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Development of a statistical model for predicting the presence of a hydrodynamic connection between production and injection wells and assessing its applicability

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Разработка статистической модели прогноза наличия гидродинамической связи добывающих и нагнетательных скважин и оценка ее применимости

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carbonate reservoir, complex reservoir, geological parameters, development parameters, viscosity, indicator studies, tracer studies, high-permeability channels, filtration flows, flooding, reservoir pressure maintenance system, distribution of injection volumes, fracturing, hydrodynamic studies of wells, linear discriminant analysis.

The problem of forecasting the hydrodynamic connection between the production and injection wells in the flooding area was considered according to the geological characteristics of wells according to hydrodynamic wells studies data and development indicators.
To create a model for predicting hydrodynamic communication, an analysis of the results of tracer studies of the Central uplift of the Tournaisian development object in the Upper Devonian-Tournaisian carbonate deposits was carried out. The tracer studies involved 5 injection wells and 17 production wells, sampling was carried out for 6 months. These studies served as a training sample. To assess the connectivity of producing wells and wells with reservoir pressure maintenance, the *dFP* parameter was proposed and calculated, which characterizes the degree of influence of an injection well on producing wells in the source. According to the calculated indicator *dFP*, the well pairs were divided into two classes: "poor hydrodynamic connectivity" ("PC") and "good hydrodynamic connectivity" ("GC").
Analysis of the average values of the considered reservoir characteristics and development indicators in classes using Student's t-test by class showed that out of 37 indicators, 7 differences were statistically significant.
When using the proposed classification in terms of *dFP* into classes "GC" and "PC", in 62 pairs of production and injection wells, a stepwise linear discriminant analysis (SLDA) was carried out in the training sample, which allowed obtaining the discriminant function *Z* for subsequent classification. The use of the obtained discriminant function and the calculated boundary value Z_{bound} on the training sample ensured the percentage of wells correctly assigned to the "GC" group - 82.1 %, for the "PC" group - 76.5 %. In general, the proportion of the correct distribution in the training sample groups was 79 %.
An analysis of the results obtained on a test sample for the adjacent West uplift in the Tournaisian deposits showed that the use of the discriminant function Z generally provided 75 % of the correct classification for all sources, which confirmed the possibility of using this model to predict hydrodynamic communication in the flood source.

Ключевые слова:
карбонатный коллектор, сложнопостроенная залежь, геологические параметры, параметры разработки, вязкость, индикаторные исследования, трассерные исследования, высокопроницаемые каналы, фильтрационные потоки, заводнение, система ППД, распределение объемов закачки, трещиноватость, гидродинамические исследования скважин, линейный дискриминантный анализ.

Рассматривается задача прогнозирования гидродинамической связи между добывающей и нагнетательной скважинной в очаге заводнения по геологическим характеристикам скважин по данным РИГИС и показателям разработки.
Для создания модели прогноза гидродинамической связи проведен анализ результатов трассерных исследований Центрального поднятия турнейского объекта разработки в верхнедевонско-турнейских карбонатных отложениях. В трассерных исследованиях участвовали 5 нагнетательных скважин и 17 добывающих, отбор проб производился в течение 6 месяцев. Данные исследования послужили обучающей выборкой. Для оценки сообщаемости добывающих скважин и скважин с поддержанием пластового давления был предложен и рассчитан параметр *dFP*, характеризующий степень влияния нагнетательной скважины на добывающие в очаге. По рассчитанному показателю *dFP* пары скважины были разделены на два класса: «плохой гидродинамической связи» («ПС») и «хорошей гидродинамической связи» («ХС»).
Анализ средних значений рассматриваемых характеристик пластов и показателей разработки в классах при помощи *t*-критерия Стьюдента по классам показал, что из 37 показателей в 7 различия оказались статистически значимыми.
При использовании предложенной классификации по показателю *dFP* на классы «ХС» и «ПС» в 62 парах добывающих и нагнетательных скважин по обучающей выборке был проведен пошаговый линейный дискриминантный анализ (ПЛДА), позволяющий получить дискриминантную функцию *Z* для последующей классификации. Использование полученной дискриминантной функции и рассчитанного граничного значения $Z_{гран}$ на обучающей выборке обеспечивает процент правильного отнесения скважин к группе «ХС» – 82,1 %, для группы «ПС» – 76,5 %. В общем доля правильного распределения в группах по обучающей выборке составила 79 %.
Анализ полученных результатов на проверочной выборке по соседнему Западному поднятию в турнейских отложениях показал, что применение дискриминантной функции *Z* в целом обеспечивает 75 % правильной классификации для всех очагов, что подтверждает возможности применения этой модели для прогноза гидродинамической связи в очаге заводнения.

