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INCREASING THE ACCURACY OF OIL RECOVERY FACTOR PREDICTIONS BY INTEGRATING LITHOLOGY DATA

The object of research in the paper is the process of oil extraction during flooding. The Buckley-Leverett method, which is widely used to estimate oil production in flooding, has certain limitations that lead to uncertainty in the results. This paper proposes to extend the Buckley-Leverett algorithm by integrating lithological data. This approach allows to take into account the influence of geological characteristics of the formation on the process of displacement of oil by water, which leads to a significant increase in the accuracy of forecasting the oil production coefficient. The effectiveness of the proposed method is confirmed on the basis of data analysis of a real oil field.

The methodology for calculating the oil recovery coefficient during flooding using lithological dissection is presented. In this work, the steps of determining the oil recovery coefficient were analytically determined, which achieves a certain degree of accuracy due to the inclusion of the lithological characteristics of the permeable zone of the formation. The basic calculation of the lithological distribution over the layer was performed using the Kriging method. To confirm the accuracy of the Buckley-Leverett method, taking into account lithological dissection, the use of data analysis, including an experimental histogram and a theoretical normal distribution plot, is proposed. For data analysis, one hundred cases of lithological distribution were generated using the Sequential Indicator Simulation method.

The comparative analysis of the data of the experimental histogram and the theoretical graph of the normal distribution of the determination of oil recovery coefficients by the Buckley-Leverett method for cases with and without lithological dismemberment allows to quantitatively assess the accuracy of both studied options. On the basis of a real oil field, it is shown that the accuracy of oil recovery coefficients by the Buckley-Leverett method, taking into account lithological fragmentation, exceeds the similar method without taking into account lithological fragmentation by 11 %.

Keywords: *oil recovery coefficient, Buckley-Leverett method, waterflooding, fractional flow curves, oil production, lithofacies data.*

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1. Introduction

Engineers tasked with estimating the oil recovery rate by waterflooding must achieve an accuracy that corresponds to future results [1, 2]. The problem is to determine the amount of oil reserves available for extraction accurately. In practice, discrepancies between forecast values and actual production rates are often observed, which requires a more detailed approach.

This problem arises due to insufficient consideration of important factors in the calculations of the oil recovery coefficient during waterflooding by the Buckley-Leverett method. The use of average values of properties throughout the reservoir leads to ambiguity in predicting the results of oil extraction [3, 4]. The lack of consideration of lithofacies distribution, which requires the determination of properties for each facies, including porosity, permeability, clay content, residual water saturation, residual oil saturation, and oil saturation, limits the understanding of reservoir dynamics and prevents accurate modeling of fluid mass transfer [5]. To solve this problem, the use of the representative elementary volume (REV) is proposed, which allows for determining the number of samples that will be satisfactory for a representative display of the properties of the represented facies in the formation [3]. It is also important to consider relative permeabilities, which are necessary for calculating the oil recovery coefficient using the Buckley-Leverett method, because the standard method does not provide for their determination in Ukraine [6–8]. The solution to this problem can be the application of the methodology that uses the properties provided by the Ukrainian standard, namely residual water saturation and residual oil saturation, for the construction of relative permeability curves. An oil recovery screening methodology using these properties allows the construction of relative permeability curves, taking into account lithofacies diversity as well as a qualitatively representative display of properties for each facies. This methodology contributes to the improvement of the three-dimensional hydrodynamic model, reduces the degree of uncertainty of reservoir properties [5].

The actual task is the application of the oil recovery screening methodology, considering innovative approaches and comparing the accuracy of the Buckley-Leveret method with and without considering the facies distribution. Using the example of a real field using innovative approaches, it is possible to evaluate the impact of facies segmentation on the results of determining the oil recovery coefficient during waterflooding. Since the facies segmentation significantly affects the structure of the permeable part of the formation, its understanding is critically important for determining the properties of each facies and the number of necessary samples for their representative representation [9–11].

