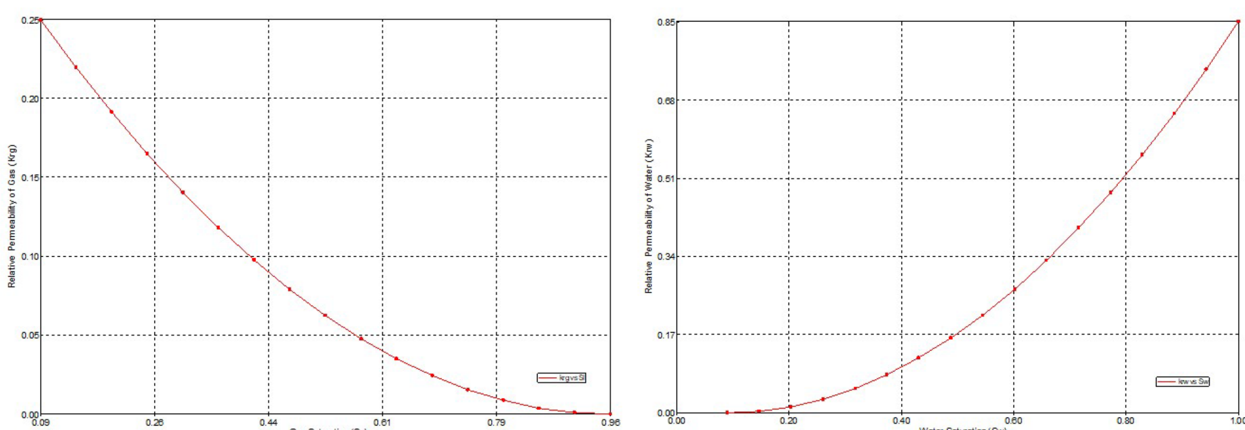

Fig. 3. Case 1: water and gas production profiles generated by reservoir simulation.

Initially, the high saturation of water in the coalbed causes a decrease in the relative permeability of gas, which leads to low rates of gas production. However, as the overlying formation becomes depleted, the average water saturation in the coal remains stable, as depicted in Figure 4. An abrupt increase in the rate of gas production may indicate a reduction in cross-formational flow, suggesting that the dewatering process has become more efficient.

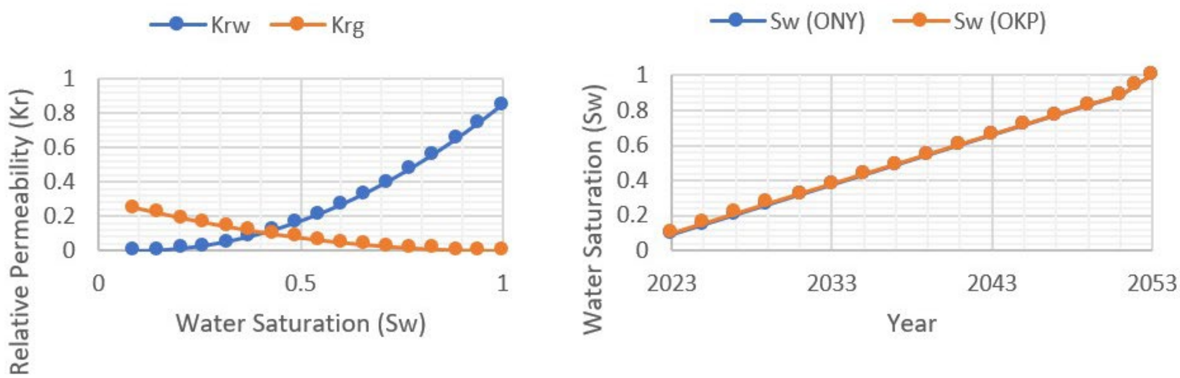

Fig. 4. Derived water and gas relative permeability plots from production data for Case 1 (ONY) comparison with Case 2 (OKP).