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Introduction

Understanding the filtration flow distribution within the productive formation is one of the key factors for the rational oil reserves exploitation. The filtration flow distribution between injection and production wells allows for the assessment of the most rapid water breakthrough directions to the bottomholes of the production wells.

Complex carbonate reservoirs have the greatest sensitivity to rapid well flooding. This type of reservoir has the greatest variability of filtration and capacity properties compared to a terrigenous reservoir due to the complex structure of the pore space (pores, caverns, and cracks). Often, water breakthroughs to production wells are observed at the early stages of development, when reservoir pressure maintenance (RPM) systems are activated [1–7]. Therefore, it is important to determine which parameters influence the distribution of injected water flows within the reservoir.

The filtration flow distribution within the reservoir can be assessed using various methods: interference well testing, tracer studies, and streamline modeling in a hydrodynamic model [8–13]. However, only tracer studies are associated with mass transfer.

Tracer (indicator) studies are a method for studying the reservoir structure by adding a labeled substance (tracer) to the injected water in injection wells and fixing the tracer in the production well. This is a direct method of studying the interwell space associated with the direct mass transfer of fluids within the reservoir, allowing identifying its heterogeneity and determining the filtration relationship [14–19].

The main objective of tracer studies is to determine the hydrodynamic connection between production and injection wells, as well as the degree of their interaction by calculating various parameters: the arrival rate of the tracer, the number of filtration channels and their permeability, and the proportion of water entering through the filtration channels from the total volume of produced water and the volume of injected water.

For this study, injection wells areas are selected, where the tracer will be injected, and production wells for determining the labeled substance. Various tracers that are well soluble in water, insoluble in oil, and stable under specific reservoir conditions are used for injection wells [20–23].

The use of interference well testing methods and tracer studies requires certain constraints during the current reservoir operation throughout the research period, such as the absence of geological and technological activities or sudden changes in the operation mode of production and injection wells. This is rarely feasible in practice and can lead to significant economic losses.

Calculations of the streamlines on hydrodynamic models allow determining the relationship between production and injection wells, but they are highly dependent on the results of hydrodynamic model calibration and the correlation quality of reservoir layers in the initial geological model. Based on the modeling practice, the use of streamlines in hydrodynamic models does not accurately reproduce the actual rate of tracer distribution observed during field studies of wells.

Therefore, the methods development for assessing the wells relationship based on the analysis of production data from the current wells operation is a crucial task.

Characteristics of the research object

The studied oil field is located in the southeastern part of Perm Krai. The work focuses on the Upper Devonian-Tournaisian carbonate deposits (productive formation T) of the Central and Western uplifts, which are the main sources of geological reserves. The researched layer has a complex structure, with three productive layers identified (T1-2, T1-1, T0). The reservoir is composed of limestones that are irregularly dolomitized. The reservoir has distinct fracturing, which is confirmed by indicator diagrams that are convex to the flow rate axis, as well as by the permeability values obtained from well flow testing which exceed those from core and log data [24–27]. According to the studies of the composition and physical properties of the in-place oil, it has been identified that the oil from the Tournaisian object is bituminous and highly viscous.