The main task of this study is to quantitatively assess the impact of facial dismemberment of the permeable part of the formation compared with the use of averaged properties over the entire permeable zone of the formation. The implementation of this task consists in the generation of random scenarios of facial distribution, as well as in the generation of random scenarios of permeable and impermeable zones in the absence of facial distribution. The estimation of oil recovery coefficients during waterflooding by the Buckley-Leverett method based on the generated scenarios in the case of facial dismemberment and without it was performed due to data analysis, using an experimental histogram and a theoretical normal distribution graph. Taking into account the lithological segmentation in the determination of the oil recovery coefficient during waterflooding will allow to obtain a more reliable three-dimensional hydrodynamic model, reduce the degree of uncertainty of reservoir properties [12].

This research entails the acquisition of supplementary core material, underscores the significance of dissecting lithofacies, and is incorporated in a three-dimensional framework. This integration enables the modeling of ongoing processes, reaffirms the suggested methodology, and enables precise forecasting. The impact of these accomplishments extends beyond theoretical realms and influences practical reservoir management strategies [5].

Thus, the *object of research* is the process of oil extraction during waterflooding.

And the *aim of research is* to enhance the accuracy of determining the oil displacement factor during waterflooding by analyzing the lithological distribution of the permeable section of the reservoir.

2. Materials and Methods

To check the accuracy of determining the oil recovery coefficient during waterflooding by the Buckley-Leverett method taking into account the facies distribution in comparison with the similar method without taking into account the facies distribution, two scenarios of modeling the random lithological distribution with and without taking into account the facies distribution were developed, which are shown in Table 1.

An actual deposit was used to create a three-dimensional model. The initial data involved core data and the geophysical interpretation of logging diagrams. To ensure more reliable results and to assess the accuracy of the calculated oil recovery coefficients during waterflooding, the maximum number of wells available for the considered area and license area was taken into account based on the random distribution of facies and zones [14–16].

It is crucial to emphasize that the evaluation of how the spreading of the rock layers in a reservoir affects the amount of oil that can be recovered is not dependent on the quality of the data being studied. It is necessary to take into account how the division of the rock layers impacts the accuracy, regardless of the quality of the data. However, when examining the accuracy of assessing the distribution of rock layers for a specific oil reservoir, the quality and quantity of available data for that reservoir might influence the precision of the evaluation.

Table 1

Methodology for modeling random lithological distribution for determining the oil recovery coefficient during waterflooding by the Buckley-Leverett method

Taking into account the facial distribution	Excluding facial distribution
1. Creation of a three-dimensional model of the deposit with geophysical interpretation, in which the lithological dismemberment in the wells is reflected in a wide spectrum	
2. Generate one hundred cases of lithological distribution between wells for a wide range of lithological fragmentation in wells using the Sequential indicator simulation method	2. To calculate a new geophysical interpretation with the help of limit values of properties, for permeable and impermeable zones of lithology
3. For one hundred cases, generate the distribution of properties with reference to the facial distribution of each case using the Truncated Gaussian Simulation method	3. On the basis of the new geophysical interpretation of permeable and impermeable zones of the reservoir, generate one hundred cases of the spread of zones between wells using the Sequential indicator simulation method
4. For one hundred generated cases, separate the impermeable zones of the reservoir using the limit values of the properties, leaving the lithological distribution in the permeable zone	4. For one hundred cases, generate the distribution of properties with reference to the distribution of permeable and impervious zones of each case using the Truncated Gaussian Simulation method
5. Based on the generated one hundred cases of lithological distribution, calculate one hundred oil recovery coefficients during waterflooding based on the oil recovery screening methodology taking into account innovative approaches [5]	5. On the basis of the generated one hundred cases of the spread of permeable and impermeable zones, calculate, respectively, one hundred coefficients of oil extraction during waterflooding based on the methodology of oil extraction screening, taking into account innovative approaches [5]
6. From the one hundred obtained coefficients of oil extraction during waterflooding, taking into account the lithological distribution, analyze the data by constructing an experimental histogram and a theoretical normal distribution graph	6. From the hundred obtained coefficients of oil extraction during waterflooding, taking into account permeable and impermeable zones, conduct data analysis by constructing an experimental histogram and a theoretical normal distribution graph
7. To compare the obtained experimental histograms and theoretical graphs of the normal distribution of both scenarios, taking into account the lithological distribution and without. On the basis of the defined sampling standards according to the «68–95–99.7» rule, calculate the difference in the accuracy of the oil recovery coefficient with and without facies distribution [13]	