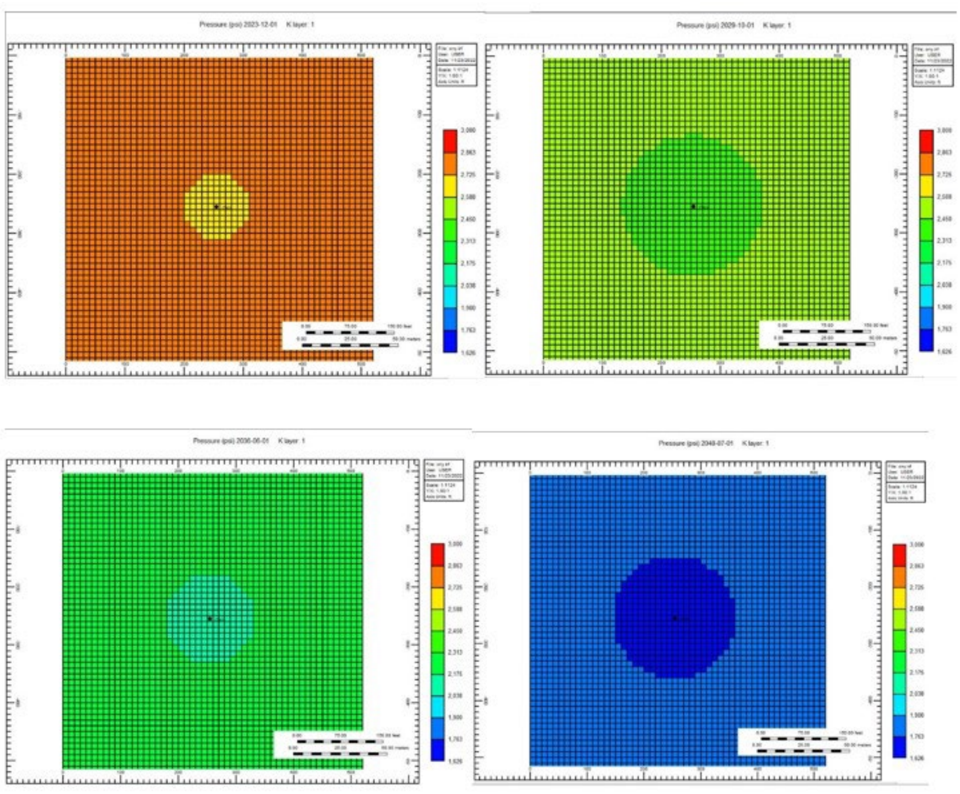

Fig. 5. Variations of gas saturation in the overlying formation for Case 1.

Fig. 5 depicts the variations in gas saturation in the underlying formation throughout the first year of production and select subsequent years. Because of the hydraulic connectedness between the coalbed and the overlaying formation, there is a large rise in gas saturation with time, enabling fluid movement in both directions. Desorbed gas replaces the water produced as it flows towards the coal layer, eventually flooding the top formation with gas after the water is depleted. Gas migration to the underlying deposit can influence production and have environmental repercussions. Nevertheless, the thief zone has little impact on the production profile because of the storage capacity and low pressure of the underlying deposit. As the contact zone may extend to freshwater aquifers, the environmental consequences of gas migration to neighbouring formations are more severe. Hence, anytime cross-flow is expected, it is crucial to undertake a hydraulic connectivity study in coal seams.

The simulated data generated a total of 4.5 x 108 SCF of gas and 40227 STB of water. The relative permeability curve in CBM reservoirs can vary considerably, and it can be influenced by different factors such as net stress, changes in porosity, viscous fingering, and buoyancy. To obtain water and gas relative permeability plots from simulated two-phase flow production data, the approach shown in Fig. 2 was followed. This study aimed to address the effect of cross-flow on the derived relative permeability plots, and the input and derived relative permeability plots were compared in Fig. 4. The difference between the two plots was due to the computation of the wetting phase saturation using cumulative water production, which takes into account the volume of water produced by both the coal and the overlying formations. When there is no cross-formational flow present, the relative permeability plots have an irregular shape, with the water relative permeability plot being concave downward because of the excessive volume of water produced by the formation above it. The gas relative permeability plot remains low but increases slightly at an average water saturation of approximately 45%, as the relative permeability plot for water is concave downward because the formation above it produces a considerable amount of water.

The findings of this study revealed that parameters of the coal seam, such as relative permeability plots and cleat porosity derived from PDA, cannot be deemed reliable if there is no hydraulic connection between the coalbed and the adjacent formation. The impact of cross-flow on the reservoir variables can be observed in this study due to significant water flow from the overlying formation. The degree of influence that cross-flow has on the computed reservoir characteristics is directly related to the amount of water flowing in from an external source. Through a case study, the study provides an in-depth analysis of the effects of low-intensity cross-flow on production performance and data processing. Furthermore, when only a small amount of external water enters the coalbed, the impact of cross-flow on the output profile is less significant.