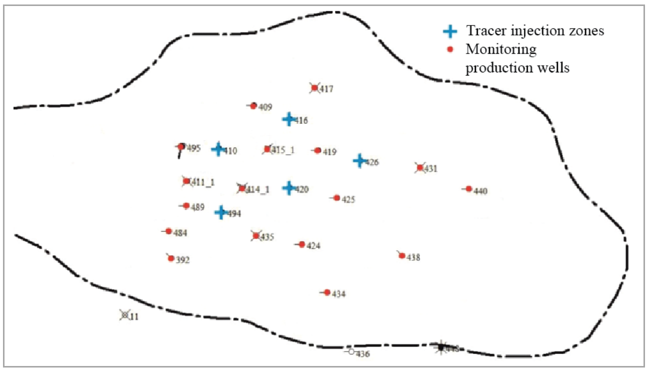

Fig. 1. Scheme of the Central uplift with tracer injection zones (training sample)

Since the beginning of the field development, high rates of well flooding have been observed. After the injection in 1983, a breakthrough of water in the extracted product was observed along with a decrease in oil production. Eight years later, the average annual water cut exceeded 45 %. Well flooding at this field is irregular in terms of the reservoir capacity and extension. The process is typical for high oil-to-water viscosity ratio, as well as for water breakthrough in highly permeable channels within the formation. The presence and potential formation of the channels may be indicated by the geological reservoir and development parameters [28–34].

Analysis of the tracer studies on the training sample of the Central Uplift

At the Central Uplift, the research was conducted in 2016 to study the existing system of filtration flows and identify the sources of production well flooding in the deposit center. The tracer studies involved five sites of injection wells (No. 410, No. 416, No. 420, No. 426, and No. 494). Monitoring of labeled substances was carried out based on data from seventeen production wells over a period of six months.

Based on the Central uplift data, a training sample was created, including the distribution parameter of filtration flows (*FF*) according to tracer studies, geological characteristics of wells according to well log interpretation results, and basic development parameters for both production and injection wells.

For production and injection wells, the following geological characteristics were considered: porosity coefficients (K_{por}), permeability coefficients (K_{perm}), oil saturation coefficients (K_{sat}), sandiness coefficients (K_{sand}) and reservoir compartmentalization coefficients, (K_{com}), as well as the effective oil-saturated formation thickness ($H_{eff.sat.}$).

Development parameters include data on: flow rates (Q) and cumulative production of liquid ($Q_{l.cum.}$) and oil ($Q_{o.cum.}$), water cut of well production (W), formation (P_{form}) and bottomhole pressure (P_{bot}) during the period of tracer studies, as well as fracturing parameters calculated on well testing data, including the proportion of fracturing (ω_{fr}), fracture opening (b_{fr}) and fracture permeability ($K_{perm\cdot fr}$) [35–39].

To account for the variability of fracture parameters along the reservoir strike, the differences in parameters between the injection and production wells in the source were calculated:

– $D\,\omega_{fr} = \omega_{fr}$ inj.well – ω_{fr} prod.well;

– $D\,b_{tr} = b_{fr}$ inj.well – b_{fr} prod.well;

– $D\,K_{perm\cdot fr} = K_{perm\cdot fr}$. inj.well – $K_{perm\cdot fr}$. prod.well.

To account for the heterogeneity of geological parameters between the injection and production well, gradients of all considered geological parameters were calculated:

GradD K_{por} = (K_{por} inj.well – K_{por} prod.well) / L;

GradD K_{perm} = (K_{perm} inj.well – K_{perm} prod.well) / L;

GradD K_{sat} = (K_{sat} inj.well – K_{sat} prod.well) / L;

$GradD\ K_{sand} = (K_{sand}$ inj.well – K_{sand} prod.well) / L;
$GradD\ K_{com} = (K_{com}$ inj.well – K_{com} prod.well) / L;
$GradD\ H_{eff.sat.} = (H_{eff.sat.}$ inj.well –$T\ H_{eff.sat.}$ prod.well) / L;
where L is the distance between wells.