The geophysical interpretation of the log charts and core data helped calculate the lithological segmentation in the well. To implement a plan that takes into account the lithological distribution of the formation, it's important to identify permeable and impermeable zones within the formation. This requires using limit values for geological and geophysical parameters, determined by laboratory studies of core material, geophysical well studies (GDS), and testing of the deposit. The limit values for parameters such as porosity, permeability, and clay content are 0.1, 0.4, and 1 fm^2, respectively. By using these boundary properties to calculate logging diagrams, the formation can be divided into permeable and non-permeable zones in the well. These zones will later be used to calculate the oil recovery coefficient during waterflooding without facial dissection.

The next step involves generating one hundred cases of lithological distribution between wells, as well as one hundred cases of permeable and impermeable zone distribution between wells. Both distribution scenarios for lithology and zones utilized the Sequential Indicator Simulation (SIS) method.

Sequential Indicator Simulation (SIS) is a technique used to model discrete variables like lithofacies or geological units. It takes into account the spatial correlation between data points and generates multiple realizations of the categorical variable. This method involves simulating the conditional probabilities of different categories at unsampled locations based on neighboring data values. SIS works by sequentially conditioning the simulation on neighboring data points, ensuring that the simulated realizations respect the spatial distribution and patterns observed in the input data [17].

In order to proceed, it is necessary to generate a set of properties including porosity, permeability, clay content, and water saturation for each lithological and zonal distribution case. These properties are then linked to specific facies and zones. The distribution of properties with respect to lithology and zones was determined using the Truncated Gaussian Simulation method (TGS) [18].

TGS is a simulation method used to model continuous variables like porosity, permeability, or saturation. It assumes that the variable follows a Gaussian (normal) distribution and takes into account both the mean and variance of the input data. TGS uses a Gaussian random field model to create multiple realizations of the continuous variable while maintaining the statistical characteristics of the input data. The term «truncated» means that the Gaussian distribution is limited within predetermined bounds, usually defined by the minimum and maximum values observed in the dataset. TGS does not directly handle categorical data, but it can be used to model continuous variables within specific lithofacies or geological units delineated using SIS or other methods.

In the previous analysis, boundary value conditions were applied to simulate the propagation of one hundred cases of permeable and impermeable zones. Now, it is necessary to apply boundary values to consider lithological fragmentation in the scenario. This involves applying similar limit values for geological and geophysical parameters to the properties related to lithofacies that have already been generated. As a result, it is possible to consider both scenarios – lithological fragmentation and the division into permeable and impermeable zones – to be balanced at this stage.

The oil recovery screening methodology entails performing laboratory studies to calculate the oil recovery coefficient during waterflooding, utilizing the Buckley-Leverett method. When dealing with distributed permeable and impermeable zones, the oil recovery coefficient remains consistent and is implemented for the permeable zone. In situations involving lithologic distribution, a weighted average oil recovery rate is applied to the facies that satisfy the boundary value condition.

The next step involves mapping out two scenarios: lithological dissection and partitioning into permeable and impermeable zones through data analysis. For both scenarios, it is possible to create experimental histograms and theoretical normal distribution graphs using one hundred oil recovery coefficients during Buckley-Leveret waterflooding with and without facies dissection. Additionally, it is possible to calculate the median and sample standard deviation for these graphs.