3.2. Case 2 (OKP)

In this scenario, the porosity of the formation underneath decreased from 0.06% to 0.04%, leading to a reduced capacity for water storage. Consequently, the overall water production decreased, and the impact of cross-formational flow was also reduced. The results are illustrated in Fig. 6, which shows both gas and water production. The water production profile was similar to that of a bounded well in an undersaturated CBM reservoir, where the effect of cross-flow on the water production profile was indistinguishable. As depicted in Fig. 7, the water saturation of the coalbed decreased more quickly, resulting in a higher degree of gas mobility. Peak gas production occurred earlier, and the gas production rate reached its maximum level. Compared to Case 1, the total gas in situ increased to 5.3 x 108 SFC/ton while the total water in place decreased to 50795 STB, indicating a decrease in water and an increase in gas.

The acquired water and gas relative permeability plots from production data were compared with the initial plots in Fig. 7. It was observed that the influence of cross-flow on the calculated relative permeability plots was much less apparent compared to the first scenario, in which a substantial amount of water was provided from an external source. The cross-flow was responsible for two critical properties in the relative permeability plots shown in Fig. 7: first, the water relative permeability plot was almost linear, and second, there was a highly critical gas saturation along the gas relative permeability plot. It is important to note that these properties are unique to the cross-flow effect and do not reflect the fluid flow characteristics of the coal formation. Fig. 8 illustrates the changes in gas saturation in the overlying formation during the first year and selected subsequent years of production, showing a gradual increase at the beginning and a decline towards the end of the selected year.

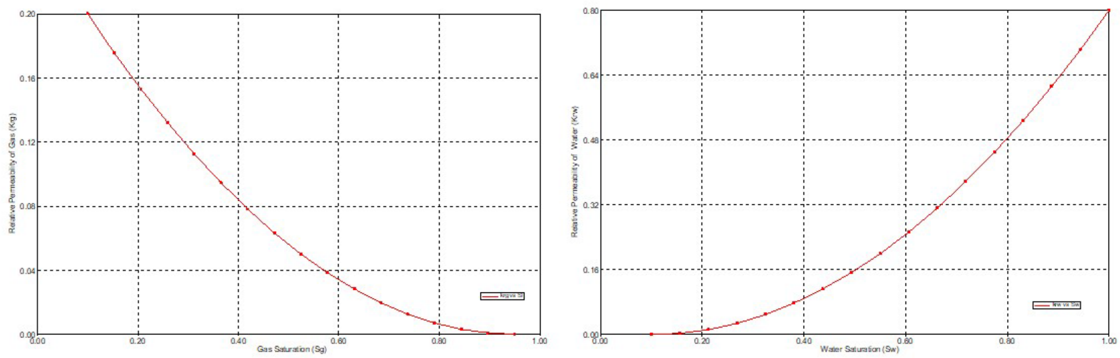

Fig. 6. Case 2. Water and gas production profiles generated from reservoir simulation.

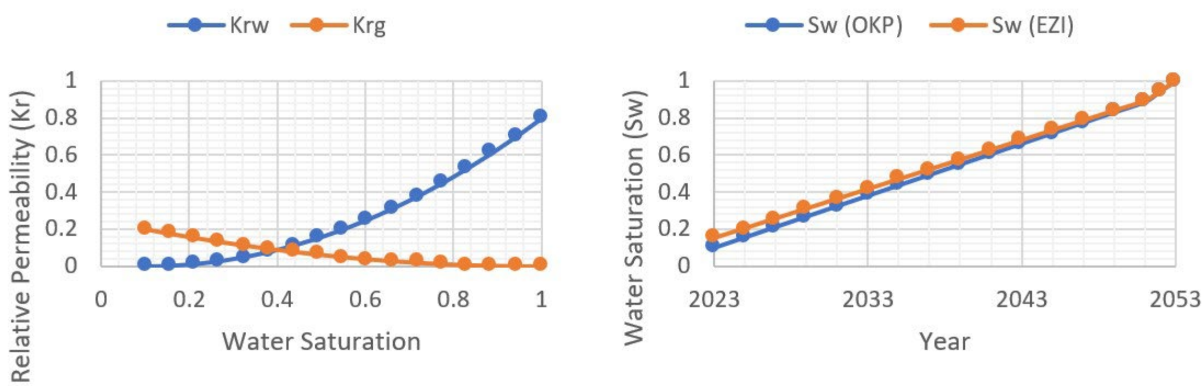

Fig. 7. Derived water and gas relative permeability plots from production data for Case 2 (OKP) comparison with Case 3 (EZI).