To assess the production and pressure maintenance wells connectivity, the *dFF* parameter was calculated, which characterizes the effect degree of the injection well on the production wells in the source, as the difference between the distribution parameter of filtration flows in the well (measured in %) and the average value of this parameter for the source:

$$dFF = FF_i - \overline{FF},$$

where FF_i is the distribution parameter of filtration flows in the i well, $\overline{FF}$ – the arithmetic mean value of the filtration flows distribution in the source.

If $dFF < 0$, then the well has a poor relationship with the injection well in the source. Conversely, when $dFF > 0$, a high influence of the injection well on the production well is observed.

The study objective is to compare the results of tracer studies (*dFF* parameter) with geological and operational characteristics.

Based on the calculated *dFF* parameter, the well pairs were divided into two classes: if $dFF < 0$, the production well has poor connectivity with the injection well in the source, and the pair of "production – injection wells" belongs to the "poor hydrodynamic connectivity" (PC) class; if dFP > 0, the injection well has a high influence on the production well, and this pair of wells belongs to the "good hydrodynamic connectivity" (GC) class. However, in the case of a high percentage of the filtration flow distribution parameter for one well in the source, the classes were adjusted accordingly.

Using Student's *t*-criterion [40, 41], a comparison of the mean values for production wells and for pairs of production-injection wells was conducted for the considered parameters.

A total of thirty seven parameters were considered, of which seven were found to be statistically significant (Table 1).

The analysis of the considered parameters shows that out of seven statistically significant differences, four parameters relate to reservoir development parameters (or 57 %) while three parameters to geological properties of the reservoir (or 43 %). All values of the Student's *t*-criterion are high and have a significance level of $p < 0.05$. The group of development parameters is characterized by an excess of the considered parameters for the "GC" class over "PC". For reservoir parameters (reservoir characteristics), only for GradD K_{com} there is an excess of the average value in the "GC" class. It should be noted that out of three considered reservoir parameters, the parameter $D\ \omega_{fr}$ – is a dynamic value, since the degree of fracturing (fracture capacity) depends on the reservoir pressure.

Development of a forecast model for hydrodynamic connectivity of production and injection well pairs on the training sample of the Central uplift

Using the proposed classification based on the *dFF* parameter a stepwise linear discriminant analysis (SLDA) was carried out in sixty two pairs of production and injection wells, within the training sample. This analysis allows for obtaining a discriminant function and determining the most significant well characteristics for effective classification [42–45].

The results of the discriminant analysis are presented in Table 2.

As a result of the SLDA, the following discriminant function Z was obtained:

$$Z = -0.58870 + 0.03517\ W - 0.38588\ P_{prod} + 0.00007052\ Q_{o.cum.} - 1.38733\ D\ \omega_{fr} + 96.27906\ Grad\ K_{por}$$

$$\text{Wilks' lambda} = 0.647.\ \chi^2 = 25.035.\ p = 0.000137.\ R = 0.60$$

The histogram of canonical values distribution of the discriminant function Z is shown in Fig. 2.

The graph shows that the wells of the “GC” category are predominantly located in the zone of positive values of the Z parameter, in the range from 0.44 to 2.5. The range of Z values for the “PC” category varies from –2.7 to 1.6, however, more than 70 % of observations are in the negative value zone. The histogram shows a significant overlap between the "GC" and "PC" classes with Z values from 0.44 to 1.6, where there is a slight excess of "GC" determinations over "PC".