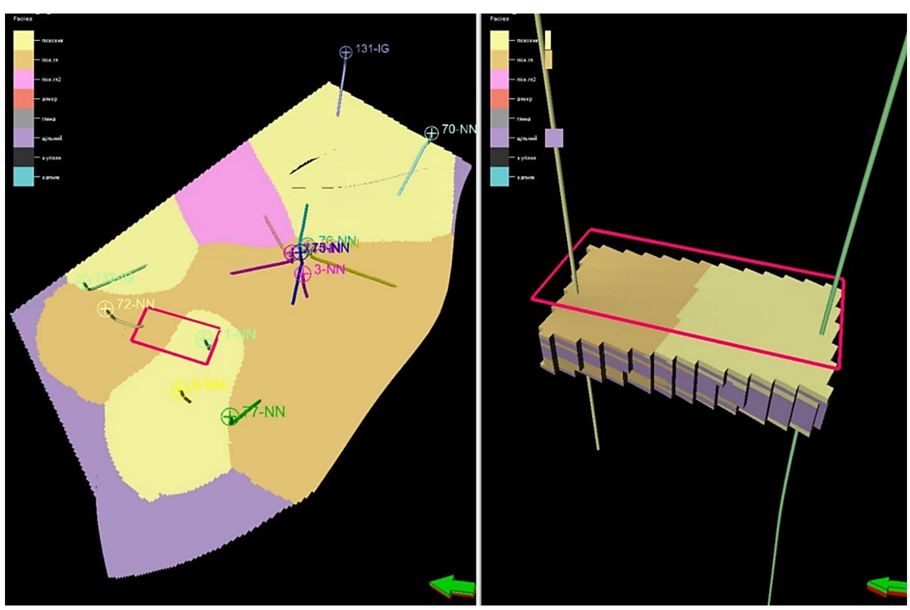
In order to compare the accuracy of the studied scenarios, such as lithological dissection and distribution into permeable and impervious zones, the «68–95–99.7» rule, also known as the empirical rule, was used. This rule helps estimate the percentage of values within certain intervals in a normal distribution: around 68 %, 95 %, and 99.7 % of the values are within one, two, and three standard deviations from the mean, respectively [13].

Kriging is a geostatistical interpolation method that provides the best linear unbiased prediction of the spatial variable. It can be applied to both continuous and categorical data. The primary goal is to estimate the value of a variable at unsampled locations based on observed data, considering the spatial correlation [19–21].

It is essential to calculate the waterflooding oil recovery coefficient using the Kriging method because it is a constant, rather than random value. This coefficient can be utilized in hydrodynamic modeling as the average of the most probable value of the waterflooding oil recovery coefficient.

3. Results and Discussion

The methodology outlined in this study was tested using a real oil field as an example. Specifically, a three-dimensional model of the V-16n horizon was simulated. Based on geophysical studies and core samples from the formation, the following facies classification was identified: sandstone, clayey sandstone, and siltstone. The Kriging method was employed to calculate the average waterflooding oil recovery rate for two scenarios based on facies distribution and zones. Using this information, a section with two wells, one for injection and the other for extraction, was identified (Fig. 1).



a *b*

Fig. 1. Map of the distribution of lithology using the Kriging method (*a*) and a selected fragment with two wells (*b*)

The Kriging properties were generated for both scenarios with reference to lithology and zones, respectively.

To calculate the oil recovery coefficient during waterflooding using the Buckley-Leverett method for two scenarios – with and without lithological fragmentation, let's apply the oil recovery screening methodology, considering innovative approaches [5]. This methodology enabled to conduct the required laboratory studies and construct fractional flow curves for both scenarios (Fig. 2).

According to the fractional flow curves, the oil recovery coefficient is calculated using the following formula:

$$RF = \frac{\bar{S}_w - S_{wi}}{1 - S_{wi}}, \quad (1)$$

where RF – oil recovery factor; $\bar{S}_w$ – water saturation to which the intersection of the tangent line with the upper limit of relative permeability corresponds; S_{wi} – initial water saturation [11, 12].