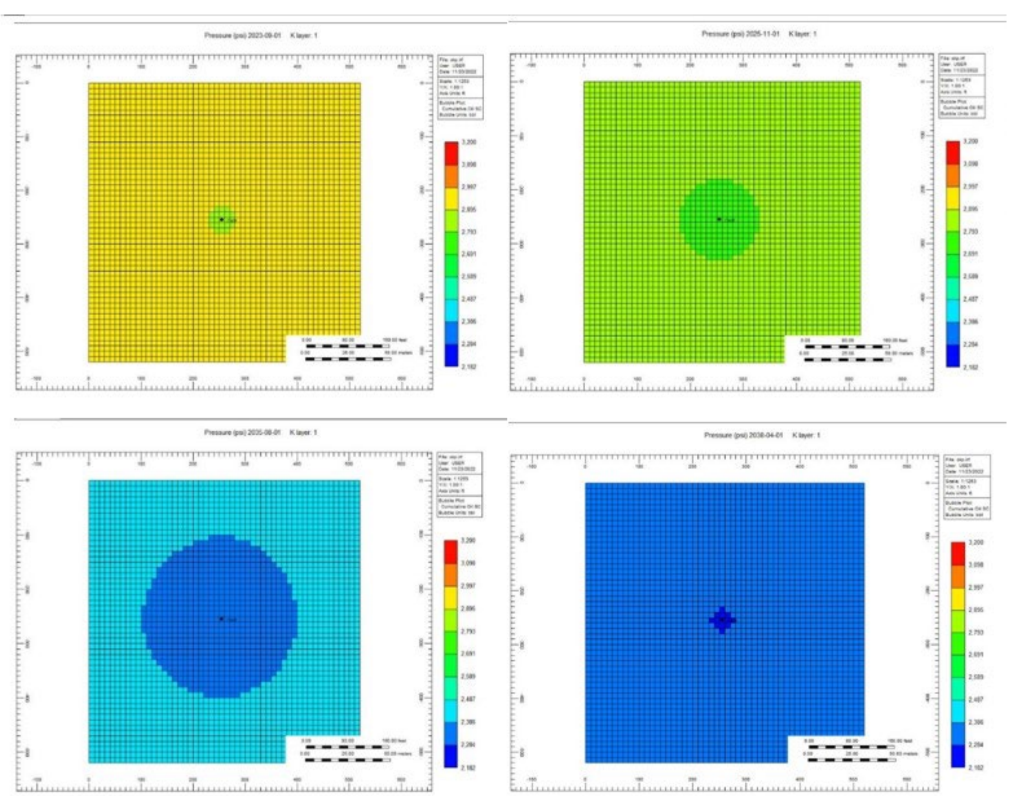

Fig. 8 Variations of gas saturation in the overlying formation for Case 2.

The relative permeability plots presented in Fig. 7 exhibit a resemblance to those observed in prior coal studies [15,22]. Consequently, the effect of cross-flow on the estimated relative permeability plots can be ignored. However, when determining relative permeability plots using similar geometries as used in this investigation, it is important to examine the local groundwater hydrology.

3.3. Case 3 (EZI)

In this case, there was a concomitant increase in permeability and cross-formational flow. While the permeability of coal is affected by both pressure and desorption, the other reservoir parameters remain constant, as in the previous scenario. To account for the impacts of matrix shrinkage and compaction on coal permeability, the Palmer-Mansoori model was utilized. Table 2 shows the parameters used in this model.