Table 1

Comparison of mean values by Student's *t*-criterion in classes "GC" and "PC"

Parameter	Parameter group	Average – "GC"	Average – "PC"	*t*-value	*p*
W, %	Development parameters	76.46	65.32	2.368	0.021
Q_l, m^3/day		21.71	15.21	3.511	0.0009
$Q_{o.cum.}$, T		39607.50	34534.40	2.189	0.032
$Q_{l.cum.}$, m^3		92941.14	70851.99	3.125	0.003
K_{com}, unit fraction	Reservoir parameters	8.96	10.29	-2.082	0.042
$D\ \omega_{fr}$, unit fraction		-0.13	0.18	-2.265	0.027
$GradD\ K_{com}$, prolayer /m		-0.000496	-0.002834	2.014	0.049

Table 2

Results of the discriminant function analysis

Parameter	Wilks' – Lambda	Partial – Lambda	*F*-except. (1.56)	*p*-level	Tolerance	1-Tolerance (*R*)
W, %	0.703241	0.920054	4,86602	0.031511	0.538430	0.461570
R_{prod}, MPa	0.807916	0.800851	13,92566	0,000446	0.445047	0.554953
$Q_{o.cum.}$, t	0.727507	0.889366	6,96623	0.010739	0.764354	0.235646
$D\ \omega_{fr.}$, unit fraction	0.747610	0.865451	8,70614	0.004623	0.698895	0.301105
$GradDK_{por}$, unit fraction/m	0.693455	0.933038	4,01898	0.049835	0.741816	0.258184

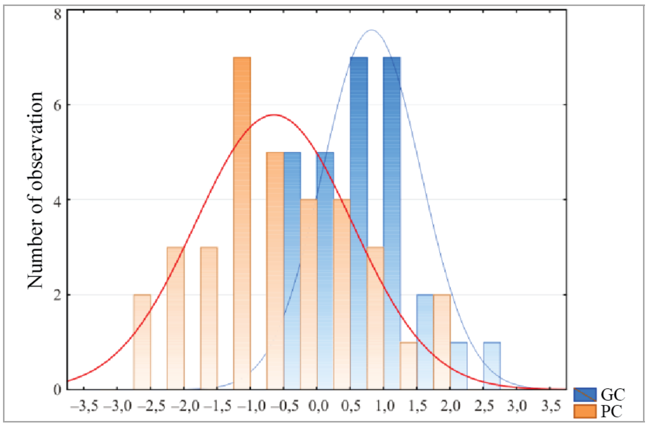

Fig. 2. Root histogram of discriminant functions by classes based on training sample of the central part of the studied field

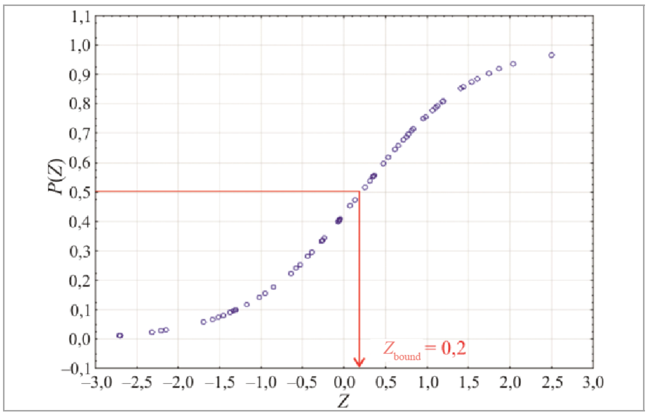

Fig. 3. Dependency of *P(Z)* on *Z* for the training sample in the central part of the studied field

Table 3

Classification results for training samples of the Central Uplift

Class	proportion of correct well classification, %	GC	PC
GC	82.1	23	5
PC	76.5	8	26
Total	79.0	31	31

Note: horizontally observed classes are shown, vertically – forecast classes.