In the lithological distribution scenario, the oil recovery coefficient will be calculated as the weighted average of all oil recovery coefficients using formula:

$$\overline{RF} = \frac{\sum_{i=1}^{n} RF_i \cdot v_i}{\sum_{i=1}^{n} v_i}, \quad (2)$$

where $\overline{RF}$ – the average value of the oil recovery coefficient by facies; ν – percentage of the volume of the facies in the rock [5].

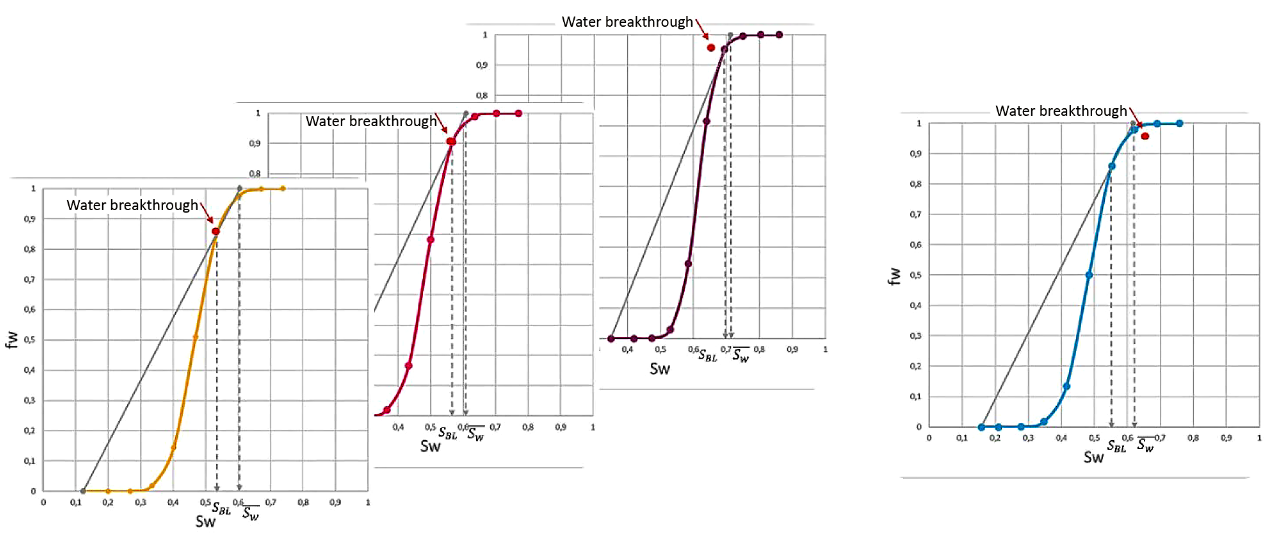
Hydrodynamic modeling was conducted using Eclipse software for two scenarios: lithological dissection and distribution into permeable and impermeable zones, employing the Kriging propagation method. The results are presented in Table 2.

In order to assess the accuracy of determining the oil recovery coefficient during waterflooding using the Buckley-Leverett method considering facies distribution, it is possible to compare it with the method that does not take into account facies distribution. One hundred cases for both scenarios and a segment with injection and extraction wells for all cases were identified (Fig. 3). For each case, it is possible to calculate the oil extraction coefficients using the Buckley-Leverett method with and without facies distribution. The results allowed to create experimental histograms and theoretical normal distribution graphs for both scenarios, with and without consideration for lithological distribution (Fig. 4).

The «68–95–99.7» rule were used to compare the accuracy of different methods with and without lithological segmentation. The medians and sample standards for both scenarios were calculated. The sample standards for the Buckley-Leveret method with and without lithological segmentation are 0.022 and 0.025, respectively. Taking lithological segmentation into account, the accuracy of the Buckley-Leveret method is 11 % higher compared to the method without lithological segmentation. This highlights the importance of considering lithological segmentation when estimating oil recovery rates during waterflooding.

The limitation of this research is the use of the proposed method exclusively for calculating the oil recovery coefficient during flooding using lithological dissection.