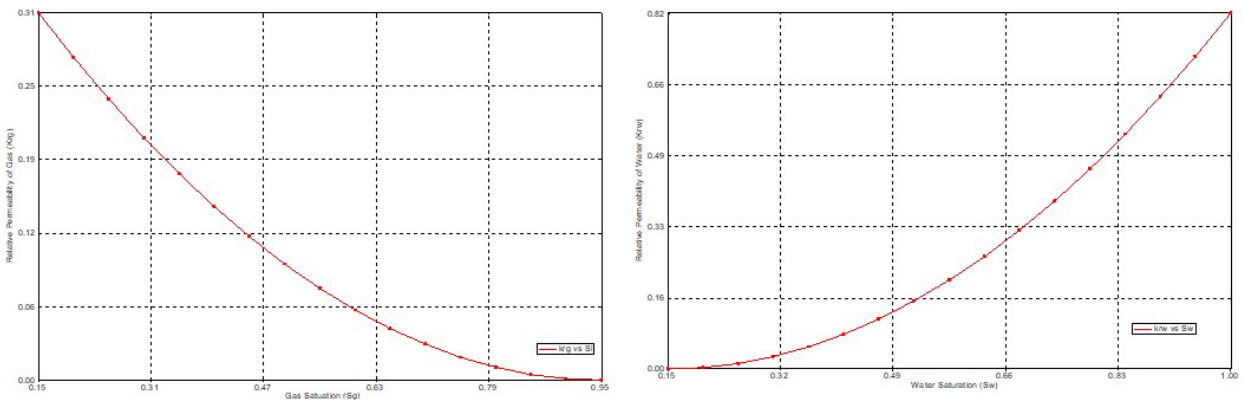

Fig. 9. Case 3: gas and water production profiles generated by reservoir simulation.

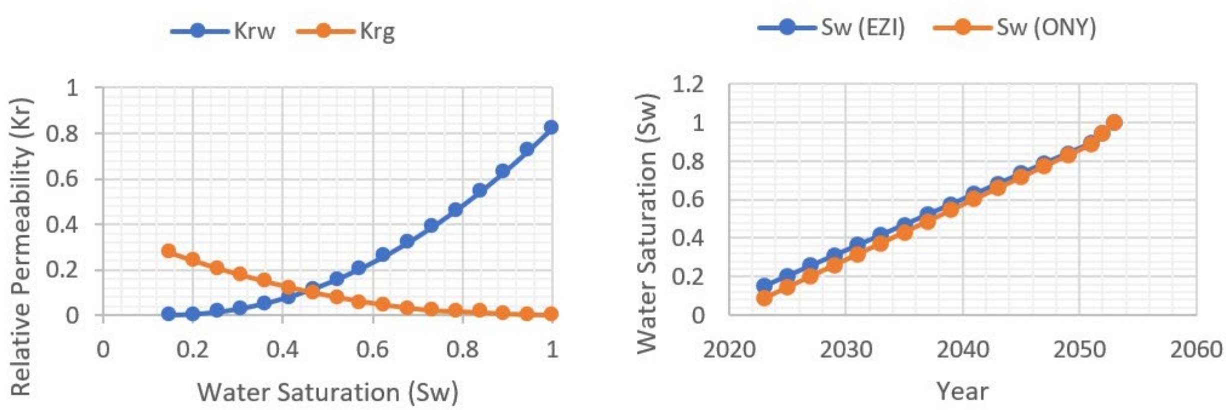

Figure 10. Derived water and gas relative permeability plots from production data for Case 3 (EZI) comparison with Case 1 (ONY).

Fig. 9 illustrates the difference between the first and second cases, where coal permeability is constant and dynamic, respectively. The latter is due to matrix shrinkage and pore pressure, which affect coal permeability, and all other reservoir parameters are the same as in the first scenario. As shown in Fig. 9, coal permeability rapidly increases from the start of production in the second scenario, resulting in increased water depletion and a constant water production rate over time. The concave-downward shape of the original water production profile indicates a positive correlation between higher permeability and water output. In Fig. 10, it is shown that water depletion occurs at a faster rate in both the overlying and coal layers in the second scenario compared to the first, indicating that permeability improvement contributes to water depletion. Additionally, Fig. 10 displays the temporal variation in horizontal coal permeability, which is influenced by matrix shrinkage and cleat compaction. As production progresses, the coal becomes more permeable in both vertical and horizontal directions, which strengthens the hydraulic connection between the coal deposit and the overlying formation.

The second case shows an increase in gas and a decrease in water as compared to case one, with a total gas in place of 4.6 x 108 SFC/ton and a total water in place of 79428 STB. As shown in Figure 11, the changes in gas saturation in the overlying formation during the first year and subsequent years of production display a gradual increase at the beginning and a slight decline at the end of the selected year. This scenario demonstrates that permeability enhancement affects the time to reach the peak of gas production and the peak of gas production itself. It encourages water and gas production from both the overlying formation and the coal beds, which are conflicting factors in the economic feasibility of CBM wells.