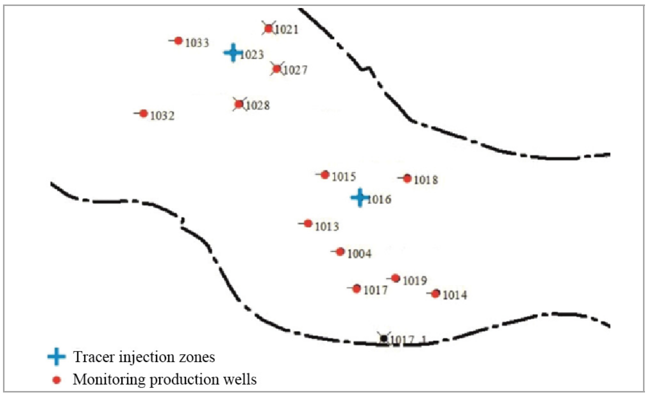

Fig. 4. Scheme of the Western uplift with tracer injections sites (test sample)

Analysis of the *Z* values shows that the greatest influence on the distribution of injected water within the reservoir is exerted by the water cut *W* parameters, bottomhole pressure of the production well (P_{prod}), and cumulative oil production ($Q_{o.cum}$), the difference in the fracturing ratio parameter between the injection and production wells ($D\omega_{fr}$), as well as the gradient of the porosity coefficient ($GradD\ K_{por}$).

Analysis of the *Z* function shows that $Z > 0$ for a pair with good hydrodynamic connectivity, which have high water cut *W* values in production wells (positive value of the coefficient at *W*). This is due to the presence of washed highly permeable water-saturated channels and steady filtration flows. The negative coefficient at P_{prod} is explained by the fact that a decrease in bottomhole pressure promotes fluid inflow into the well due to an increased depression. A positive coefficient for the cumulative oil production parameter $Q_{o.cum}$ indicates the need for long-term operation and the formation of washed zones. $D\omega_{fr}$ parameter has a negative slope coefficient, which is explained by the positive effect of low fracturing in the reservoir pressure maintenance well and high fracturing in the production well, since low fracturing in the injection well promotes even spread of the displacement front in all directions, and high fracturing in the production well facilitates to obtain the part of the filtration flows from zones more remote from the well. The positive coefficient value for $GradD\ K_{por}$ is explained by the high porosity in the injection well, which promotes greater reservoir pore capacity and accumulation of elastic energy in the well area and a small distance between the production and injection wells. High values of $GradD\ K_{por}$ are typical for wells that are close to each other.

To determine the boundary value Z_{bound}, which allows us to separate the class "PC" from "GC" class according to the discriminant function, we will use the dependency of the posterior probability of belonging to the group "GC" – *P*(*Z*) on the *Z* values (Fig. 3).

The graph shows that the boundary value Z_{bound} for classifying a well into the category with good connectivity is equal to 0.2. Wells with a *Z* value less than 0.2 will be classified in the "PC" category.

The percentage of correct production well classification based on the training sample of the central uplift is presented in Table 3.

Using the the obtained discriminant function ensures the classification rate of wells into the "GC" group of 82.1 %, and for the "PC" group of 76.5 %. In general, the share of correct distribution in the groups was 79 %. Using the obtained discriminant function ensures a correct classification rate of wells into the "GC" group of 82.1 %, and for the "PC" group of 76.5 %. Overall, the share of correct classification within the groups is 79 %.

Verification of the obtained model for predicting the hydrodynamic connectivity of production and injection wells pairs on the Western uplift

To verify the obtained model, based on the discriminant function *Z* for the training sample, tracer studies data from the Western Uplift of the studied field were used.

Tracer studies of the productive formation were conducted in October 2016 and included the sources of two injection wells (No. 1016 and No. 1023) and twelve production wells within them, which became a training sample (Fig. 4). These data were not used for conducting the SLDA at the previous stage to obtain the *Z* function.

For the wells of the training sample, the necessary characteristics for applying the forecast model of the interconnection class "GC" and "PC" were used and calculated: *W*, P_{prod}, $Q_{o.cum}$, $D\ \omega_{fr}$., $GradD\ K_{por}$.

The application of the obtained *Z* forecast model for the adjacent western uplift is acceptable, since both research productive formations are a single deposit, bounded by a single oil-bearing contour, with similar geological parameters, fluid properties and a single approach for development.