The conditions of martial law in Ukraine did not affect the conduct of the research and the results obtained.



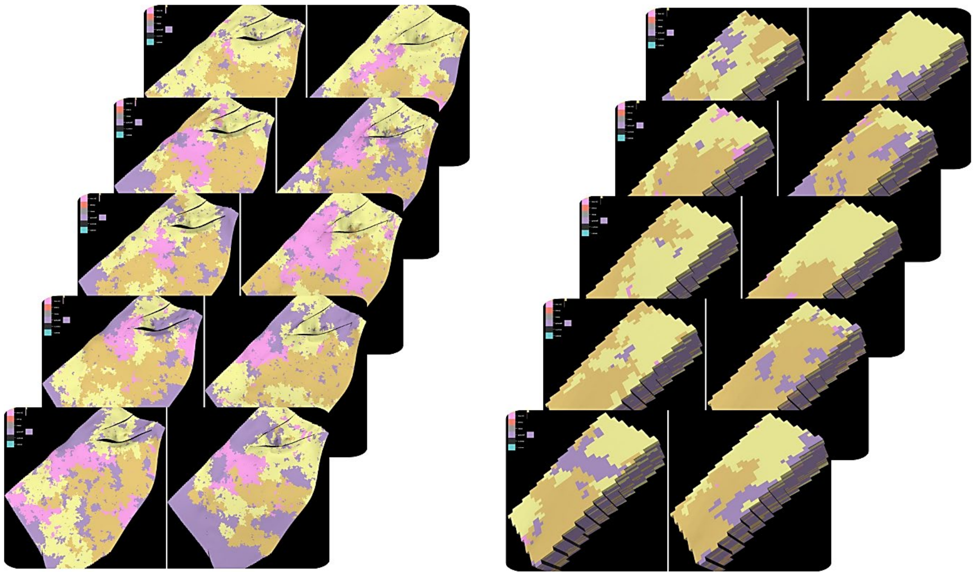
a *b*

Fig. 2. Curves of fractional fluxes for two scenarios, with and without consideration of facies diffusion: *a* – curves of fractional flows for facies sandstone, clayey sandstone, siltstone; *b* – curve of fractional flows for the permeable zone of the reservoir