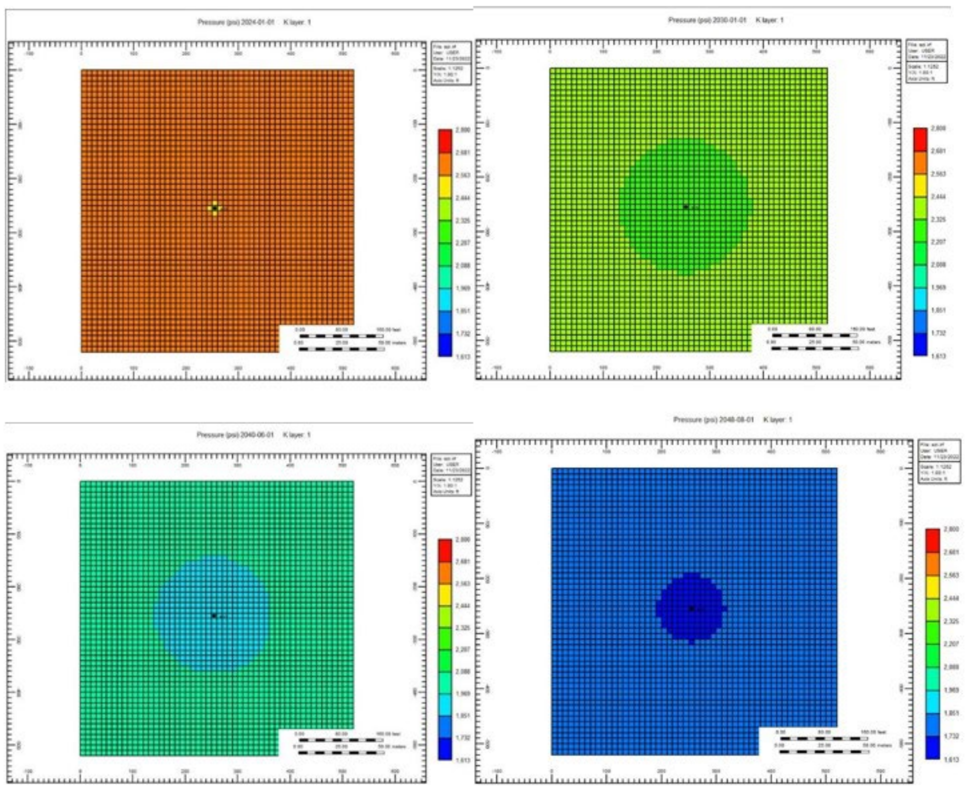

Fig. 11. Variations of gas saturation in the overlying formation for Case 3.

4. Conclusion and recommendations

Based on the simulation results, CBM wells located in contact zones can produce significant amounts of water, and the production rate is dependent on the level of connectivity between the coal beds and the adjacent strata. The presence of water in the coal bed, maintained by the cross-flow of water, can delay peak gas production. However, as the water in the adjacent formation linked to the coalbed gets depleted, the water saturation in the coal will decrease. The total water in place ranges from 40227 to 79428 STB, and the total gas in place ranges from 4.5 x 108 to 5.3 x 108 SFC/ton in the cases studied.

Furthermore, the study found that cross-formational water flow from an external source into a producing coal bed could significantly affect the interpretation of reservoir parameters and dynamics as well as production data computations. Neglecting cross-flow can lead to an overestimation of the estimated cleat porosity from cumulative water production data. Moreover, the water and gas relative permeability plots derived from the simulated production data were found to be different from the initial plots, with distinct properties. A concave downward relative permeability was observed due to excessive water flow from an external source into the coal. The gas's relative permeability was low for a specific water saturation range, followed by a rapid increase, and then another decrease. Even after history matching, assuming that all flow originates from the coalbed can lead to erroneous relative permeability plots, which are often used as parameters for history matching.

Finally, to prevent environmental issues and optimize production efficiency in future field development plans, it is advisable to conduct hydraulic connectivity evaluation using zone isolation tests or well logs when cross-flow is suspected. This assessment will help confirm the level and intensity of hydraulic interaction in the area.

Availability of data and material: *Data are available upon request*

Competing interests: *The authors declare that there are no conflicting interests regard this manuscript.*

Authors' contributions: *VF and EA: Proposed and conceptualized the title of the manuscript, sourced information, wrote the main text and created a thorough structure for the manuscript. SO, KE and PO: Reviewed, proofread and edited the manuscript text. The final manuscript has been read and approved by all of the authors.*

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