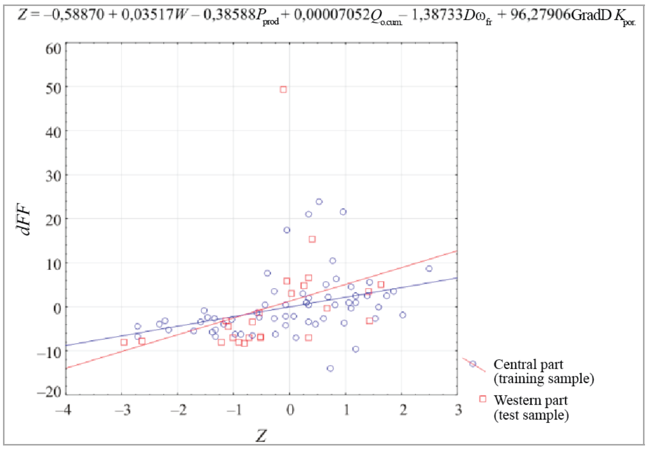

Fig. 5. Correlation fields between *Z* and *DF* according to the Central and the Western uplifts of the studied field

Table 4

Classification results for the training samples of the Western uplift

Training samples	Proportion of correct well classification, %	"GC"	"PC"
GC	62.5	5	3
PC	81.3	3	13
Total	75.0	8	16

Note: horizontally observed classes are shown; vertically – forecast classes.

Based on the previously obtained discriminant function *Z,* constructed on the training sample from the central part, the *Z** parameter was calculated for the training sample, and using the boundary value $Z = 0.2$, the class for the wells pair in the source was determined.

Using the results of tracer studies from the Western uplift, the criterion *dFF* was calculated, according to which the actual classification of wells was made. Then, a comparison of the predicted and actual assessments of hydrodynamic connectivity was made.

Figure 5 presents the correlation field between *Z* and *dFF*.

It can be seen that, despite the generally low *r* value, there is a positive relationship between the actual characteristic of the production and injection wells connectivity (*dFF*) and the calculated characteristic *Z*, based on the characteristics and parameters of the wells operation.

The correlation fields of the training sample (Central uplift) and the test sample (Western uplift) coincide quite well. There is a single outlier in the training sample with a value of $dFF = 49.16$. This high value of *dFF* is associated with an abnormally high percentage of the filtration flow distributed to well No. 1018.

Overall, a small variance in values is noted for $Z < 0$, indicating better convergence of values for the well category with poor hydrodynamic connectivity.

The percentage of correctly recognized categories "GC" and "PC" for the training sample from the Western uplift is presented in Table 4.

For the waterflooding source of well No. 1023 in the Western Uplift, the proportion of correct classification into the "GC" group was 66.7 % (two out of three wells), and into the "PC" group – 88.9 % (eight out of nine wells). For the waterflooding source of well No. 1016, classes were correctly identified in three out of five wells in the "GC" group, which amounted to 60 %, and five out of seven in the "PC" group (71.4 %).

Overall, the correct classification for all source was 75 %.

Conclusion

To assess the degree of injection well influence on the production well in the waterflooding center, the *dFF* parameter was proposed and calculated, which characterizes the hydrodynamic connectivity based on the tracer study results.

It was determined that for the training sample of the Central Uplift, the following parameters have the greatest influence on the distribution of filtration flows: water cut, bottomhole pressures in production wells, cumulative oil production, porosity gradient and the proportion of fracturing in the well area.

Using SLDA, a model for predicting the "GC" and "PC" classes was obtained, based on the discriminant function *Z,* and the critical value of *Z* was determined, which makes it possible to determine the class of connectivity between wells.

Verification of the model on the training sample from the Western Uplift showed a good forecast ability of the obtained model for well connectivity. Thus, the applied approach can be used to predict the filtration flows distribution in the reservoir.

The obtained results do not provide an accurate numerical assessment of the filtration flow distribution within the formation but rather allows for a qualitative characterization of hydrodynamic connectivity between wells in the center and enables its use as a trend in hydrodynamic modeling.

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