Table 2

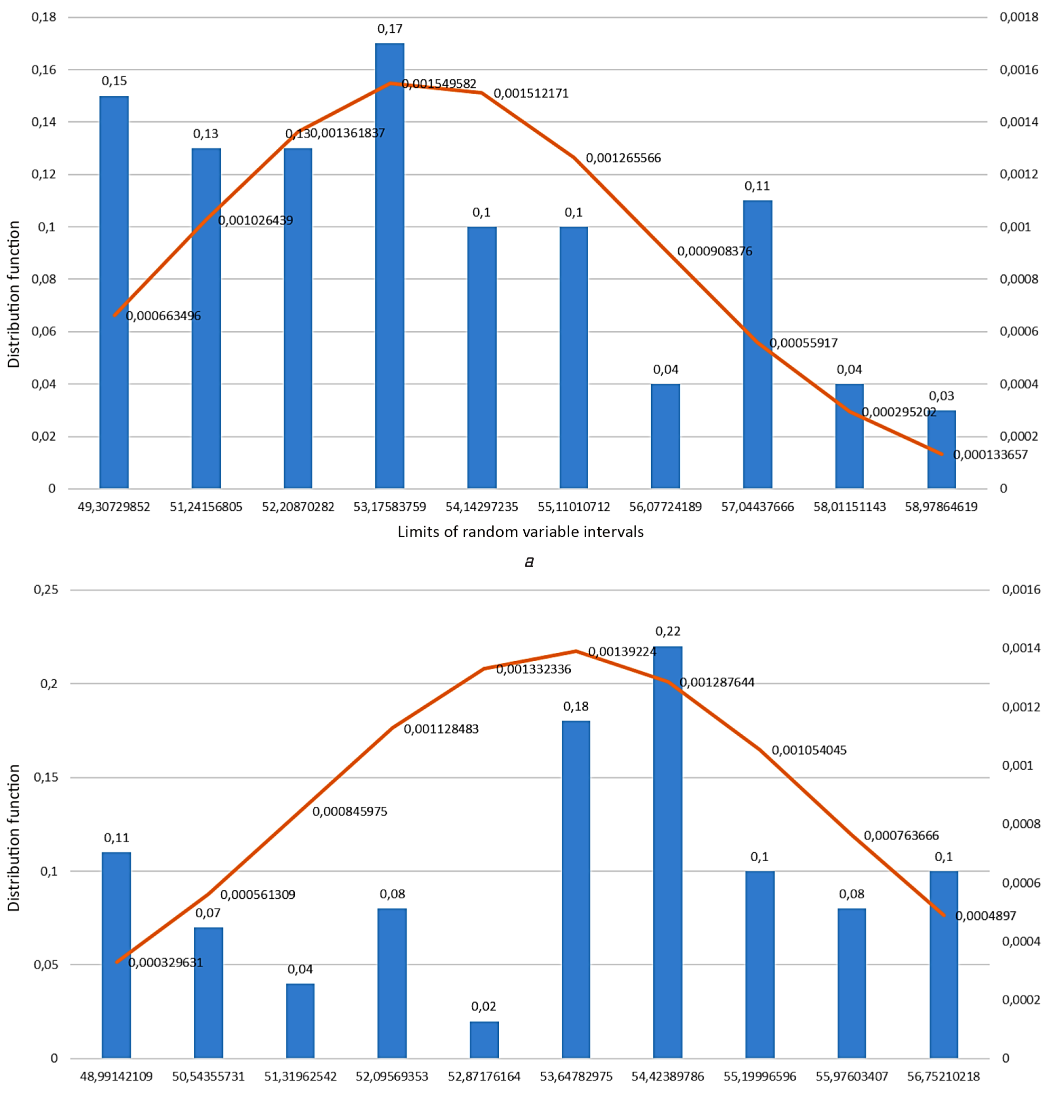
Oil recovery coefficients by the Buckley-Leverett method and hydrodynamic modeling with and without facies spreading

Coefficient of oil recovery during waterflooding	Taking into account the facial distribution	Excluding facial distribution
Buckley-Leverett method	0.54	0.539
Hydrodynamic model of segment	0.525	0.527



a *b*

Fig. 3. Generated cases of lithological distribution along the reservoir: *a* – using the Sequential Indicator Simulation method; *b* – separated segments



b

Fig. 4. Experimental histograms and theoretical graphs of the normal distribution: *a* – with consideration of lithological distribution; *b* – without consideration of lithological distribution

4. Conclusions

The study explores the process of oil recovery through waterflooding by using the Buckley-Leverett method. This method is widely used but has certain limitations that can lead to uncertainty in the results. To address these limitations, the proposal is to enhance the Buckley-Leverett algorithm by incorporating lithofacies data. This will enable the consideration of the influence of geological characteristics of the formation on the displacement of oil by water. This approach significantly improves the accuracy of predicting the rate of oil production.

The method proposed for calculating the oil recovery coefficient during waterflooding uses lithofacies distribution, which is calculated using the Kriging method. Data analysis, including an experimental histogram and a theoretical normal distribution plot, was used to confirm the accuracy of the Buckley-Leverett method, taking into account the facial distribution. One hundred lithological distribution cases were analyzed using the Sequential Indicator Simulation method.

The experimental histogram and the theoretical normal distribution graph were compared to quantitatively assess the accuracy of the Buckley-Leverett method, with and without facial spreading. The results indicated that incorporating the lithological characteristics of the formation's permeable zone improves the accuracy of predicting oil recovery coefficients by 11 %.

The proposed approach integrates lithofacies data into the Buckley-Leverett method, leading to significantly improved accuracy in oil production forecasting. This improvement has been confirmed by real oil field data, making the method more reliable for practical application in various geological conditions.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

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Availability of data

Data will be made available upon request within a reasonable scope.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating this work.

References

1. Cvetkovic, B. (2009). *Well Production Decline*. Available at: https://www.semanticscholar.org/paper/Well-Production-Decline-Cvetkovi%C4%87/7a541f814c78fa6579b510db902cb958b9a3eab0
2. Blunt, M. J. (2017). *Multiphase flow in permeable media: A pore-scale perspective*. Cambridge university press. doi: https://doi.org/10.1017/9781316145098
3. Martus, O., Petrash, O. (2022). Improved methodology development for assessing the reservoir collector properties by the quantitative reservoir characterization tools. *Technology Audit and Production Reserves, 4 (1 (66)),* 42–46. doi: https://doi.org/10.15587/2706-5448.2022.263640
4. Martus, O., Agarkov, V. (2022). Development of improved method for evaluation of reservoir properties of formation. *Technology Audit and Production Reserves, 5 (1 (67)),* 33–37. doi: https://doi.org/10.15587/2706-5448.2022.266572
5. Martus, O., Cvetkovic, B. (2023). Development of oil extraction screening methodology taking into account innovative methods using the example of the Ukrainian field. *Technology Audit and Production Reserves, 6 (1 (74)),* 47–53. doi: https://doi.org/10.15587/2706-5448.2023.294081
6. Leverett, M. C. (1941). Capillary Behavior in Porous Solids. *Transactions of the AIME, 142 (1), 152*–169. doi: https://doi.org/10.2118/941152-g
7. Buckley, S. E., Leverett, M. C. (1942). Mechanism of Fluid Displacement in Sands. *Transactions of the AIME, 146 (1),* 107–116. doi: https://doi.org/10.2118/942107-g
8. Willhite, G. P. (1986). *Waterflooding*. SPE Textbook Series. Richardson. doi: https://doi.org/10.2118/9781555630058
9. Singh, S. P., Kiel, O. G. (1982). *Waterflood design (pattern, rate, and timing)*. SPE International Oil and Gas Conference and Exhibition in China (SPE-10024). doi: https://doi.org/10.2523/10024-ms
10. Forrest, F., Craig, J. (1971). *The reservoir engineering aspects of waterflooding*. Society of Petroleum.
11. Langnes, G. L., Robertson Jr, J. O., Chilingar, G. V. (1972). *Secondary recovery and carbonate reservoirs*. American Elsevier Publishing Company, 304.
12. *Interstate Oil Compact Commission*. (1983). Improved Oil Recovery.
13. Huber, F. (2018). *A logical introduction to probability and induction*. Oxford University Press, 304.
14. Ringrose, P., Bentley, M. (2016). Upscaling Flow Properties. *Reservoir model design*. Germany: Springer, 115–149. doi: https://doi.org/10.1007/978-94-007-5497-3_4
15. Bear, J. (2013). *Dynamics of fluids in porous media*. Courier Corporation.
16. Lyons, W. (2010). *Working guide to reservoir engineering*. Gulf professional publishing. doi: https://doi.org/10.1016/c2009-0-30573-5
17. Mizuno, T., Deutsch, C. (2022). *Sequential indicator simulation (SIS)*.
18. Beucher, H., Renard, D. (2016). Truncated Gaussian and derived methods. *Comptes Rendus Geoscience, 348 (7),* 510–519. doi: https://doi.org/10.1016/j.crte.2015.10.004
19. Matheron, G. (1963). Principles of geostatistics. *Economic Geology, 58 (8),* 1246–1266. doi: https://doi.org/10.2113/gsecongeo.58.8.1246
20. Bohling, G. (2005). Introduction to geostatistics and variogram analysis. *Kansas geological survey, 1 (10),* 1–20.
21. Isaaks, E. H., Srivastava, R. M. (1990). *An Introduction to Applied Geostatistics*. Oxford University Press, 592. Available at: https://geostatisticslessons.com/pdfs/sequentialindicatorsim.pdf

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